Applied Seismology for Engineers

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Week – 02 Lecture - 01

Lecture – 02

Music. Hello everyone, myself Dr. Abhishek Kumar. Today we are going to discuss in continuation to whatever we have discussed in last class. So, if you remember, in last class we were discussing about different layers in which the earth can be divided into, both in terms of composition as well as in terms of physical properties. Earth, which appears to be composed of soil and rock on the surface, but as you go deeper, there will be different material, different composition of the material existing at different levels beneath the ground surface. Secondly, we discussed depending upon the depth as well as the material existing, you can have sometimes molten material, sometimes solid material is also there. Thirdly, we discussed that because as you are going away from the surface of the earth, as you are going deeper, there will be increase in effective stress or overburden pressure because of overlying medium, considering the thickness or the diameter of the earth close to 12,500 kilometers.

If you move to the center of the earth, that is the core, you can see this different combination of overlying pressure as well as the temperature. As a result, if you start moving from the crust, then to the mantle, then to the core, different layers are there, some are in viscous state, molten state, some are there in solid state. In addition to that, we also discussed that there will be significant increase in the temperature starting from the surface. We had considered average temperature of 0, and as you go deeper and deeper, the temperature reaches sometimes of the order of 400 degrees centigrade, and subsequently, if you reach to the center of the earth, the temperature is reaching up to 7,200 degrees centigrade. Depending upon if you compare the density of the material available on the ground surface and average density of the earth, we can interpret that subsequently, at deeper depth, there are mediums of higher density, and these mediums are available in abundance. That means these are controlling the overall mass as well as the overall volume of the earth.

Because of variation in the temperature between each of these layers, consider an example of mantle. So, upper mantle and lower mantle, if you take the temperature variation between upper mantle and lower mantle, as the material solidifies or gets cooled down, the material becomes heavier, it will start sinking within the same layer. As it is moving down, the material will be experiencing increase in temperature, significant increase in temperature. As a result, the material will undergo expansion, it becomes lighter, and then it will come onto the surface. So, the continuous chain of sinking of the material and rising of the material will result in development of convection current in different layers. As far as the movement of the crust is concerned, primarily the convection current generated in upper mantle is responsible. It has been established that though there is convection current in lower mantle as well, that convection current's contribution to the movement of the plate is relatively negligible. Then we also discussed that depending upon the convection current generated in outer core and the movement of inner core with respect to outer core will decide the configuration of magnetic North and magnetic South Pole, and there are chances that the magnetic North and magnetic South Pole can change their positions. It can interchange with respect to each other. So overall, if you summarize whatever we have discussed in last class or in lecture one, is like, because of convection current, there will be development of stresses at the base of, primarily at the base of, crustal medium, as a result of which, whether it is oceanic crust or continental crust, each of these are in continuous motion. Depending upon the direction of convection current under a particular continental or oceanic crust, that will decide in which direction the particular landmass or the oceanic crust will be moving. Secondly, the rate at which it is implying the pressure or the base of the crust, that will also tell you the amplitude at which a particular plate is moving.

We have also discussed that different plates are composed in the earth. So, if you consider the surface of the earth, you can divide it primarily into seven major plates, and subsequently, 14 overall smaller plates are also included there. So, entire plates on the earth, we can divide it into 14 minor plates. So, in continuation to that, we also discussed depending upon the boundary at which the plates are moving, there can be possibility the two plates are moving towards each other. That is called as destructive plate boundary or convergent plate boundary. Secondly, is divergent plate boundary when the two plates were moving away from each other, or that is called as constructive plate boundary, and the third one is transform plate boundary where you will not have any kind of construction or destruction of the crustal medium. Rather, there will be slight past or relative motion between the two plates. So, that was an overall understanding about what is happening beneath the ground surface. Now, as for our understanding which we have developed from lecture one, we can say different plates are there which are moving away from each other in different direction and at different rates.

In today's class, we will discuss more about the fault, what are the faults, where earthquakes are happening, what are the important terminologies related to the fault, and what happens during a particular earthquake, and for our understanding, how we can correlate the process which is happening at the point of location of the focus of the earthquake in general understanding. So, the topic fault plane solution basically is an indication of what is happening at the fault plane or the location where the kind of stresses are getting released during a particular earthquake. So, there is a correlation between the movement of the plate and the occurrence of the earthquake, which we will discuss in today's class. So, this topic fault plane solution that will continue for more than one class. So, you may see some overlap of fault plane solution to lecture three also.

So, where do earthquakes occur? We have understood based on our lecture one content that there are different plates moving, and depending upon the direction, sometimes these two plates are coming in contact with each other. We also discussed when two plates are coming in contact with each other, usually the younger plate bends down under the older and relatively thicker plate. Now, at the process of going down, the younger plate will also experience significant increase in temperature, results in melting of the material, which subsequently comes onto the surface in terms of volcanic eruption. Sometimes you can also have ridges, valleys at the boundaries. So, when we are interested to learn about earthquakes, earthquake occurrence where primarily the earthquakes have been witnessed, we see a strong correlation between occurrence of earthquakes and the plate boundaries.

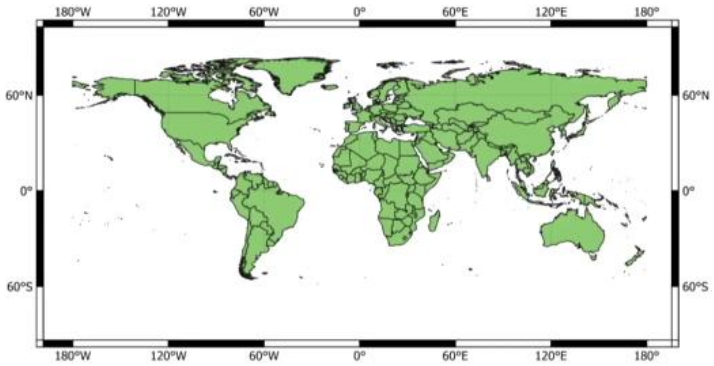

Fig.1 Earthquakes occurred in the year 2021 and the tectonic plate boundaries

So, over here you can see different continents across the globe. In order to understand where the earthquakes are generally happening, we can superimpose the earthquakes which have occurred in the year 2021.

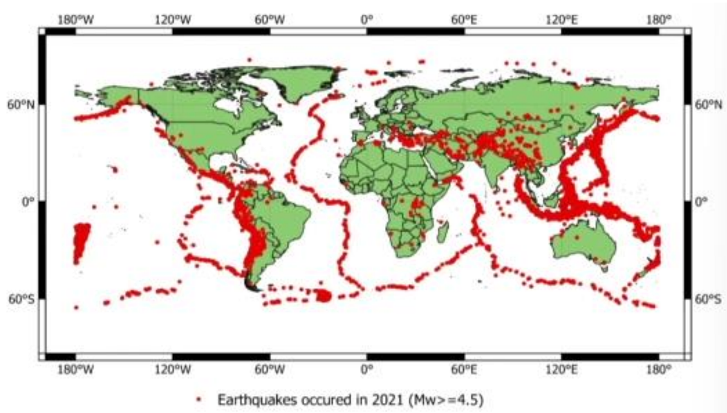

Fig.1 Earthquakes occurred in the year 2021 and the tectonic plate boundaries

Please understand, here I am taking into consideration only those earthquakes which are having magnitude greater than or equal to 4.5, just for representation. So, magnitude of the earthquake is not very important here, but what we are trying to understand is, if you take into account the boundaries of major plates and minor plates also, and the location of significant number of earthquakes happening across the globe, you will see these are the, so there in this particular slide, so far, you are having different continents and major earthquakes which have happened in the year 2021.

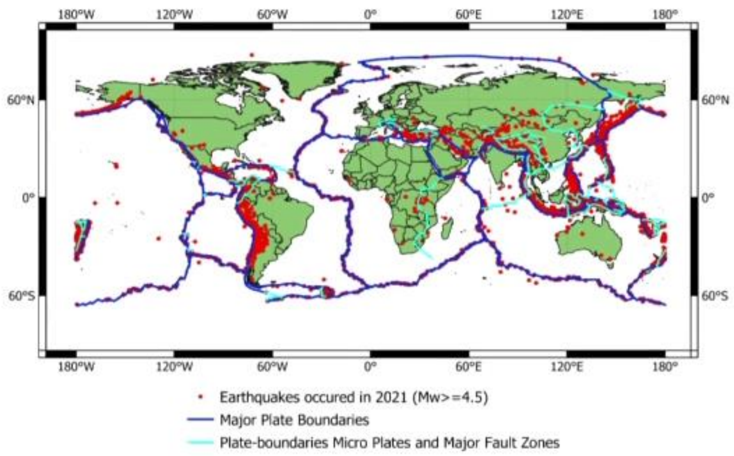

Fig.1 Earthquakes occurred in the year 2021 and the tectonic plate boundaries

If you superimpose this with respect to major plate boundaries, what we can understand, if you compare this particular image with respect to the previous image, we can understand that there is significant correlation existing between the plates or the plate boundaries and the occurrence of the earthquake or the location where earthquakes are very frequently witnessed. Even in one year, majority of the earthquakes are confined primarily to the plate boundaries. It is not only limited to major plates, but also minor plates also. So, one analogy which can be developed is there is some correlation between the plate boundaries, as well as the location of the earthquake or the epicenter of the earthquake, what is known at the ground surface. So, it is observed that most of the earthquakes occur near the plate boundaries.

Now, remember what has been discussed in lecture 1, plate boundaries means when the two plates are coming in contact with each other, generally in convergent plate boundary, there will be development of stress beneath the older plate and above the younger plate. So, if you see these two plates, one plate is going down; you can see the common area between these two plates is experiencing some form of shearing. So, this plate is moving, and this plate is overriding, so there will be shearing happening at the common interface between the plates, and this is the phenomenon which is happening at the plate boundary. Let's move. So, once we have seen that plate boundaries and the occurrence of earthquakes have significant correlation, the occurrence of earthquakes is usually along the convergent plate boundary because there will be development of stress there, and unlike the divergent plate boundary, you can see the majority of earthquakes primarily occur at the convergent plate boundary. So, you can see over here the occurrence of earthquakes in convergent plate boundaries. Again, in this particular picture, you can also locate what are the major convergent plate boundaries across the globe, what are the important divergent plate boundaries, and transform plate boundaries. So, you can see the majority of the time, very high occurrences of earthquakes are witnessed in convergent plate boundaries.

So first, this correlation between plate boundaries and the occurrence of earthquakes, then among different plate boundaries, there is a very high chance of the occurrence of earthquakes at the convergent plate boundary. The movement of the plates, which is happening at the plate boundaries, results in what I was mentioning also: when the two plates are coming in contact with each other, usually at the convergent plate boundary, there will be a building up of stresses over here in the common area. There will be a building up of stresses, and these two plates are running for hundreds and thousands of kilometers. So, depending upon the location primarily where this particular kind of overlapping or building of stresses and building up of strain energy is happening, that will define what the locations primarily are where there is storage of strain energy. Remember, this storage of strain energy is happening within the medium. Generally, the rocky medium is available; the crustal medium is there in which this building of strain energy is happening. This building of strain energy will continue as long as the strength of the material—there is one material over here, and this one material over here—as far as the strength of these materials is able to withstand the strain energy which has been built up because of the two plates' movement, there will not be any failure in the material. The moment the building of strain energy exceeds or the stresses which were developing at the interface between the two fault planes or the common area between the plate boundary exceed the in-situ strength of the material involved, so, there is material involved here, and the material involved here, when the shear strength of this particular material is exceeded by the stresses which are developing at the interface, the material will undergo failure. So, there can be rupture, there can be melting as a result of this particular phenomenon, we call it the occurrence of an earthquake. So, two materials, plate boundary, because of convection current, these two plates come in contact with each other. Because of the development of stresses, since these two plates are still moving towards each other, it is not like at the time of convergence the plates are moving, and then once they start colliding, it stops. So, it did not stop. The continuation of the movement of the plate boundary is still happening, and part of this energy is also getting stored at the common interface, which subsequently results in the development of stresses at the common area. How much stress can be stored will be defined by what the shear strength of this particular material is. Once the shear stress developing at the interface exceeds the shear strength of the material, the material will undergo failure in terms of melting, in terms of rupture, and then when the material undergoes rupture, there will be the development of disturbances or waves, which we will discuss in later classes.

So subsequently, what we have understood is that because of the movement of the plate, there is a building up of strain energy, which is a continuous process. Across the globe you will see on the plate boundary there will be development of stresses. Where the development of stresses is more or the release of energy is happening frequently, you will witness frequent earthquakes. Where the development of strain energy is taking longer or where the strain energy is stored but there is no earthquake, you can experience major to great earthquakes, as have been witnessed in the past. So, these are continuous processes happening across the globe. So based on this particular slide, we can understand that the occurrence of earthquakes is primarily confined to plate boundaries. Further, at the plate boundary, it is because of the building up of stresses at the plate boundaries. Subsequently, as we discussed in the last class also, the storage of strain energy, though it is confined to the plate boundaries, will subsequently also see some kind of storage of strain energy within the plate itself that will result in the occurrence of earthquakes within the plate itself. So, though you can see primarily the occurrence of earthquakes has been confined to plate boundaries, at the same time, there are earthquakes that are happening within the plate also. So, these earthquakes are basically the result of the building up of strain energy or storage of strain energy within the plate itself. But still, we can understand the majority of the earthquakes are happening along the plate boundaries.

Again, we can also see over here the Himalayas, which are over here. In the last class, we discussed the Indian and Eurasian plate boundary. So, you can see over here the Indian plate and the Eurasian plate, where the Indian plate is subducting under the Eurasian plate. What we see in general is the development and rise of the Himalayas. The process of the development of the Himalayas started somewhere around 50 million years ago, and still, we can see the Himalayas are rising. So, this process of rising, development of ridges, valleys, mountains, volcanic eruptions, and long chains of ridges are continuously witnessed all across the globe.

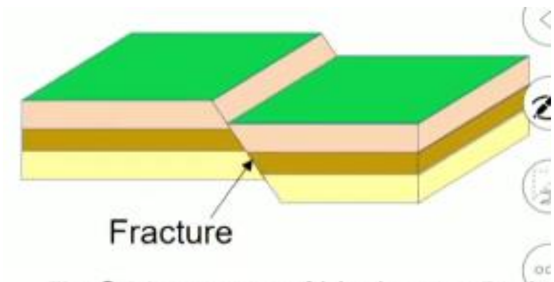

Fig. 2 Movement of blocks on a Fault

So, in general, we discuss the plate boundaries in order to understand, on a regional scale, where the earthquakes are happening, one term that will often be called is fault. So, you can see in this particular image also when we were discussing the plate boundaries, the two plate boundaries were either moving towards each other or away from each other. But if you focus on the plate boundary, there will be some three-dimensional plane involved over here, as witnessed over here. So, if you take a cross-section of the plate boundary, you can see primarily there will be some thickness of the material involved; some stratification is also involved, and then during the process of plate movement, the two plates—here you can see the two plates are actually moving away from each other. That is why you can see the two plates are actually—one is going down; one is going up. As a result of this, on this particular common area which is common to both parts—part one as well as part two—these two are in continuous motion, and there will be the development of stresses in this common area. So, this process of development of stresses, whether it is happening at the plate boundary or within the plate itself, is mainly confined to faults. So, a fault is basically a crack or fracture in the earth's crust along which two blocks are present on either side. So, from now onward, we will not call them plate boundaries because there can be the development of stresses within the plate itself. So what we are generalizing at this moment is wherever there is a building up of stresses, usually it will be happening along a linear segment available on the surface, even a curved segment on the surface, or if you see in the plan such that on either side of this feature, there will be relative movement of the two blocks: one block located on one side of the linear feature and the other block located on the opposite side of the linear or curvilinear feature.

So, this particular block, this particular feature, is called a crack or fracture, and in general, it is the fault. So, it is basically the linear feature which is available on the earth's surface. If it has been located or mapped such that the two blocks—one on the left-hand side, the other one on the right-hand side—are moving with respect to each other. So cracked features where there is no movement of the blocks with respect to each other are generally called joints. So, if there is no movement; you call it a joint. If there is movement, you call it a fault. The movement along the fault that I am showing over here is a kind of inclined movement. You can see here; this movement is like inclined movement. So, if you see from the top, you will see one block is like this, one block is like this, and these two blocks are moving with respect to each other as they are moving away from each other. Such movement, depending upon the inclination of this particular plane, this movement can be completely vertical if the fault plane is such that the edge of the fault is completely vertical, and there is a relative motion, so you can call the two blocks are moving with respect to each other in elevation. Similarly, it can be inclined as shown in this particular picture, it can be horizontal also as you see in transform plate boundaries, so two blocks are moving with respect to each other. So horizontal is also possible, vertical is also possible, inclined is also possible, and the last one is it can be a combination of vertical or horizontal or inclined or two inclined movement. So, this is also possible there. So, any kind of movement along the fault which is happening within vertical, horizontal, inclined, or the combination of these two, that is generally the procedure happening at the fault.

So, movement along the fault can be vertical, it can be horizontal, or it can be a combination of more than one kind of movement. The movement of the block can be seen many a time as very fast movement or progressive movement, and it can be very steady movement or very slow movement also. Now, again, depending upon the geometry of the plate boundary, you can see the movement, the rate of movement, it may remain uniform throughout, or there can be subsequent variation in it along the plate boundaries. Then in terms of faults, we can see sometimes the faults are ranging maybe 30, 40, 50 kilometers, but at the same time, you will also see some faults which are running for 500, 1000 kilometers in length. The information about the fault is very important depending upon the geology of particular segment of the earth one is interested in.

So, if you are interested to understand the geology, the faults, because there is some kind of movement happening along the fault, which is going to give you more information about the geomorphological feature in and around that particular study area, that will help you in understanding the geology of your study area. A critical example is if you are interested to study about the mountains, ridges, valleys, volcanic eruptions, certainly these features you will also find out in and around your fault because the fault will create an environment such that these features can be created as secondary effects of fault movement. Now, when we discuss about the fault, we have understood fault means there is a fracture in the rock as evidenced on the surface, which is running maybe hundreds of kilometers in length and subsequently of the similar dimension in perpendicular direction. So in order to understand what kind of movement is happening when we say about fault plane solution or the movement, that means we are interested in how these two blocks are moving in general such that when we are interested in finding out what has happened during a particular earthquake, we will be able to understand maybe one block has moved away from each other, one block has moved down with respect to the other block, it has moved up with respect to the other block, or there can be different combinations of the movements. So certain terminologies which will come into the picture as far as the movement of a particular fault is concerned.

The first one is strike. Strike is very important because when we see a particular fault on a map, we will only see a linear feature; if you see in the plan, strike is going to tell you what is the orientation of this linear feature with respect to the north direction. So, because if you see in the plan, it can be inclined in different orientations, in order to have a generalized understanding about what is the orientation of the fault, the term strike comes into the picture. So, it is going to tell you the strike of a fault is its bearing or geographic direction of a line obtained by the intersection of the fault plane in the previous slide we have fault plane. So, this fault plane, this particular line, if you see the line which is created over here, the intersection of the fault plane with respect to ground surface, that is going to give you the trace of the fault or how the fault is appearing on the ground surface. Now, this particular trace, what is the orientation of that trace with respect to the north direction?

So, sometimes you can also call it bearing or geographic direction of a line obtained by the intersection of a horizontal plane, that is, ground surface, and the fault plane. So, if you have an intersection of a fault plane, which is running at some inclination or maybe vertical and ground surface, you will end up getting a line. The bearing of that particular line with respect to north is basically defining the strike of the fault. The only thing, the direction of the movement of the strike has to be kept in mind such that the fault is dipping to the right side of the observer. If I am the observer, I am standing on the fault and looking in one particular direction of the fault, I have to make sure that the fault is dipping. Dipping means the inclination of the fault is happening towards the right-hand side of the observer. This will make sure that when the dip is happening on the right-hand side of me, then the direction in which I am looking is the direction whose inclination with respect to north I have to measure. So, if I am interested, I am looking in this particular direction on the ground surface or perpendicular to the board, then what if I am looking in a particular direction, and this is the direction of the north? So, the inclination which these two hands are making or the angle which these two inclinations are making such that when I am looking in the direction of the fault trace, the fault is dipping towards the right-hand side. If I take a particular fault like this, so dip means the inclination of the fault plane with respect to horizontal. So, this particular inclination, what is given in the previous slide also, this particular inclination of the fault is the dip of the fault. So, when I am looking, when I am standing on the fault trace and interested in finding out the fault strike, I have to orient myself such that my line of sight is in the direction that my left-hand side I am able to measure the dip of the fault. If this is happening, then certainly I am in the right direction; whatever the inclination of my line of sight with respect to north, that is defining the strike of the fault. So, it is usually measured in a clockwise direction with respect to north, depending upon the dip of the fault and the orientation of the fault, the strike value may vary from 0 to 360 degrees.

The next term which comes into the picture is the dip. The dip of the fault is its inclination. Remember, we are discussing the fault plane. So, the dip of the fault plane means the common plane which was common to both blocks, the inclination of that particular common area with respect to horizontal, with respect to ground surface, whatever is the inclination. So, if I am talking about a fault which is completely the fault plane, which is completely vertical, I can say the dip of the fault is 90 degrees. If it is slightly inclined, then depending upon what is the orientation of this inclined surface with respect to horizontal, that is going to give me the dip value. Now, if you see in section, if this is the fault, this is the line indicating the inclination of the fault, and I am the observer who is supposed to give you the strike and dip value. So, I will stand like this, and if on the plane, this line is indicating the fault trace. So, I am standing such that the measurement of dip is on my right-hand side, and the direction in which I am looking into, that is basically defining the strike, the orientation of that line with respect to north, it is going to give me the strike value measured in a clockwise direction.

The next term which will come into the picture is hade. So, hade is basically the inclination of the fault plane with respect to vertical but not with respect to horizontal. So, the hade of the angle hade is the angle which the fault plane is making with respect to the vertical. So, if you add up hade as well as dip, it will completely add up to 90 degrees. So, one is with respect to horizontal; that is the dip value. The second one is the hade value, which is with respect to vertical. The fault plane or the fault surface is the surface or the plane on which the two blocks, one block which is above the fault plane and the other block which is below the fault plane, actually are undergoing some kind of movement. So, this common area which is marked over here, the entire trace of that common area on which the two blocks are moving with respect to each other, that is basically the fault plane or fault surface. Now if you again look into the slide, so there are two blocks: one block which is located above the fault plane, and the other block which is located below the fault plane. So, the block which is located above the fault plane, you can call it as hanging wall; the other one which is located below the fault plane, you call it as foot wall. It is easy to identify as far as you are having an inclined fault plane; if the fault plane is vertical, then there can be anyone can be hanging wall, other one can be foot wall. So that is how you can get an understanding about what is happening at the fault plane. So right now, it is going to basically only give you information about the orientation of the fault plane or the orientation of the fault. Fault stack is going to give you the orientation of the fault trace. Dip is going to tell you if there is a fault plane, what is the orientation of that fault plane with respect to the ground surface. Hade is going to tell you what is the orientation of this fault plane with respect to vertical. Then fault plane is already given there: whatever block is located above the fault plane, that is called as hanging wall; which is located below, that is called as foot wall.

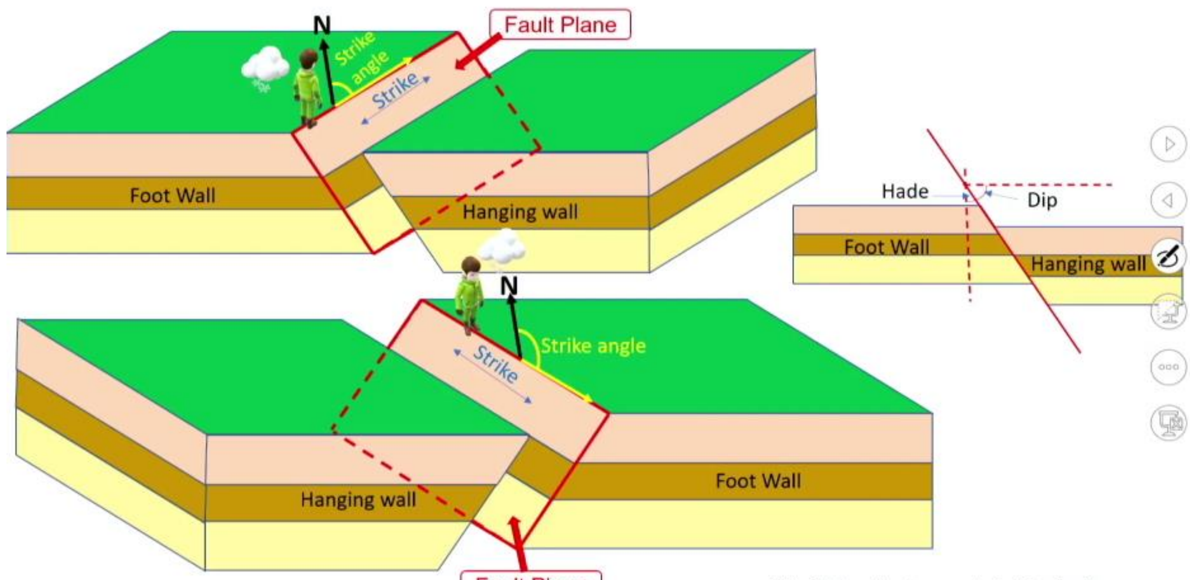

Fig.3 Terminology related to fault

So, you can see in this particular picture the observer is standing over here, and this is your fault inclination; this is your fault plane; this entire area is basically the fault plane; this is fault block 1, and this one is fault block 2. Remember fault block 1, fault block 2, it is a general understanding of the geometry of your problem definition where the earthquake is happening. So, this is fault block 2, this is fault block 1; if you look at the plate boundary, you can say one is coming from plate boundary 1, and the other one is coming from plate boundary 2. Now in this particular case, you can say this is representing a divergent plate boundary if the two fault blocks are moving away from each other. If these two are moving towards each other or the moment is the hanging wall is moving upwards, the foot wall you can call it as a convergent plate boundary. Again, over here, you can see there is an observer. The observer is standing in such a way that the orientation with respect to horizontal, the orientation of this particular fault block is actually located on the right-hand side of the observer.

Now I am pointing in some direction; I have to measure the orientation of this fault trace. You can call this as fault trace, this as fault plane . So, inclination of fault trace with respect to north, is going to give you the value of the strike angle. Inclination the fault plane is making with respect to horizontal is going to give me the value of dip. The other value, what it is making with respect to vertical, is going to give me the value of hade, and now here you can see this was a fault plane. So whatever block is above the fault plane, that is called as hanging wall; which is below, it is called as foot wall. So, fault plane is there, dip is there, hade is there, strike is there, hanging wall is there, foot wall is there; all these things are only going to tell you the position of the blocks and the orientation of your fault plane. This is the fault plane, and what is the orientation of the fault plane, which is the hanging wall, which is the foot wall, and now if you have all these information, you can at least locate your fault plane. Still, it is not indicating the direction in which the two blocks are moving. Right now, I cannot say whether the foot wall, the hanging wall is moving up, or it is moving down; even in the other one also, the second picture also, I cannot say whether it is moving down or it is moving up because so far, I do not have complete information about the movement. It is only going to tell you what is the configuration, what is the position of the fault plane, and the position of the two blocks, which block is above the foot wall or which block is below the hanging wall. So, you have some more terminologies to come in the next slide.

Let us see about rake; this is one important terminology because this is going to tell you the direction in which the hanging wall along the fault plane is moving with respect to the foot wall. Usually, the value of rake, because it is an angle, it is measured in an anti-clockwise direction with respect to the fault strike. So, you have, based on the location of the dip, you have decided in which direction one has to look in order to measure the strike value. Now with respect to that direction, which direction the hanging wall is moving, that particular angle in anti-clockwise direction once you measure it is going to give you the rake angle. So up till the information about strike, dip, and rake angle, it is complete information about what is the orientation of the fault, what is the orientation of the fault beneath the ground surface or fault plane, and what are the possible movements during a particular earthquake. The dip and strike are not going to change during different earthquakes, but certainly, if the two blocks are moving towards each other, away from each other, or slide past each other, that will be indicated by the value of rake of that particular event.

Slip is basically going to define any point before the movement and after a movement how much displacement, relative displacement of that particular point has happened when the two blocks, that is, hanging wall and foot wall, were in contact with each other completely or before the movement. So, this is always a relative position because the process of movement is continuous. If I am interested to find out how much movement has happened in the last 5 years, last 50 years, then I will pick up a point and then find out how much movement when this point was common to foot wall and hanging wall 50 years back or 10 years back and what is its configuration at present. So, if one point was common with respect to foot wall and hanging wall, and the position of that point 50 years ago and the new displaced position of this point at present, this particular distance is going to give me the information about the slip value. Generally, it is measured along the fault plane.

Separation is expressed as the distance between two points or two faulted beds or layers with respect to when these two points or this particular location was firmly attached with respect to each other or when this particular point was common to both foot wall and hanging wall. Now, in order to differentiate or in order to define different values of movement, generally, three terms are used: one is offset; it is the normal horizontal displacement measured perpendicular to the faulted horizon in the horizontal plane. So, it is going to tell you how much horizontal displacement has happened in the direction perpendicular to the faulted plane, and measured in the horizontal plane. The second one is throw; it is the vertical component of dip separation measured in the direction perpendicular to the strike of the fault. So, you are basically going to measure how much is the vertical component which has happened in the direction of movement measured perpendicular to the strike direction in vertical direction. Same thing, if you are measuring in horizontal component of the movement with respect to strike, that will be called as heave direction.

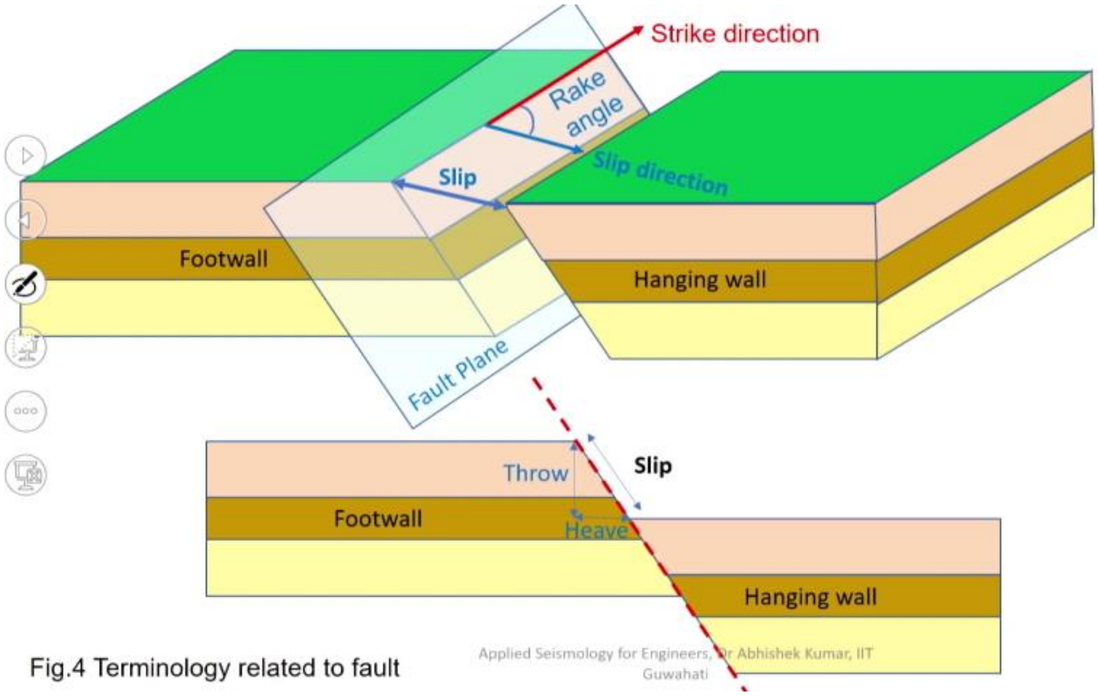

Fig.4 Terminology related to fault

You can see over here, so there is a fault plane over here. Again, there is hanging wall and foot wall depending upon which portion is located above and below. You can see over here that direction in which the hanging wall, same point in the hanging wall, is moving with respect to foot wall, measured with respect to strike direction in anti-clockwise direction, that is going to give me the rake angle. Again, throw: how much movement, again this is relative movements, how much movement in vertical plane along the fault block which has been happening because of movement of the foot wall and hanging wall in a given time. So, throw is going to give you the vertical component, and heave is going to give you the horizontal component considering these two points, this particular point which is a point of observation with respect to which you are interested to find out the throw and heave. At some point of time, this point was located common between foot wall and hanging wall. So, suppose you consider a point at the current configuration over here; how much this particular point, if I am interested to find out the heave value in the next 20 years, how much this particular point has moved in the next 20 years, in 30 years, and then measurement with respect to its initial position along the fault plane, that is going to give us the value of heave and the value of throw. So, it is basically an indication of how different points along the fault plane have moved with respect to time, which subsequently were at some common location between hanging wall and foot wall, but because there is continuous movement between hanging and foot wall, there has been some relative motion which can be measured in horizontal as well as in vertical direction.

Some other terminologies: shear zones, basically these are the areas which consist of rocks which are relatively under more strain in comparison to the surrounding zones. So, if you go to particular zones and try understanding what are the rocks which are more stressed with respect to other rocks, so generally such zones are called shear zones, where there is more dominance of shearing happening in the particular region because of governing tectonic setting, because of geomorphological features that can come under shear zone. Now, depending upon the characteristics which shear zone shows or the material and within the shear zone show, you can have again four classifications. One is brittle shear zone; as the name suggests, generally in this particular zone the material will show brittle characteristics or brittle deformation, or there will be cracks or fractures. Then you go to brittle-ductile shear zone, so it has combined features of brittle as well as ductile characteristics, that the material is undergoing movement displacement. Then ductile shear zone, so there will not be any formation or any features of brittle shear zones, but completely it will be ductile; you can see some kind of relative motion with no fractures or brittle deformation. Then semi-brittle will be there, so here generally there is release of pressure which was building up, which will also result in the development of cataclysmic flows. So, such features are called semi-brittle features or semi-brittle shear zones.

The importance of shear zones is it is going to provide you a lot more information about the building up of stresses, how it has been happening throughout the history of the deformation of the rock. This will also help in understanding how much development of stresses, how much storage of strain energy in geological time scale has been happening in a particular shear zone. So, these are important because that can basically correlate the storage of strain energy here and what is happening to the in and around of that particular area, primarily in terms of building up of stresses in faults. So basically, this is going to give you more indication about what has happened in the past in terms of building up of strain energy, what might have also triggered earthquakes in and around that particular area. So, shear zones are quite important in order to understand the complete history or at least a significant portion of the history that will give you more confidence about what is the pattern of development of strain energy or storage of strain energy in a particular zone, what are the features which are responsible for that, and what will be the effect of those features on governing tectonic settings for a particular fault which is available in the nearby region.

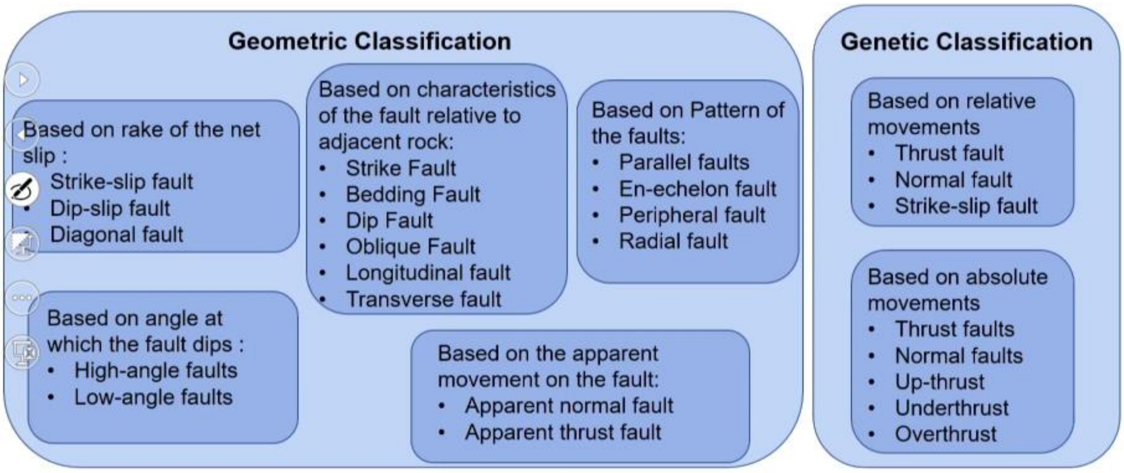

Fig.5 Diagram to show different type of classification and types of fault in each classification (Billing, 1946)

Again, when we come for classification of the fault, that means depending upon the movement of the fault primarily, we can go for classification of the fault that will help in understanding what is the dominating way in which the fault is going to be responding in the geological time scale. So usually, this classification occurs in a variety of ways. We can see over here one is geometric classification; that will be completely dominated by the geometry of the fault. Other one is genetic classification; in genetic classification, we try to understand or classify the fault based on the nature of relative movement. The first one was based on the dimensions; the next one is based on the relative movement of the fault, and generally, when we go about classification or nomenclature in the particular fault, we generally refer to genetic classification. So here is a complete picture of classification in a variety of ways a fault can be classified into. So first one, you can see over here based on geometric classification; the one which is given based on the relative displacement on a particular fault. First one is you can see over here based on the rake of net slip; if you see some slide back, we have also indicated the slip. Slip means any particular point when it was common to both strike and dip and how, because of the movement of the fault, this particular point has changed its position between the hanging wall and the foot wall. So, based on the slip or the nature of the slip during movement happening at the fault block, we can classify a particular fault as strike-slip fault; that means the slip is happening along the direction of the strike, that is called as strike-slip fault. Same way, you can have dip-slip fault; so, you know what is the orientation of that particular fault with respect to the ground surface. If the hanging wall and foot wall movement is happening along that particular direction, then you call it a dip-slip fault. Diagonal fault, you can have both the components of strike as well as dip-slip; that will come under diagonal fault. Now, depending upon the angle of dip, you can call it a high-angle fault if the angle of dip is significantly high, or if the dip is a very low value, then you call it low-angle faults.

Then depending upon the characteristics of the fault related to adjoining rocks, you can call it a strike fault, bedding fault, dip fault, oblique fault, longitudinal fault, transverse fault. Again, based on the pattern of the fault, you can have parallel faults; many a times, you will find a number of segments of the faults parallel to each other, en-echelon faults, peripheral faults which are running along the periphery or in a curvilinear fashion, then radial faults are also there originating from a common region and radiating in different directions. Depending upon the apparent movement of the fault, you can have apparent normal fault or apparent thrust fault. So, this is, in a nutshell, you can classify the fault depending upon which characteristics of the fault movement is known to you; you can pick up the defining criteria and then further you can classify that particular fault and its associated movement in terms of geometric classification. Next one, you go for genetic classification; then based on relative movement, we have already discussed thrust fault when the two blocks, hanging wall and foot wall, are moving relative to each other; there is no movement along the dip, you call it as thrust movement. Normal faulting when the two blocks are moving away from each other, strike-slip faulting when the movement is happening along the strike of the fault.

Again, based on the absolute movement, you can have thrust fault, normal fault, up-thrust fault, under-thrust fault, over-thrust fault. So please understand this is a general understanding about the fault available in a particular region, primarily based on what is the characteristics of the medium and what is the relative motion happening between the fault block, foot wall, hanging wall with respect to strike, with respect to dip, again with respect to orientation of the fault plane or the value of the dip, whether it is low value, high value, whether the slip is happening completely along the dip or along the strike or a combination of both. So, this classification was given as per Biling 1946.

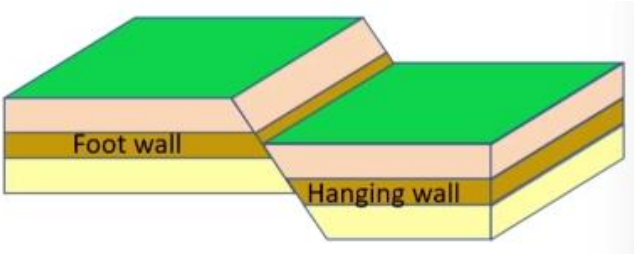

Fig.6 Normal fault

So over here you can see again based on the type of movement that there are two blocks which at the fault plane are moving away from each other. You can see over here in the case of normal fault, the hanging wall moves downward in relation to foot wall. So, there is a hanging wall which is moving downward in this figure also you can see. So, there is one block which is located above the fault plane but it is moving down, it is moving down along the fault plane but still it is above the fault plane, it is moving down.

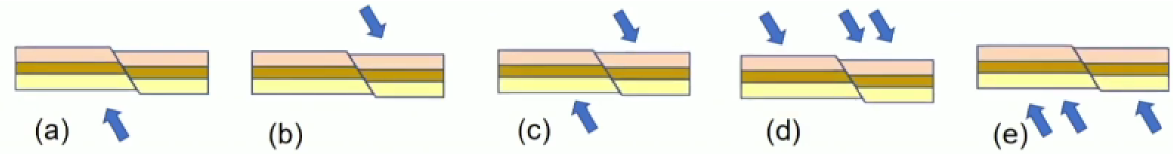

Fig.7 Motions of the blocks in the case of normal faults

Now depending upon the relative movement there are different combinations. First one, figure A suggests that the foot wall is moving up; that means the hanging wall is considered downward movement. Second one is the hanging wall is moving downward. Third one is both hanging wall and foot wall are suggesting movement away from each other. Fourth one, the hanging wall is moving downward with higher magnitude with respect to foot wall, which is also moving downward. So that will also show you, relatively, there will be downward movement of the hanging wall with respect to the foot wall. Same way, if the foot wall is moving upward with larger magnitude and the hanging wall is having relatively smaller magnitude, again that will indicate some kind of normal faulting. So, it is not always that the two blocks should be moving; absolute movement should be there in the two blocks. Even relative motion between the two blocks suggesting the two blocks, hanging wall and foot wall, are moving away from each other, that will be called as normal faulting. Usually, the rake angle is minus 90 degrees if there is pure movement along the dip. These are also indications of extensional faults or divergent plate boundaries. If you look at plate boundary, that will be called as divergent plate boundary or extensional plate boundaries. Most common divergent plate boundary example is rift valley of East Africa.

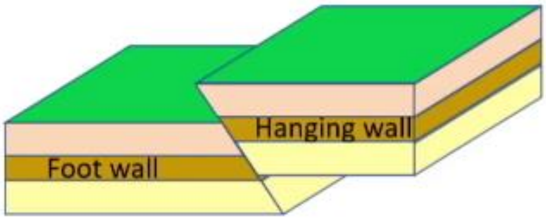

Fig.8 Reverse fault

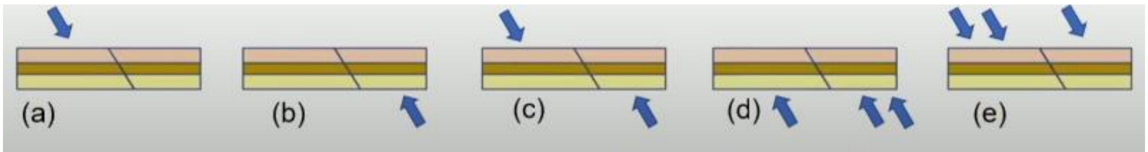

Fig.9 Motions of the blocks in the case of reverse fault

Then we can see about reverse faulting. So, it is just the reverse of normal faulting. In normal faulting, the hanging wall was moving away from the foot wall; here, the hanging wall and foot wall are moving towards each other. So, in figure A, you can see the foot wall is moving towards the hanging wall. In figure B, you can see the hanging wall is moving towards the foot wall, such that if you see the relative motion, the two blocks are coming closer to each other or there is an indication of compression. The third one, if you see, the two blocks are both in motion and both motions are towards each other. Fourth one is ; the hanging wall is also moving, foot wall is moving, but the hanging wall movement is more; that is also an indication of reverse faulting. In the fourth one, the downward movement of the foot wall and slower movement of the hanging wall, but as a result, the relative motion between the two is these are moving towards each other, not away from each other. So, all these possible combinations A, B, C, D, E indicate the potential movement which a reverse fault can show in actual site conditions. So, rake angle for reverse fault is plus 90 degrees. We can also interpret the movement of the hanging wall measured in the anticlockwise direction with respect to strike, indicating the movement of the hanging wall along the fault plane. So, if you start interpreting that direction, you will see the reverse faulting, indicating a rake angle of above 90 degrees.

Again, depending upon if it is purely along the dip or if it is having a horizontal component also, you can determine the rake angle accordingly. Critical example of reverse faulting is the Basin Province of the United States; again, because it is indicating that two blocks are coming with respect to each other. So, you can also see this as a characteristic of convergent plate boundary; that's why the other example of India-Eurasian plate boundary is given, which is the result of the creation of the Himalayas.

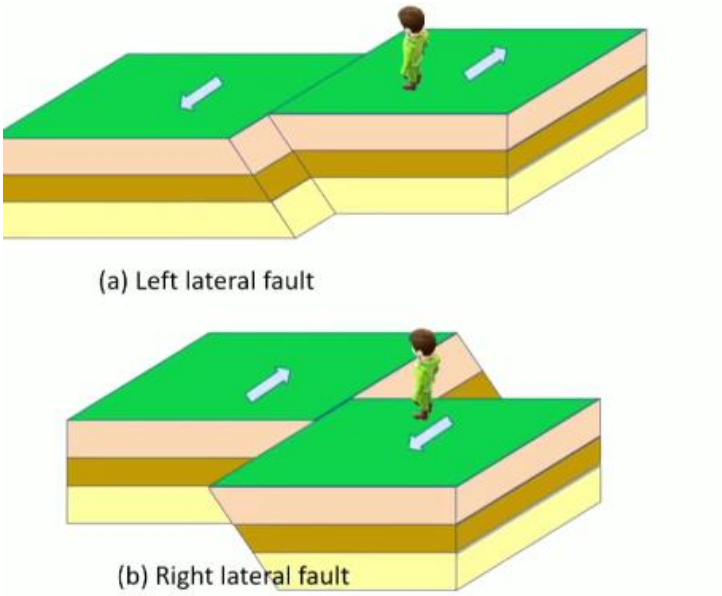

Fig.10 Motions of the blocks in the case of Strike slip fault

The last one is strike-slip faulting. Now, again, you can see strike-slip faulting. So, in reverse faulting, the two blocks were coming towards each other; in normal faulting, these two are moving away from each other or divergent plate boundary. The third one, the thrust faulting or strike-slip faulting, as the name suggests, it is basically any kind of slip along the fault plane happening in the direction of strike. So, strike, we know that the inclination with respect to north as measured on the ground surface, which is also along the line of fault trace. So, any kind of movement which is happening along the fault trace, purely, there is no component towards dip, that will be called as strike-slip fault. Again, in the pictures, you can see; so potential two kinds of movements are possible: one is when the two blocks are moving away from each other, the second one, the two blocks are coming towards each other. So, this strike-slip faulting can further be classified into left-lateral fault or right-lateral fault. In a right-lateral fault, whenever you are standing on the hanging wall, the adjoining block or the foot wall will be moving towards the right-hand side of the observer. Please remember that the classification, whether it is right-lateral or left-lateral, is based on the direction of movement of the other block, not the block on which the observer is standing. If you go with the classification with respect to the block on which the observer is standing, the classification will be completely reversed. So always we have to keep in mind the direction in which the other block, on which the observer is not standing, whether it is moving towards the right or it is moving towards the left, you can call it as right-lateral or left-lateral fault, as indicated over here.

So, in the first one, with respect to the observer, the other block is moving towards the left-hand side. So, you can call it a left-lateral faulting. Second one, the observer is standing on one block and the other block is coming towards the observer; or if that particular movement continues, it will move towards the right-hand side. So, from the right-hand side, it will leave the observer and go further; that is called a right-lateral strike-slip fault. Again, you see over here there is only a pure component of movement in the direction of strike, here also here also. So, the movement is only in the direction of strike, whether you call movement in this direction or the other direction, there is no component of movement along the dip, that's why it is called strike-slip faulting. Example is the San Andreas fault. Rake angle for strike-slip faulting: left-lateral faulting, the rake angle is zero; for right-lateral faulting, the rake angle will be 180 degrees because the orientation of strike will remain the same, but the direction in which the movement is there with respect to left-lateral will be diagonally opposite. So, where left-lateral is indicating a rake angle of zero, right-lateral will be having a rake angle of 180 degrees, and then that will continue.

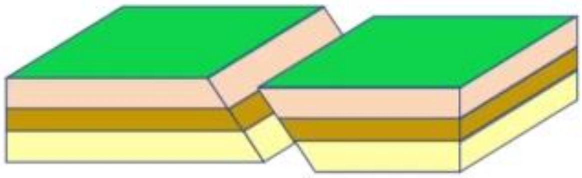

Fig.11 Oblique fault

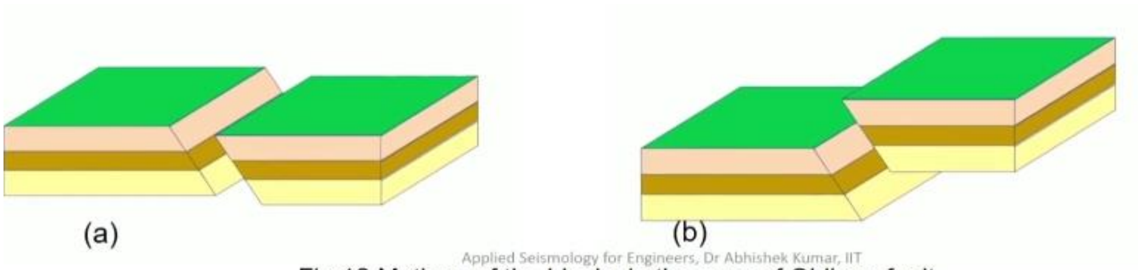

Fig.12 Motions of the blocks in the case of Oblique fault

Oblique faulting, many times you will not see any component of movement along the strike alone, but movement along the dip also. So, in this particular picture, you can see oblique faulting means there is some vertical component and there is some horizontal component as well. So, faulting which has both the components, horizontal as well as vertical, that is called as oblique faulting. Now, oblique faulting in this particular picture, figure 11, it is shown for a fault which is not having a dip angle of 90 degrees. But if a fault is having a dip angle of 90 degrees, again there can be horizontal as well as vertical components. That means the hanging wall and foot wall movements are not happening all along the dip or strike but a combination of those. So that is called as oblique faulting. The rake angle of oblique faulting can be between zero to 180 degrees or between zero to minus 180 degrees depending upon whether you are dealing with right-lateral or left-lateral or the movement of hanging wall and foot wall are towards each other or away from each other. That will define whether it will be in the range of zero to 180 degrees or diagonally opposite, that is from zero to minus 180 degrees. So that is the possible range of rake angle for oblique faulting.

The importance of knowing about the fault is because if there is identification of the fault, you can get an understanding that governing tectonics is not stable, but it is quite active. So, for any construction purpose, information about the faults which is indicating there is building up of stresses and chances of earthquake occurrence is there, that will come into the picture so that will have an important decision-making as far as the selection of a particular site is concerned. As far as possible, any important structure when you are deciding the site, you try to locate that site as far away from your fault. Again, because it is leading to the presence of the fault, as far as it is active, it is also leading to seismic activity. So, any kind of slope, any kind of dam, bridges, any other important structure is there. So, if there is a fault in and around that particular area, that will certainly generate some vibration or some loading, and that vibration may cause some kind of instability in case of slope landslides; if a dam is there, it is going to induce more loading; if a building is there, it is also going to induce more seismic loading. So that's why, the primary objective is to avoid it. If it is not possible, then it will become highly important that we take into account the information about the fault and its chance of producing earthquakes in the near future, primarily during the design life of the structure. Again, for pipelines, for the transmission of oil, we have to have more information about the fault information because there will be connection between the pipelines and the ground, so you have to design those connections also properly, and subsequently, many numbers of utilities which are indicating by the information about the movement of the fault and the presence of the fault are important in a particular region. So, I will stop here and then we will discuss some information about the indication of the presence of the fault in a particular region and then potential movement, how this potential movement on a fault which is witnessed over a period of time can be represented on a piece of paper so that just by looking at that particular piece of paper we can understand what is the governing movement in a particular region. Thank you, everyone, and we will continue on this particular topic in the next lecture.