Applied Seismology for Engineers

Dr. Abhishek Kumar

Department of Civil Engineering

Indian Institute of Technology Guwahati

Week – 02 Lecture - 02

Lecture – 03

Hello everyone, myself Dr. Abhishek Kumar. Welcome to lecture 3 of the course Applied Seismology for Engineers. This particular lecture is part 2 of the topic Fault Plane Solution. In the previous lecture, that is lecture 2, we discussed different kinds of movements which are possible along the fault, including the movements which are happening in the direction of the strike, movements which are happening in the direction of dip, and movements which are having a component in horizontal as well as vertical direction. In addition, we also discussed that in order to track these kinds of movements which are happening possibly during an earthquake, there are various measures which have been defined, including strike, dip, and many more things, such that once you know the value of each of these parameters—strike, dip, rake angle—it will help you in understanding, for a given fault plane solution or for given values of fault, dip, and rake angle, what possibly the orientation of the fault existing in a particular region is, in terms of how it appears on the ground surface or the place where it is exposed on the ground surface. Many a times, if it is not exposed to the ground surface, it is going to give you what is the orientation of the fault at the topmost part of the fault.

In addition, dip is going to tell you what is the orientation of a two-dimensional plane, which is called as fault plane, with respect to the ground surface or horizontal surface. These two parameters, that is, the strike value and the dip value, are going to tell you only about the inclination of the line, which is the intersection of the fault plane and the ground surface, and what is the orientation of the fault plane with respect to the ground surface. In addition to these two parameters, because these parameters are not discussing any kind of movement possibly happening along the fault plane. So, we will be bringing in another parameter, that is rake angle, which is going to tell you the direction with respect to the strike in which the hanging wall is moving with respect to the foot wall. So, this is going to give you an indication about whether the hanging wall is moving in the direction of the strike, whether the hanging wall is moving in the direction of the dip, whether the hanging wall is moving just 180 degrees with respect to the strike value or with respect to dip measurement, or there is some value which is other than 0 degrees, 90 degrees, 180 degrees (plus and minus). So, this is going to give possible ways in which two blocks, that is, block 1 and block 2, which are actually interacting at the fault plane, are actually moving, and these are moving primarily because of convection currents which are pushing different parts of the plates, which we also discussed in lecture 1 in terms of divergent plate boundary, convergent plate boundary; we also discussed some of these in lecture 2.

Continuing with the topic of fault plane solution, so far, based on the discussion, we have understood that there is a fault which is primarily an indication of some kind of movement happening on either side of that particular line. Fault plane means the orientation of the plane on which the two blocks are moving with respect to each other, whether it is kind of pure shear in the direction of strike or in the direction of dip, or a combination of both. Fault plane solution is indicating how, based on in-situ measurements—because these are important as far as the understanding of the earthquake, the seismicity of a particular region, the orientation of the fault, and the governing mechanism which happened during a particular earthquake.

So, fault plane solution—the name solution suggests that we are interested in finding out what was the fault plane details: strike value, dip value, and rake angle—because depending upon the rake angle, you may discuss it as a normal fault, reverse fault, oblique faulting, vertical dip slip fault, strike-slip fault; so, all these things will come into the picture when we take rake angle also into account. So, fault plane solution in complete will tell you all these details as inferred from in-situ measurements. When we talk about in-situ measurements, primarily we will be discussing or we will be taking into account the recording stations. So, primarily, whenever there are earthquakes, there will be a lot of recording stations in and around that particular region. There will be recording stations located far from the epicentral region, which will actually sense the vibrations generated from the source and have been transferred to that particular recording station. We will discuss this in more detail when we come to the propagation of waves between the source and the site.

As far as today's topic is concerned, based on the information which we will be gathering from recording stations, we will try to find out what was the possible orientation and what was the possible governing mechanism which happened during a particular earthquake. So, fault plane solution means a solution which is going to help you in understanding possible kinds of fault planes and possible movements which have triggered during a particular earthquake. This will be important not only to understand what has happened during past earthquakes; as we know, the higher the magnitude of the earthquake, the longer it will take to store a particular level of strain energy to cause a particular magnitude earthquake. So, in order to understand the governing tectonics, in order to understand whether the slip is happening in a particular direction, whether the offset is possible on a particular fault, what is the correlation with respect to the slip accumulating on a particular fault with respect to the magnitude of the fault, and how frequently these occurrences of earthquakes and non-occurrences of earthquakes have been reported on a particular fault, all will be an indication of the seismic activity of that particular fault. So, fault plane solution will help in understanding not only what has happened during a particular earthquake but, in general, what is the nature in which a particular fault has been responding year after year, decade after decade, century after century, depending upon how much information is available with the observer.

Just continue with the topic of faults; we discussed possibly the kinds of movements which are happening primarily because of plate boundary activities or within the plate because of in-situ stresses which are mobilizing within the plate itself. So, there will be a resultant earthquake occurrence. In order to demarcate or in order to understand what is the importance of faults, why it is important to know about the fault, see some of the examples written over here. So, faults mark the sites where dislocations of the ground—dislocations meaning the ground initially was in a level condition, but some kind of disturbance, whether it is in a vertical direction or horizontal direction, has occurred because of earthquakes in the past or it can also get repeated in the near future. These possible dislocations are an indication that some kind of movement has been happening in a particular section; that particular section you can call as fault. Now, as far as any particular important infrastructure is concerned, we have to have an understanding about this particular fault because, if there is a fault in and around your study area, definitely it is also indicating that some kind of seismic activity is also building up on that particular fault. Taking into account what the design life of the structure is and how much seismic force is likely to occur because of the presence of that fault, and taking into account the seismic activity of that particular fault, that will help you in understanding the feasibility of the finalized design with respect to the fault on a particular structure. So, that is why the importance of the presence of the fault, its type, its extent, and its effect—what will be the effect we will discuss in coming classes—all these things collectively help you in understanding how much seismic force is likely to be encountered by a particular project just because of the presence of a fault in a particular region, how much region that depends upon generally the importance of the structure as well as the seismicity of the region. It is ideal; generally, we say it is ideal that you select a site for any kind of construction as far as possible from a fault.

The two challenges which generally are encountered are: first, we do not have complete information on all the faults in a particular region. So, most of the time, you will encounter a region where complete information about all the faults that are present in a particular region mostly will not be available. You will have information, but whether it is complete or some part is still missing, that is to be looked into. Secondly, how many times do we have the option to move your project to some different site? Nowadays, we are hearing that the availability of land is a big issue, so whenever you are getting some land, you have to deal with whatever possible situation and challenges likely to be encountered on that particular site. You have to deal with it and then go ahead, whether it is in terms of design, construction, or material selection, but certainly, selection or shifting of a particular site will not be the very first step. So, we have to take into account what the faults are available, how we can deal with those faults, or how these faults have been responded to in the past.

So, faults can cause instability because faults mean some kind of dislocation is there, which is primarily resultant in the form of earthquakes. So, whenever an earthquake is happening, there will be disturbance created at the source of the earthquake, and this disturbance will travel to larger distances in terms of seismic waves; we will discuss these in later lectures. So, as far as possible, we will try, but how many times it is possible depends from site-to-site condition and from one project to another project. But certainly, we are clear that whenever there is movement, it is going to cause some kind of instability to the proposed structure. It is critical to understand the location and the nature of the fault, where the fault is available, what is the possible movement which is dominating on a particular fault, as has been evidenced in the last 50 years, 60 years, 100 years, depending upon how much data with respect to the fault movement is available with us or how much data has been inferred based on indirect measurements suggesting the possible kinds of movement in terms of the nature of the fault. For any kind of construction of dams, reservoirs, again you have to have a clear-cut indication about what are the possible faults or at least the faults which are known; all complete information about known faults should be there with you as far as the dam and reservoirs related seismic activity and seismic safety are concerned. At times, it has also been seen that because of the loading which is created by the reservoir, that can also, at times, cause seismicity which comes under the category of induced seismicity.

So, we have to also take into account whenever we are taking any particular site for the construction of a dam or reservoir that even though the fault is not showing significant activity by its intended nature, because of the nature of the particular project, it can still cause some kind of induced seismicity. So, faults can have an impact on pipelines; we have seen oil pipelines, so whenever these are running across the faults also, along the faults also, and take into account that possible movement is also happening along the fault, so we have to be very careful in terms of construction of these pipelines, particularly the foundation, as well as the connection between the foundation and the pipelines. That has to be ensured that any kind of movement likely to occur on a particular fault, the connections which are connecting your pipeline with the foundations are able to withstand that particular movement. Otherwise, any kind of earthquake, any kind of movement, and the connection fails, and then that can lead to a major disaster. It's critical to understand the location and nature of the fault while building these pipelines. Similarly, with respect to a number of slopes and hillsides, again, if there is a fault nearby, any kind of seismic activity it is going to trigger can cause instability to the slope.

Many a times, we also see some kind of slope failure, particularly in a hilly terrain, which is also part of moderate to high seismicity region in an epicentral region or some major fault which has triggered larger or greater earthquakes in distant locations; that can also cause some kind of instability. Similarly, in the case of landslide hazard assessment, also, the information about the existence of the fault and its nature is also very important. Faults are potential; we cannot deny the fact that faults are potential locations for future earthquakes. So, as far as earthquake-related information is concerned, it's not only about the loading it's going to cause; it's also many a times what is the most frequently earthquake-causing fault or which is the fault that is more deadly or more hazard-causing when it comes to seismicity of a particular region or any particular structure. So, information about the fault types, as far as possible, in terms of past history, as it is inferred from it, is very important to know about the fault and its nature; that is also going to give you an indication about the possible movement or generated ground-level vibrations.

So, any kind of movement or seismic waves, when it is transferred from your focus or from the source of the earthquake to your site of interest, it will be recorded in terms of ground vibrations, ground shaking. You put a recording station; whatever this motion sensed by the recording station, that will be defining how much is the level of ground shaking which has been induced by that particular earthquake at your site of interest. So, based on the expected level of ground shaking, one can design a particular kind of structure. So, in order to have a clear indication about what is the expected level of ground shaking, one has to have more confident information about the presence of the faults, historically what earthquakes it has triggered, and what is the current situation of that particular fault; that is going to give you more and more confidence about the fault and its seismic activity.

Now, there are ways you can have an idea about that there is a presence of fault; one is abnormal behavior of strata. As we have learned based on lecture 2 and today's lecture, that fault means any kind of possible dislocation. When this dislocation is happening, definitely there will be an abrupt termination of a group of beds. So, there will be soil stratification which, in some geological time scale, might be continuing, but because of the relative motion between two sides of the fault block, now there is an abrupt termination or abrupt discontinuity in terms of layers; even you can see this discontinuity on the ground surface. So, on one side of the fault, you might be having some kind of deposition; on the other side of the same fault, you might be having a different kind of deposition. Then, taking into account that there is different weathering as well as deposition agencies active throughout, there will be some repetition of layers because of whether deposition agency is dominating or weathering agency is dominating. Similarly, there will be some omission of certain layers which are present on one side but not on the other side because these sides which are exposed to the ground surface, because of the movement of the fault, and if they have been subjected to a weathering agency more prominently, then certainly these layers will be vanished or these layers will be completely removed from that particular parent position. So, feature characteristics—the last one—also we can see offset. So, generally, there will be displacement along the beds also. So, a bed is there, and then there is relative movement, so you can see there, because of discontinuity, which is also an indication that some kind of movement is predominantly happening along this particular cross-section, and that is how it is an indication that this particular location is a possible fault.

Again, feature characteristics of fault planes are the presence of slicken sides, polished and stated surfaces, mullion structures consisting of larger grooves, furrows. So, any kind of deposition which is mentioned over here—large grooves, polished and stated surfaces—are also indicating that some kinds of depositions are getting eroded or getting travelled along the fault plane and getting deposited to other stratification. Silicification and mineralization are also quite dominating in terms of fault plane movement, and that is why these are also considered as another feature which can help you in the identification of a possible fault in a particular region. So, fault fractures are the path for moving solutions; these solutions replace rock with fine-grain quartz. So, you can often see some kind of movement happening along the fault plane of some moving solution from lower bedrock to upper stratification, which is generally an indication of silicification; many a times, mineralization will also be seen in terms of faults. The last part is physiographic evidence, so some topographical features will also indicate that at a particular site the ground is not stable—meaning there is some kind of movement which is happening within the ground.

Typical features include fault scarps; so, at certain places, you will see one part of the ground is significantly raised and the other part is at its initial position; that is a possibly indication of raising of the fault during a particular earthquake. Then, springs near the foot of the mountains are also an indication of that there is building of strain energy, which sometimes leads to hot springs also. Then, truncation of structures by mountain fronts—these all are easily visible if you study the topographic maps or aerial photographs or even remote sensing-based images. You can locate some of these features if you go to the site and do a detailed investigation; again, some of these features can be explored at a particular site that will help you in understanding the possible orientation of a particular fault.

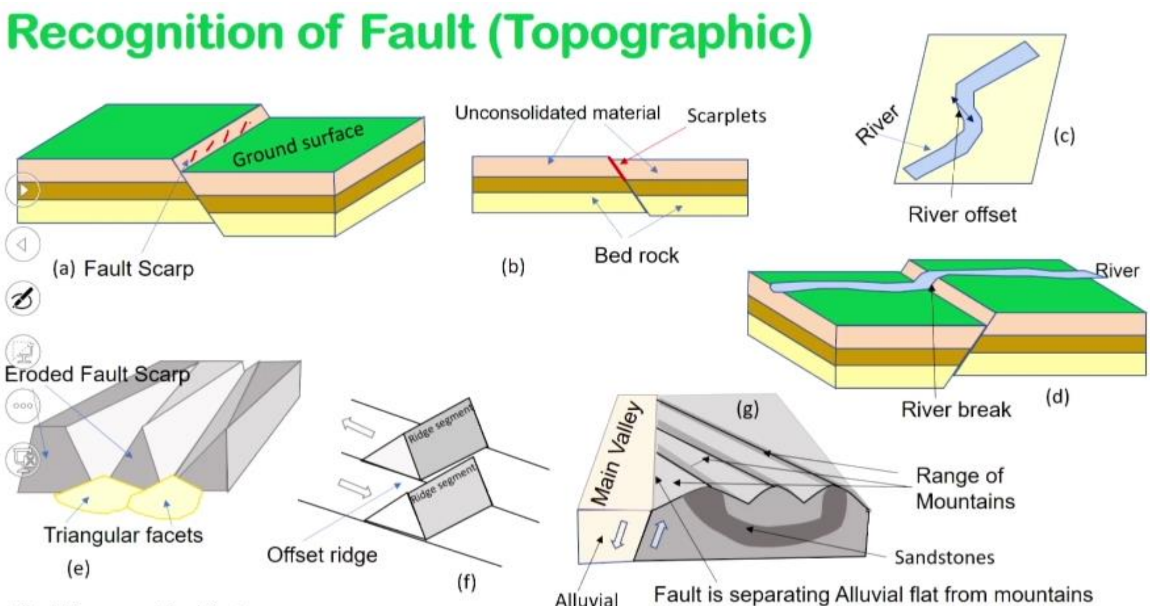


Fig.1 Topographical features

Some of the features which are indicated over here are: the first one you see is fault scarps. So, during a particular earthquake, the ground on one side has moved up while the other side has moved down, so you can see over here that this particular trace can be called fault scarps. On the ground surface you will see that a certain part of the ground has been raised while the other ground remains in its initial position. Then, unconsolidated material and scarplets—you can see over here getting deposited—and some kind of movement to the upper layers is also possible. Third, that is figure C, you can see, then there is a river, but because of the movement along the fault, you can see the sudden change in the orientation of the river. So, that is also an indication that there is a presence of fault which is possibly undergoing some kind of deformation; as a result, the course of the river has undergone significant change. It is not following the general trend, which was very gentle; suddenly, there is a change in the course of the river. In the figure D part, you can see again some kind of—so in the first one you see the course in the plan, there is some change. Again, you can see in the last part, that is figure D, that because of the fault scarps, again, there is some sudden jump in the course of the river. That is also clearly indicating the presence of fault and its induced ground deformation. Figure E indicates triangular facets, which is also an indication that because of gradual rise or movement on one side, the sediment has started depositing on the lower course. That is how you can see these triangular facets, indicating that some kind of deposition which is otherwise moving from these fault scarps has been continuing for some time now. Then you can actually see these in aerial photographs or in remote sensing-based images. You can basically see some kind of triangular facets, which is also indicating that some part of the ground is actually undergoing rise, and as a result, the development of triangular facets has come into the picture. The second last, figure F, shows there was a ridge which was continuous, but because of prolonged movement along these possible fault lines, there has been a discontinuity or offset created along the ridge. So, if you see these kinds of offsets in your actual site condition or in your maps, that is also indicating that primarily there is a presence of fault. The last one also—you can see there are mountains which are suddenly and abruptly ended by means of valleys, indicating again that this particular mechanism is dominated by the presence of the fault. So, all these features which are mentioned over here are topographical features. So, you study the topography of a particular region and look for these particular features in that region. That will help you in understanding where the possible faults are in a particular region, and as I mentioned earlier, the identification of faults in a particular region is a continuous process. It is very difficult to say that all the faults which are located in a particular region have been identified; there will always be some faults where the dominating mechanism has not been understood, or there are faults which have been developed in the very recent past. So, this is a continuous process, and so is the identification of faults based on topographical features.

In addition to this, there are other ways based on which, once we go for detailed investigation, this will also help in the identification of faults. Now, I am not going to cover all these details in this particular course, but if someone is interested, you can look into the existing literature on each of these topics as far as the identification of faults is concerned. These methods include geological mapping, geophysical surveys, remote sensing, borehole data, historical records, field observations, and laboratory-based analysis. So, based on these methods, one can also progress into detailed assessment and identification of the faults which are likely to be present in a particular region, and we should not forget the importance of the fault. Because wherever there is a fault, there will be some building up of strain energy, and depending upon the rate at which the energy is getting accumulated and the history of its seismicity, it will likely help you in understanding what seismicity you are going to witness in the near future.

So, fault plane solution, as I discussed in the beginning of this particular lecture, fault plane solution basically helps you in understanding what is the orientation of the fault line, what is the orientation of the fault plane, and what likely has happened during a particular earthquake in terms of hanging wall and foot wall movement. So, fault plane solution gives you a geometry—what is the orientation of the fault. Depending upon the length which is available on the topography, you can also find out approximately what is the length of the fault. The next part is the movement which has happened. As I told in the beginning, though the strike and dip are going to give you some information about the fault plane solution, these are not complete because they do not give you any indication about the movement which has happened during a particular earthquake. But fault plane solution will give you that part also. So, in order to describe the geometry of the fault, suppose I am interested to understand a particular fault. Based on the existing literature, what I will do is search for possible fault plane solutions. Fault plane solution is a kind of readymade solution which will help you in understanding what kind of strike, what is dip, and possible orientation or in terms of whether it was a strike-slip fault, whether it was a dip-slip fault, whether it was a normal fault, reverse fault, oblique fault, vertical dip fault, or strike-slip fault. All these things one can understand just by looking at the fault plane solution, which is many times readily available. The best part with fault plane solution is it will help develop an understanding about a particular fault, and if you continue this for a number of faults which are present in a particular region, that will help you in understanding overall how a particular region is responding in a definite time interval in terms of earthquakes, in terms of building up of strain energy, and further you can correlate with respect to possible ground shaking each of these earthquakes, each of these faults which are going to trigger to a nearby structure or to a recording station.

So, seismograms obtained at different recording stations—basically, seismograms are the records that will help you as you obtain from different recording stations. You take these and once you start analyzing these, they will help you in understanding what kind of—not only the ground motion detail—but also what kind of fault plane solution, what kind of dominating movement has triggered during a particular earthquake. Consider an example of the 2015 Nepal earthquake. So, if I am interested to know what had happened during a particular earthquake in terms of movement of a particular fault which triggered that particular earthquake, I can simply go to the literature and find out, or based on the recordings which are available in that particular region. If I am able to develop the fault plane solution which is given in different ways, then I can understand what kind of movement had triggered during the 2015 Nepal earthquake or the earthquake which happened in February in Turkey. So, if I am interested to know again what was the dominating fault mechanism, again I can look into the recordings which have happened in the epicentral region and can come up with a possible fault plane solution, or if the fault plane solution is existing there, I can check that and then see whether it was oblique faulting, strike-slip faulting, dip-slip faulting, and so on and so forth. So, the technique has the advantage of the fact that the pattern of radiative seismic energy is taken into consideration. So, we are not putting some sensor right at the epicenter, but whatever has been sensed after this particular earthquake has happened on the recording stations which are installed in and around that, that itself—so recordings not at the source, but the recordings which have happened other than the fault plane—actually help me in understanding what is happening at the fault plane.

So, there are different ways. Primarily, you take into account the polarity of the first P wave motion at the recording station. What are the different kinds of waves? If you go through later lectures, you will come across what are the different kinds of waves. As far as this lecture is concerned, we just focus on that whenever there is an earthquake, different kinds of waves will be generated. The primary wave will be the first one to reach the recording stations. So, taking that primary wave signature, or the first arrival of primary waves nature or polarity, into account, that itself indicates what kind of movement has happened during a particular earthquake on a particular fault. So, fault plane solution can be derived from the nature of the first P wave motion as recorded at different recording stations.

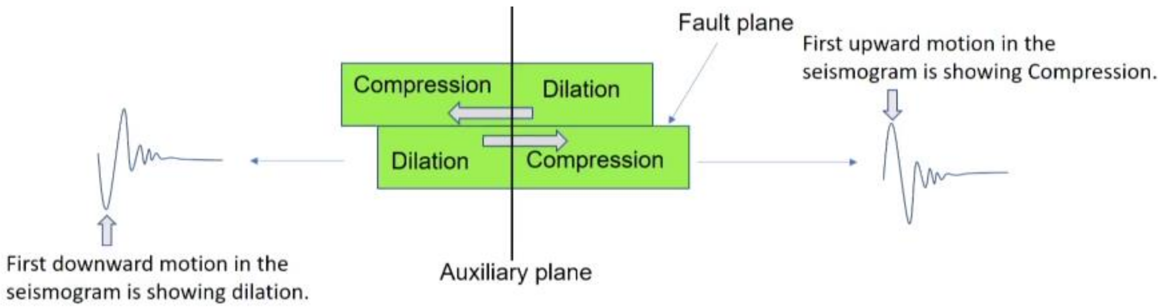


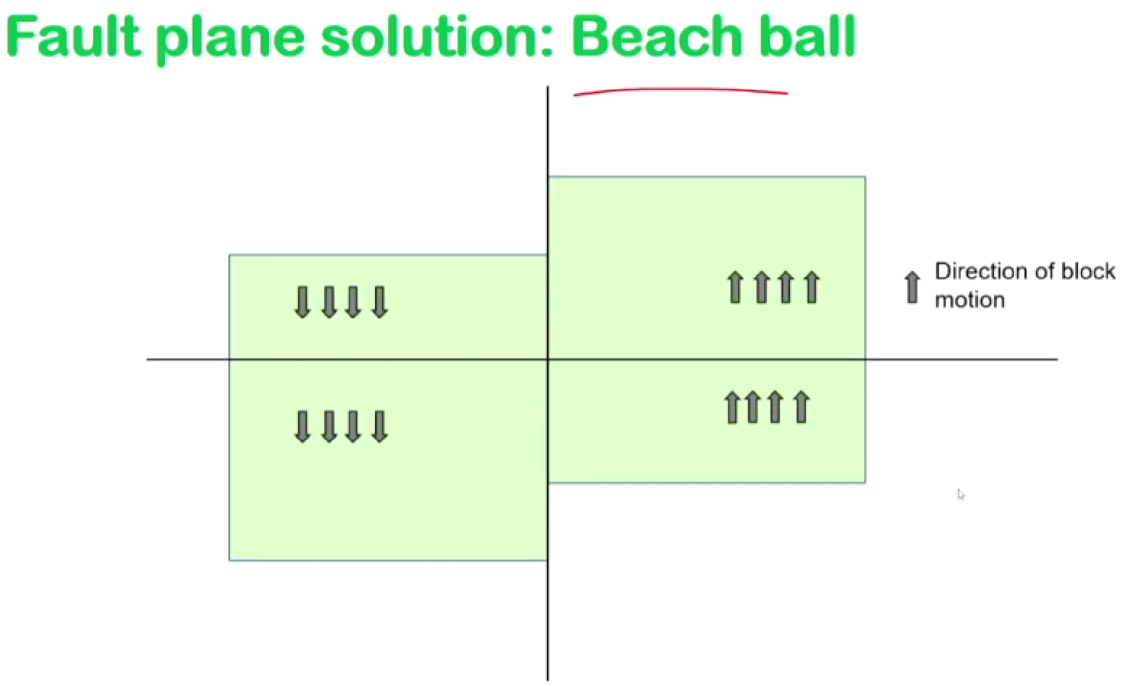
Fig.2 First motion (P-wave) at recording station in relation to the orientation and movement on the fault

You can see over here the first P wave motion which has been recorded at different recording stations during a particular earthquake. Now, you see over here, the picture shows two planes. One is— you can see over here—there are two blocks: block 1 and block 2. Consider an example of strike-slip faulting. So, along this particular fault, block movement is happening like this. This is my fault plane, and the two blocks are moving like this. This particular figure shows the indication of the movement of two blocks along the strike. So, you can say maybe this is the direction of the strike. So, here in this particular figure, you can see a possible fault plane which is given over here, and then, perpendicular to the fault plane, there is another plane which is called the auxiliary plane. However, in actual physical interpretation, there is no auxiliary plane. We will understand the importance of the auxiliary plane later. So, there is a fault plane along which the two blocks are moving. You can call this fault block 1 and you can call this fault block 2. The two are moving with respect to each other, considering an example of strike-slip fault. Now, when this movement is happening, you can see over here that the movement is happening along the fault plane. But in order to understand the nature of this movement, primarily in terms of the first P wave, you can see over here that the first thing is it is experiencing some kind of dilation. Or if I put a recording station over here, you see with respect to this recording station, this block is moving away, so this recording station will experience tension. Similarly, there is a recording station over here. Remember, this is shown in the plan because it is a strike-slip fault. Another recording station is there; along this particular recording station, the block is coming towards it, so you will see if any recording is here, it will be indicating the first P wave motion as compression.

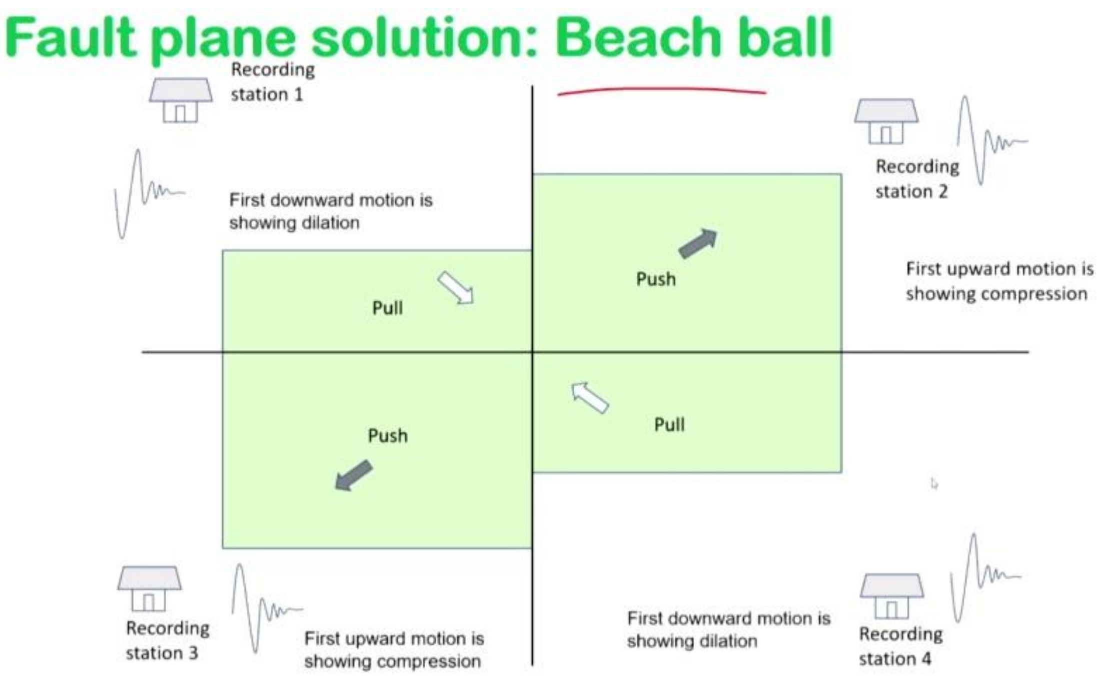
Similarly, if a recording station is over here also—because there is a fault, and there will be a number of recording stations all around the particular region—you have to take into account the first P wave motion which has been detected at the recording station. What I am trying to show here is there is a fault movement. When this fault movement is here, depending upon the relative motion of these blocks with respect to the recording station, you will see some part of the fault block which is moving away from the recording station; it is possibly indicating dilation because it is moving away. The second recording station, where the fault block is coming towards you, will show compression. The third recording station, again, will show dilation because this block is moving up the other side. And if there is another recording station over here and the block is moving towards the recording station, that is how you will get compression over here. So, if you have n number of recording stations all across, these will help you in understanding what kind of movement, which particular regions are there which are having compression, and which are the regions that are having dilation.

Now, if you go to any recording station, as I mentioned earlier, you have to take only into account the first P wave motion. So, you see over here that the first P wave motion is indicating upward movement. Upward movement is an indication of compression. So, wherever there is a recording station, you take the P wave component, and if the first P wave motion or the polarity of the first P wave arrival, if is showing an indication of upward movement, you will say that my recording station has detected compression. In the same way, if your recording station is located over here, it will be indicating downward movement, which is shown over here. So, that downward movement is indicating that my recording station has assessed tension.

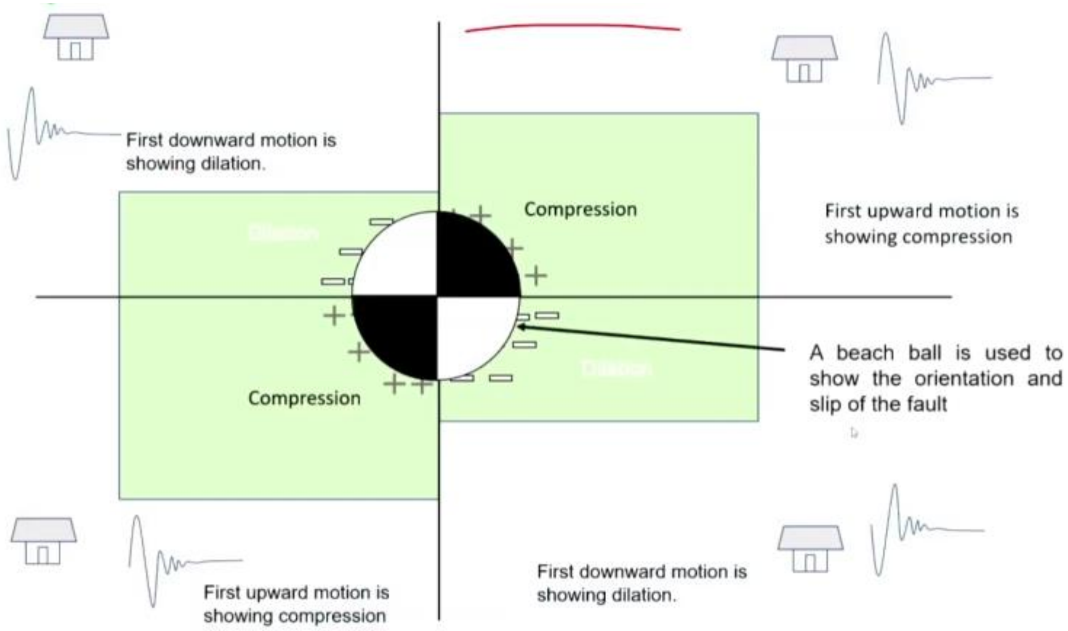
Similarly, 'n' number of recording stations which are located over here will help you understand where you are having tension and where you are having compression with respect to your fault plane and with respect to your auxiliary plane. So, taking into account the nature of the first P wave motion all across your fault plane, you will be able to understand which particular quadrant is having compression, and which particular quadrant or which particular side you are having—if you divide this into four parts with the fault plane and auxiliary plane—that will help you in understanding which particular part will undergo compression and which has undergone tension. And remember, you are not doing any kind of measurement at the fault plane; all these are based on the recording station. What the recording station has sensed, based on that alone, you are able to understand whether your recording station has undergone tension or compression. If you collectively analyze that, it will help you in understanding the fault plane solution.



Consider again; we will be discussing first about the beach ball solution. As the name suggests, we will be indicating or studying the beach ball solution or the fault plane solution in terms of a beach ball. Some of you have gone to the beach and have seen this kind of ball which appears like alternate bands of—I have shown over here—black and yellow bands, but generally, a beach ball will have black and white bands. So, any kind of band-like ball indicated here is a kind of beach ball I am trying to highlight. So, whenever we go with fault plane solution using a beach ball, this is a kind of ball that will represent the possible movement along the fault plane. Now, you see this particular part: the two blocks are there which are moving with respect to each other. These are the fault lines. This is the strike of the fault; you are calling it a strike-slip fault.



So, again, that is a strike-slip fault. So, there is forward, and backward movement. Taking that into account, if you have four recording stations, some will experience push because of their relative position with respect to the position where the waves have initiated, and then the other part will have compression. So, compression and pull or dilation—collectively, you take that into account—you will have some primary wave motion as compression and some primary wave motion as dilation.



Take that into account, now you can locate what is the region indicating compression (which we call positive) and what are the regions indicated by tension (which we call negative) as an indication of dilation. So, taking those into account, you can draw a circle, highlight the locations which are an indication of tension by white and compression by black. This is the beach ball solution. So, again, if you see in plan, this is a strike-slip fault. The two blocks are moving with respect to each other. We have seen that based on the first P wave motion, there will be movement away from each other. So, there will be some recording stations which will be indicating compression based on the first P wave motion, and some will be indicating tension based on the first P wave motion. Identify those locations on this particular fault, and you will be able to identify the regions which are having only compression, the regions which are having tension. You are seeing from the top; generally, a beach ball will be represented on the lower hemisphere. So, you see over here, this is the kind of beach ball you are actually able to see from the top, or even from the bottom, you are able to see the same thing. So, wherever you see on a particular map that a possible fault is there and on that particular fault any kind of projection of these particular compression-tension zones on a piece of paper—that is an indication of the beach ball solution of that particular earthquake. So, next time if you see a beach ball solution, you will be able to understand that if I am seeing from the top, if I am seeing in the lower hemisphere, then there are the regions which have actually experienced compression during that particular earthquake and the regions which have actually experienced tension in a particular region. And remember, I have shown here the beach ball solution which clearly you can see. If this is the fault orientation or fault line, you can say this particular fault, though it has experienced strike-slip faulting, the strike is also oriented in the direction of north.

So, that means if this is my direction of north and the fault plane is also having a movement in this direction, this is how the beach ball will appear. Of course, right now I am showing you on my right-hand side; it is going up. It can be vice versa also. So, if the right-hand side is going down, you will have tension in the black current black zone and tension in the current white zone. So, it will change. In the same way, if the orientation of the strike also changes so, rather than the strike in the direction of north, if the strike changes like this, the beach ball will also change like this. So, the four quadrants of compression, tension, or black and white will remain there, but that will not always be vertical because that is defined by one line indicating the fault plane and the perpendicular line indicating the auxiliary plane. So, one is the fault plane; the other one is the auxiliary plane. Now, every time when we deal with beach ball solution, we have to take into account any kind of beach ball solution gives you two possible orientations because the beach ball is not going to tell you whether this is your fault plane or this is the fault plane. Once you get a beach ball, you have to actually cross-verify with respect to the geology of a particular site whether this is the orientation of the fault available at a particular site or this is the orientation of the fault available at that particular site. So, one is the development of the beach ball, and in order to find out again which fault is which is the orientation of the fault plane and which is the orientation of the auxiliary plane, you have to take actual geometry or actual geology of the site into account. That is the reason many a times when we search for beach ball solutions, you will often encounter terms like nodal plane, which is an indication of one plane which may or may not be the fault plane and an indication of the other plane which may or may not be a fault plane. But certainly, either of these two planes will be the fault plane and the other one will be the auxiliary plane. So, that's how you can get the beach ball solution for strike-slip fault. As we discussed earlier, there can be a number of ways in which the movement along the fault is possible.

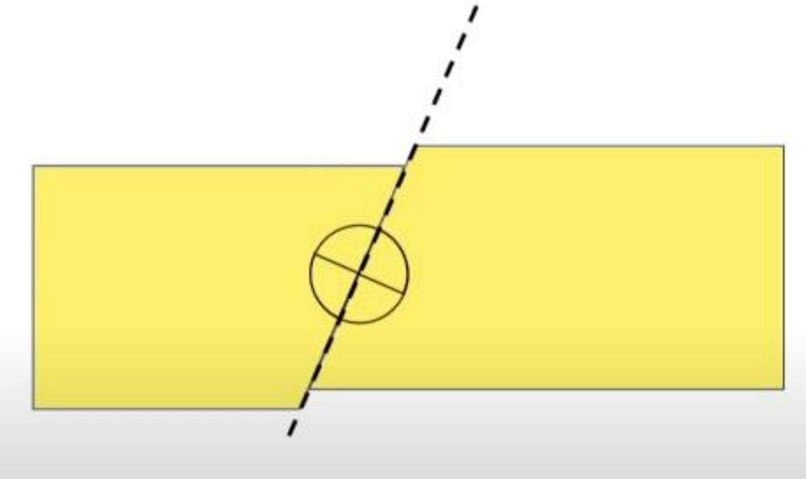


Fig.4 Beach ball solution of a normal faults

Again, you can see over here, so this is an indication of normal faulting where the hanging wall is moving away from the foot wall. This is your fault plane, and again, if I try to understand the nature, certainly I cannot understand the nature from the top because the movement is happening perpendicular to your ground surface. So, if I have to see the nature here, I have to see actually along the fault plane. Again, there will be some development of waves, and depending upon which wave is experiencing compression or which recording station is experiencing compression and tension, again you can identify because these waves will continue and will be detected by a recording station. So, depending upon the first P wave which will be recorded at the recording station, you can again identify whether it was compression or whether it was tension and continue the same activity we have done earlier. There will be tension also. So, compression, as I mentioned earlier, is indicated by black and tension by white.

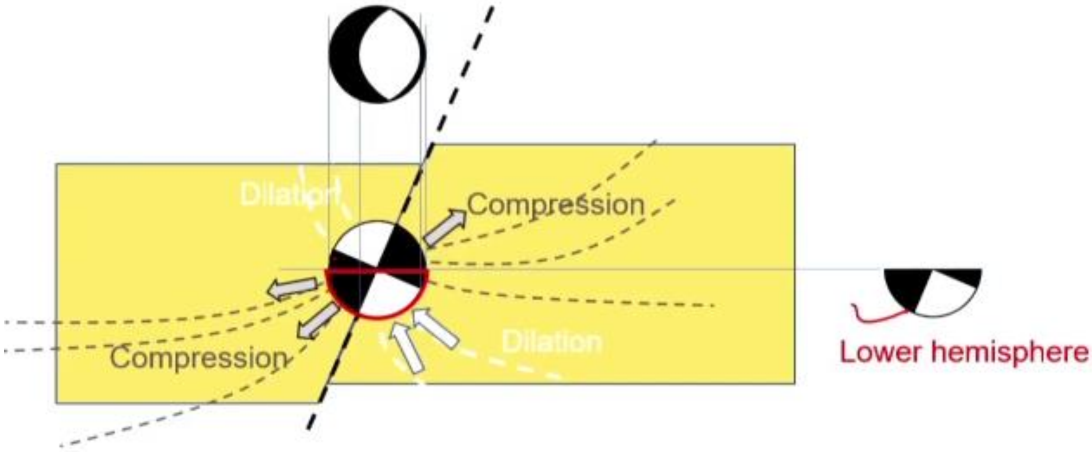
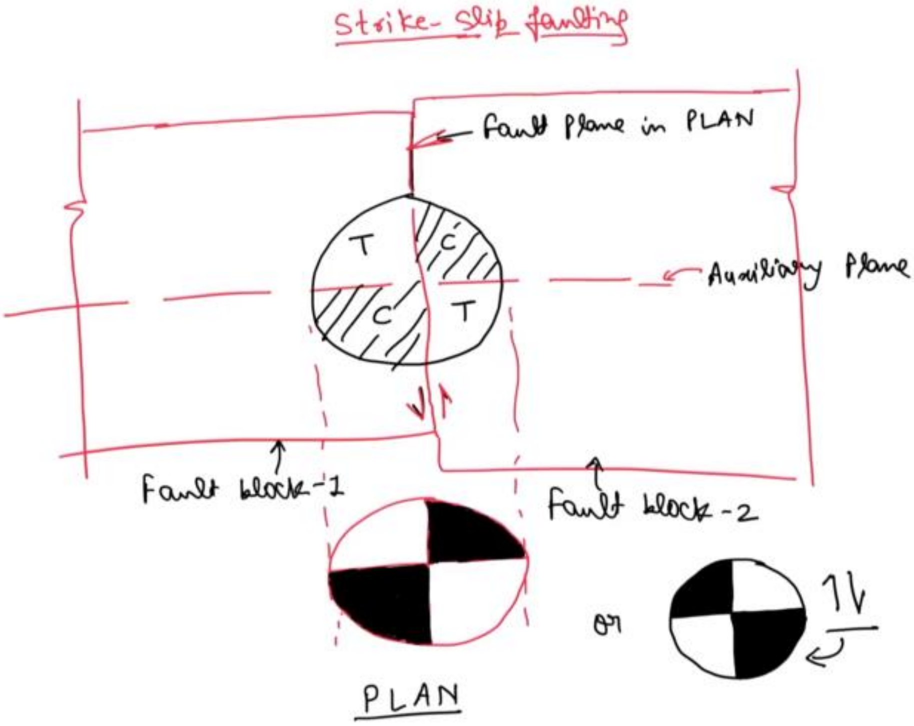


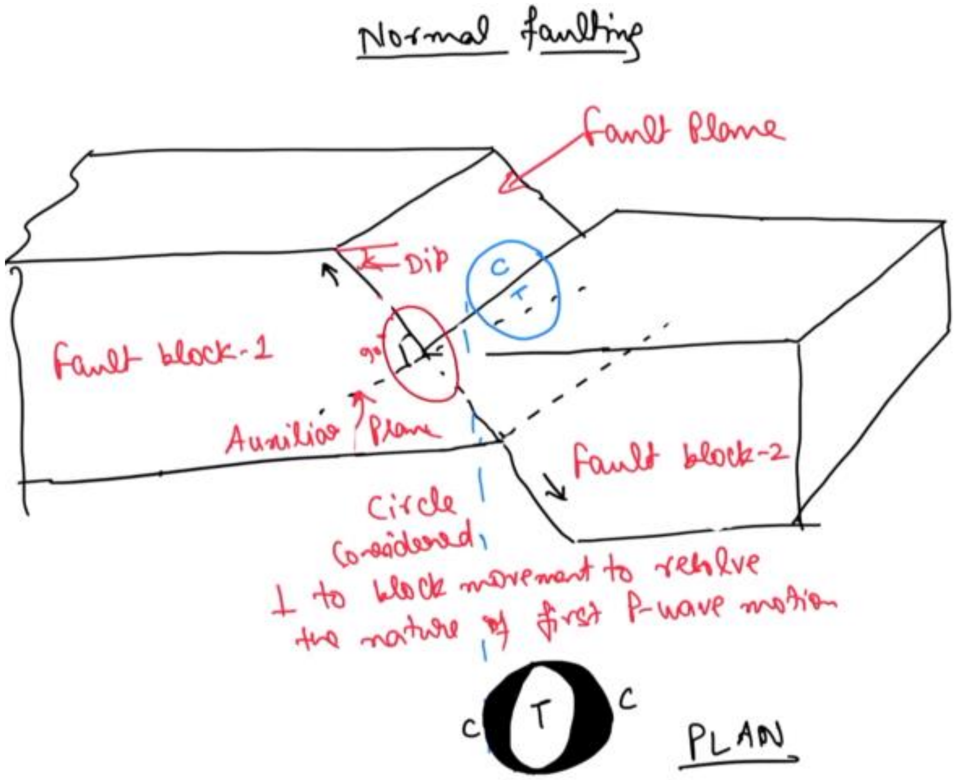
Fig.4 Beach ball solution of a normal faults

So, you can again see though it is appearing to the beach ball very much similar to strike-slip fault, remember this is not the beach ball you will be seeing in plan. In plan, you will be seeing the beach ball appearing from the bottom. So, if you keep it like this, whatever you see from the bottom—that is on the lower hemisphere—this is actually the figure on the right side. This is actually the nature of the first P wave motion which is indicated on the lower hemisphere, but again this is on a plane which is not from the surface. Remember, the beach ball I am representing on the ground surface is indicating on a plane which is perpendicular to the ground surface. So, I have to again take the projections; that's how it will look on the surface. So, what it means, if this was the beach ball solution which I can see over here, as you can also see in front of the camera, if this is the beach ball solution, if I start looking from the bottom or, for ease, if I turn this ball by 90 degrees, you will get something which is appearing very much similar to the one which is going to give me the quadrants of compression and tension as appearing on the lower hemisphere on a plane. So, whatever you are representing is actually on the plan because this beach ball solution you will be representing on a map, so everything has to be represented in plan. So, this is called the beach ball solution for normal faulting.

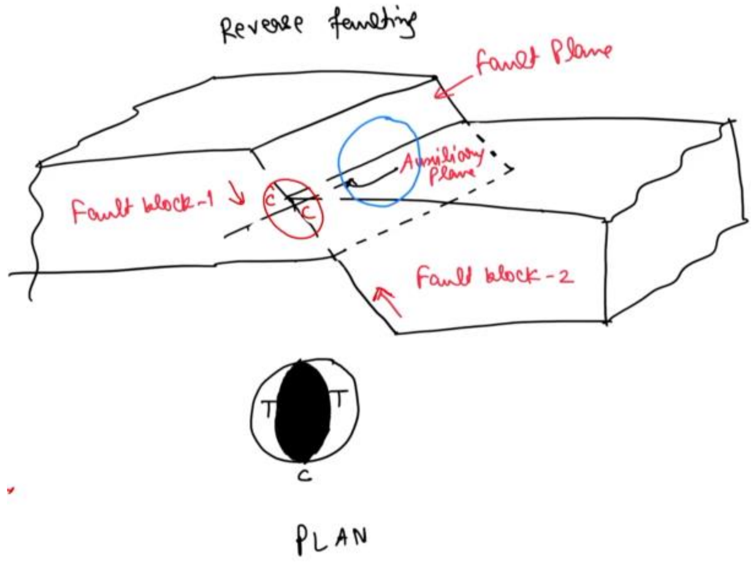
Similarly, for other faults, you can determine the beach ball solution. The beach ball is a lower hemisphere equal projection of the focal mechanism, so you can call it as fault plane solution or focal mechanism which has happened during a particular earthquake. So, focal plane solution or focal mechanism solution, you can say. Now, there can be two planes: one is the fault plane, and the other one is the auxiliary plane, which are orthogonal with respect to each other. These planes you have to identify based on actual site details, like out of these two, because these two will be having different values of strike. So, you have to go to a particular site or explore the geology maps or the fault or seismic atlas map of a particular region and then identify which of these two orientations is matching with the orientation of the fault in actual site conditions. That's how you can correlate and identify the fault plane and the auxiliary plane. This is very important because the auxiliary plane is actually not there, but in order to derive the beach ball solution, one has to have four quadrants. That will require both the fault plane as well as the auxiliary plane.



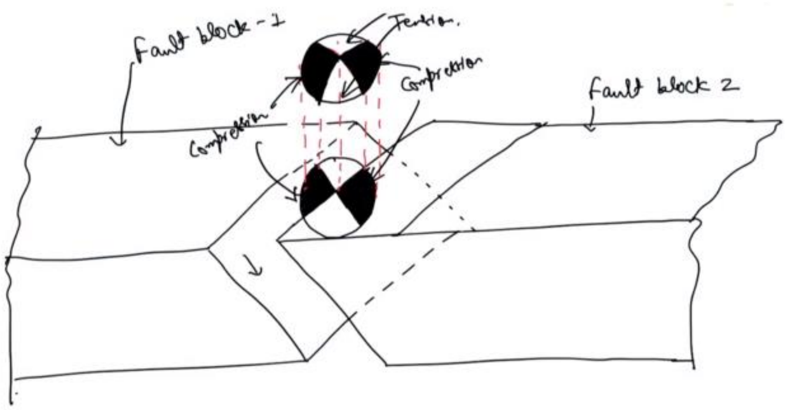
Now, here you can see again the strike-slip faulting which I have already shown there. So, I will not be covering this particular part once again. You can see everything is shown in the plan. You have the fault plane and the auxiliary plane, and depending upon the first P wave motion as appearing on each of these four quadrants. So, recording stations which are located over here will have compression. Recording stations located over here will have tension or downward movement. Recording stations located over here will have upward movement. Recording stations located over here will have downward movement. And again, there will not be only two or three recording stations; you have to have a greater number of recording stations in order to understand confidently and accurately what kind of movement you are dealing with. So, whenever we are interested in developing a beach ball solution, firstly we have to understand where the movement is happening, whether the movement is clearly visible on the ground surface, movement is visible perpendicular to the ground surface, or any other plane on which the movement is clearly visible.



Again, you can see for normal faulting we have already developed here. So, we have seen if you take a cross-section over here and try to understand, so this circle which I have just drawn is basically perpendicular to the fault plane. So, again, you see over here this will be experiencing compression, this will be experiencing compression, this will be tension, and this will be tension, actually on the vertical face perpendicular to the fault plane. If you see it from the side, that is perpendicular to the fault plane, you will be able to get almost like this: compression and tension. Then, take the lower hemisphere and then the projection on the plan, you will get the beach ball solution which is appearing like this, which you can see over here also. So, this is the beach ball solution for normal faulting. If you go for reverse faulting, again the process remains the same, but the only thing is there will be upward movement of the hanging wall with respect to the foot wall, and you have to interpret where there will be compression and where there will be tension. I prefer to have blocks, and then you can actually see upward movement, downward movement, and take a circle which is having one section with respect to the fault plane and the other perpendicular line with respect to the auxiliary plane.



So, for reverse faulting, again it remains the same. So again, if I am interested to find out the beach ball solution over here, I will take a circle which is perpendicular to a fault plane and also to the ground surface and try understanding because this is going up, the hanging wall is going up, this is going down. So, certainly when this is going up, you will have compression over here and then you will be having compression over here. You will have compression here, you have tension here and tension here, so this will not be compression, tension, compression, and compression because I have to take into account with respect to if the recording station is located over here, what will be the nature? So, since the block is moving away from your recording station, certainly there will be tension over here and tension over here, compression here and compression here. Then, take the projection on the lower hemisphere and then transfer this projection to your surface. So, this is primarily the beach ball solution on the ground surface on the section which is perpendicular to your fault plane. You look from the bottom, you will get this particular beach ball solution, which is appearing to be like this particular part. So, this part is tension, and the center part is compression. So, anytime if you see the beach ball solution represented over here, you will see this is an indication of reverse faulting, and remember I am showing here the strike of the fault is oriented with respect to north. So again, you can see the beach ball solution remains the same, but you can see some kind of rotation. So, this is C, T, and T. So, the difference between this part and this part is that the strike value has changed, as a result of which the orientation of the fault line has changed and that has resulted in rotation of the beach ball. So, initially, the beach ball was like this. Now I have rotated the beach ball because the orientation of the fault is basically indicated by these two points. That is actually an indication of the beach ball solution for reverse faulting.



Oblique faulting

Now, oblique faulting—when we are interested in strike-slip faulting, you can see the movement from the top. When you are interested in normal faulting and reverse faulting, you can see the movement from the side, but in oblique faulting there will be a combination of horizontal and vertical. So, the hanging wall is moving downward as well as sideways. In such a case, if I am interested to know the nature of compression and tension, certainly I cannot take, I cannot look in plan, I cannot look inside; I have to take this nature of movement along the fault plane. Again, along the fault plane, you can divide, so this is your fault line, this is your fault plane, and perpendicular to that, this one is an indication of the auxiliary plane. Remember, I am able to draw here the auxiliary plane and fault plane because the geometry itself is in front of me. But if I give you a fault plane solution, you have to again go back to the site and try finding out which of these two are indications of the fault plane and which one is the auxiliary plane. So, again, you develop depending upon the movement of the hanging wall with respect to the foot wall, where you are having compression, where you are having tension. I have developed over here; if you take two blocks in hand and then start taking this movement and then see because this movement is there, if there is a recording station here, that recording station will only sense compression, and that recording station on the other side will also sense compression.

Recording stations which will be recording waves from this particular quadrant will have tension, and subsequently, here you will have tension. Again, in this particular case, you will have some quadrants of tension, compression, compression, and tension like these. But remember, what I am showing you here is perpendicular to your line of sight. Considering the orientation of the fault is not, it is not a 90-degree dip, but something which is less than 90 degrees. So, what will happen? This particular projection, which was otherwise perpendicular to your line of sight, will actually rotate slightly, indicating a value of the dip less than 90 degrees. In such a case, whatever you are able to see from the front, that will be an indication of the fault plane solution on the fault plane. Now, if I am interested to know how it will appear on the ground surface, I have to see from the bottom, and at the bottom, you will see something like this. What is mentioned over here? This is for one moment and this is for another moment. That is how you will get the two kinds of moments which are mentioned over here. So, the hanging ball is moving away and downward, you will have these two blocks of tension and the other two blocks of compression. So, this will be called as the beach ball solution for oblique faulting, which is an indication of both horizontal as well as vertical movement. Again, one thing has to be taken into account. The first part is the orientation of the strike. Second, depending upon, you can see over here, this is the beach ball solution for a particular oblique fault. Now, you keep on changing the orientation or increasing the dip value, you will see rotation. So, initially, this part was clearly visible, then after some time you will see only these two parts were visible, after some time you may see the other part started visualizing. So, it all depends upon what is the orientation or what is the value of the dip of a particular fault plane on which this particular movement has happened. So, these three or four examples—that is, strike-slip, normal faulting, reverse faulting, and oblique faulting—I have given you to practice. You can practice and try understanding where there will be the development of compression, where there will be the development of tension, and how that will appear on the particular ball. That will help you in understanding the four quadrants. And remember, in each of these quadrants, there will be in one quadrant or one line oriented towards the fault plane; the other will be perpendicular to the fault plane, that is, the auxiliary plane.

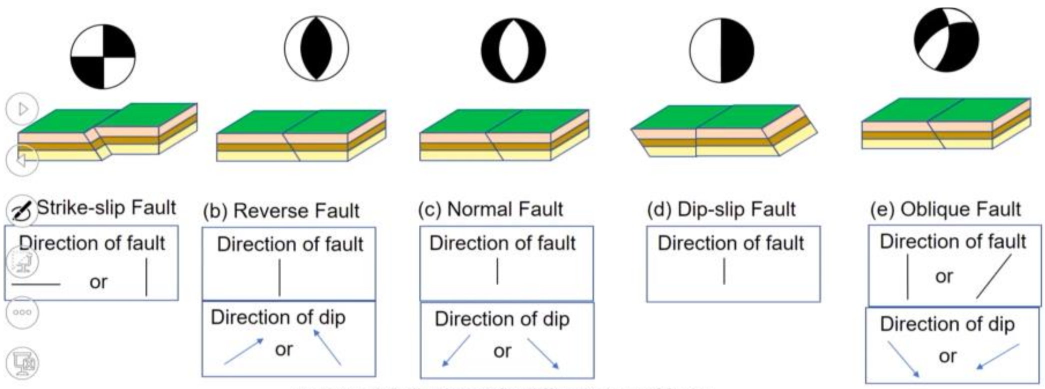


Fig.5 Beach ball solution for different type of faults

So, in general, fault plane solution, if you see, there are different kinds of movements which are shown in this particular picture. You can see over here the strike-slip faulting, the dip-slip faulting—I have not shown over for vertical dip-slip also—so if the second one was for reverse faulting, then normal faulting, and you can see over here possible directions of dip also. For vertical dip-slip fault, you see half side is compression, half side is tension because again you will be seeing from the top, I mean how it appears or the circle will be developed in order to understand the compression and tension from the top. And the last one is, of course, about the beach ball solution of oblique faulting.

Fault plane solution: Moment Tensor

Moment as force Couple

U → Ground displacement obtained from Seismic wave form

M → Moment Tensor

G → Green's Function

$$U = G \times M$$

or

$$M = G^{-1} \times U$$

Seismic moment 'M_0' is also a function of average displacement at the Source as:

$$M_0 = \mu \, u \, A$$

μ → Shear modulus of the rupture medium.

u → average ground displacement.

A → area undergone rupture.

In addition to the beach ball solution in determining the fault plane solution, you have another way of determining the fault plane solution that is called the moment tensor solution. So generally, if you take the strike-slip faulting as mentioned over here, there will be moments on two parts of the fault plane. So, if you take that into account for the fault plane and strike-slip faulting, then two moments will be there: one on one side and one on the other side. Coupling these two, you can take into account as a force couple of the moment in order to balance that. So, you will apply another force couple; that is how it becomes a double couple. Now the displacement, because we start with offset, dislocation—every time there is an earthquake, before that there will be accumulation of strain energy or there will be some displacement which is getting accumulated in terms of strain energy. So, this displacement can be correlated with respect to this double couple related moment by means of Green's functions, or you can determine the value of the moment tensor by means of G inverse times U. So, that is an indication of if you know the average displacement and the Green's function, you can actually determine what is the state of forces and the corresponding displacement which is dominated in a particular earthquake-related fault moment.

So, U is obtained from the seismic waveforms; you can take different recording stations along your recording station and try determining the ground displacement. M is the moment tensor, and G is Green's function. Taking these three things into account, it can be correlated like this. Again, on the other hand, seismic moment M_0 is also a function of average displacement. So, the size of the earthquake, that is, seismic moment, can be correlated with respect to displacement. This displacement can also be evaluated by means of Green's function in terms of moment tensor solution. So, moment tensor solution will also help you in understanding what kind of nature of forces has been mobilized. Subsequently, using Green's function, you can also find out what is the average displacement in the dominating directions, that is, the fault plane and other directions.

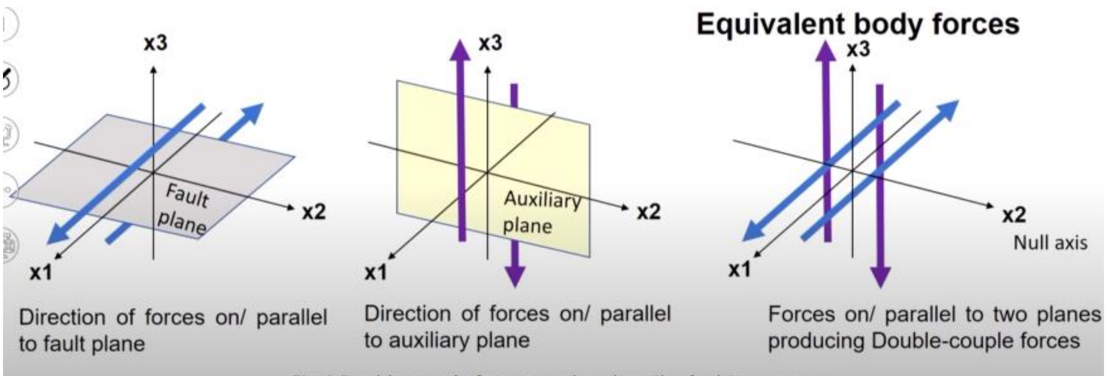


Fig.6 Double couple forces used to describe faulting process

So, here you can see the first one is the fault plane and possible moment along the fault plane; secondly, perpendicular to the fault plane, again there is some kind of moment; and the last one is equivalent body forces. So, you can see primarily three axes: X_1, X_2, X_3, and corresponding to those axes, depending upon whether the moment is along the fault plane or the nature of forces perpendicular to the fault plane or an auxiliary plane, and these are the equivalent body forces or the double couple.

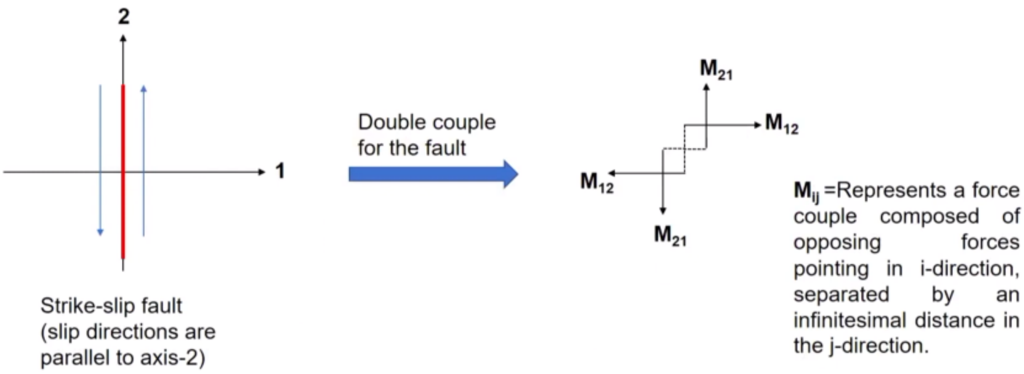


Fig.7 Double couple for fault

Similarly, this can also be developed using the means of M_{21}, M_{11}. So, 2 is an indication of the direction in which the force is applicable, 1 is the direction in which it is perpendicular, similar to your stress tensor; that's how you can develop these force tensors or moment tensors.

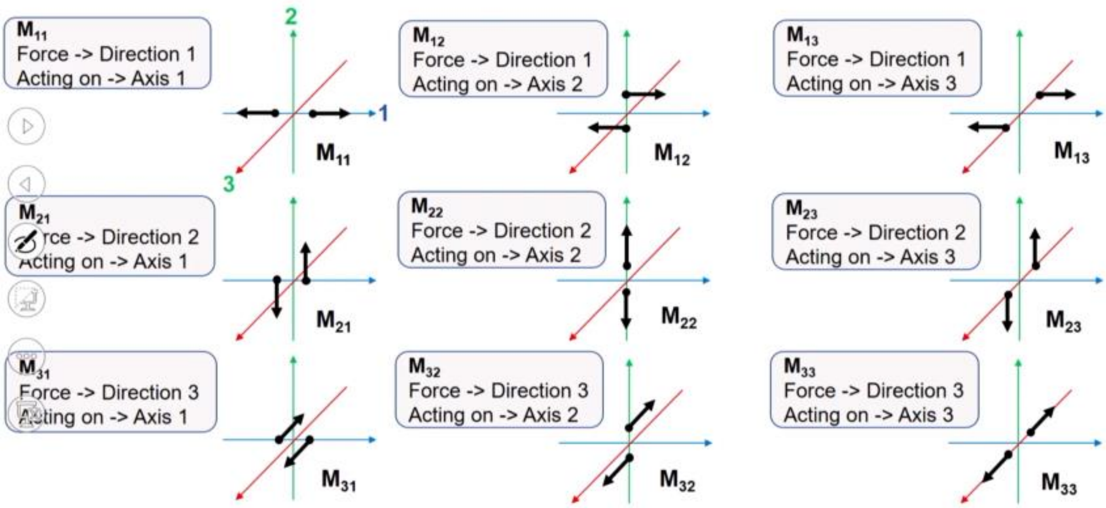


Fig.8 All 9 possible generalised couples

Again, depending upon the directions you can see over here, so possible nine components you can develop. So, M_{11} is an indication; the first suffix is an indication of the direction in which force is applicable, and the second one is on which direction this particular force is applicable. So, if you see M_{11}, it means the force is applicable in the direction of 1, and the direction of the force itself is also 1. M_{12} is the force acting in the direction of 1 on 22, or the axis on the plane perpendicular to axis 22. The same way with respect to M_{13}, M_{21}, and subsequently, here you can see altogether these components which are an indication of possible movements because the moment tensor is directly indicated with respect to ground displacement. So, you can see over here, depending upon the direction in which the force is applicable and the plane which is perpendicular to a given axis, you can have all these components. These all will give you a general understanding about what is happening at the point source in terms of average displacement and what are the dominating directions of application of force couples.

Again, I gave you very preliminary information about moment tensor solutions. Thank you so much.