Applied Seismology for Engineers

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Week – 04 Lecture - 01

Lecture – 07

Hello everyone, welcome to lecture 7 of the course Applied Seismology for Engineers. Myself, Dr. Abhishek Kumar. In earlier discussions, we have discussed the occurrence of earthquakes, which is primarily related to the movement of the plates, convection current generated in deeper layers of the earth. Now, whenever an earthquake happens at the source, there will be material involved, primarily the material which is available on the fault plane. Whenever, because of strain energy accumulation and the stresses which are developing, exceeding the in-situ shear strength, the material will undergo failure. Whenever we are talking about failure, sometimes it will be melting, sometimes it will be rupture. As a result of disturbance, some sort of disturbance will be created at the source or at the focus of the earthquake, and this disturbance, or the energy which has now been released at the focus, will start propagating in all directions with respect to the focus. So, if this is the focus, then in all directions with respect to the focus in three-dimensional space, if we see, the energy will be propagating in all three dimensions away from your point of origin or the focus from where the seismic energy was actually initiated during a particular earthquake. Now this energy, released from the source and propagating, will happen in terms of seismic waves.

So, there will be a disturbance which will be created at the source, and as the seismic energy is interacting with the medium, you might be remembering this is a crystal medium in which the the focus of the earthquake is located. So, from the focus of the earthquake, the seismic waves will come into the picture as the disturbance or seismic energy is propagating. Now, because of these seismic waves coming into the picture, there will be different kinds of movement happening in the propagation medium. So, you see there is a medium involved over here. This medium will undergo different kinds of disturbances, even whenever we are hearing and experiencing any kind of earthquake. Suppose some earthquake happened in the near-epicenter region and we are also standing over there; many a time, we will also sense some kind of vibration happening in the ground.

So that vibration can be understood as the response of the system when a particular seismic wave is propagating through a particular medium. Whenever we are discussing about recording stations, so again, there is a seismic wave which has been generated from the focus, propagating in different directions. Wherever a recording station is coming into the picture, the recording station will actually sense the amplitude of vibrations with respect to time, which is changing when seismic wave is propagating through your recording station. So, whenever a recording station is there, it is the response that is recorded by the recording station. Whenever a building is there, the same seismic loading will help in the response of the particular building. So, if the building is designed for that response, the building will be able to withstand that particular earthquake loading. Otherwise, there will be minor cracks; there can be collapse also. So, every time, whether we are feeling the earthquake or there is recording or a building is there, basically it is the response of that particular system related to seismic waves which are actually propagating through that particular system location and primarily at that particular location. Many a times we will install recording stations, maybe in bedrock medium, maybe in soil medium, but not at the ground surface but at deeper depth. So accordingly, the vibrations will keep on modifying themselves as these are interacting with the material properties.

Further details about seismic waves, propagation, how these are interacting with the medium, and what are the governing equations which will control the motion properties, that we will discuss when we will discuss in detail about seismic waves, ground motion, and ground response analysis. So, in today's topic, that is in lecture number 7, we will be discussing what are the different kinds of seismic waves—an overview, the governing equation of these waves, how it is propagating through a particular medium, what is the resistance the medium is offering which ensures that the wave is propagating through a particular medium—that we will discuss in later lectures. So, in today's lecture, we will be discussing what are the different kinds of seismic waves. As the name suggests, seismic waves mean different kinds of waves which come into action, which come into existence primarily because of some seismic activity. Now, by virtue of the characteristic that when these waves propagate through a particular medium, some will cause compression, rarefaction, some will cause elliptical motion, some will cause lateral motion, some will cause shearing. Each kind of wave propagation will be responsible for each different kind of particle motion in the medium. As motion in the particle is happening, the system is going to respond to the earthquake loading condition. And of course, whenever seismic wave we are interested to talk about, we will be also interested to know if there is a way, a mechanism based on which we can locate the epicenter of the earthquake. That means whenever a recording station is there, which is actually sensing the vibration because of a particular earthquake at different locations. So certainly, whenever a record is there, we do not know where actually earthquake has happened.

So, we have to analyze the earthquake characteristics based on the ground motion record which is available to us. That is how we will be able to locate the earthquake epicenter, and as I mentioned in earlier lectures also, if one is interested to find out the focal mechanism of an earthquake. What was the dominating kind of movement at the source, at the fault plane, which has triggered during a particular earthquake? Normal faulting, reverse faulting, strike-slip faulting, dip-slip faulting. So, all those information about fault mechanism can also be developed based on the ground motion recorded at different recording stations. So, in today's lecture, we will be discussing seismic waves and how the ground motions which have been recorded by different recording stations can be used to find out the epicenter of an earthquake.

So, earthquake, as we have been impressing upon, the earthquake directly does not cause any kind of damages. It is basically how a particular system, whether it is a building, whether it is a dam, whether it is a bridge abutment, or any other infrastructure. So how this particular infrastructure is going to respond to a particular earthquake or earthquake-induced vibration will define the fate, whether the structure will undergo partial damage, whether the structure will undergo total collapse, or there will not be any damage at all. Simply the system will go back and forth motion and then come back to its original position once the wave passes. So, it is basically the response of a particular structure or a particular system to earthquake loading. If it is able to withstand, it will retain. If it is partially undergoing damage, that means partially it was able to withstand, partially there were some places where the in-situ strength has exceeded. So certainly, in those cases, there might be some development of cracks, shear cracks, and many more signs of damages. If it is unable to withstand the earthquake loading condition, certainly in such cases, it will undergo complete collapse. It can be a bridge, it can be an abutment, it can be a turbine, it can be tunnels, depending upon the structure with which we are dealing. So, it is basically the response of the structure to earthquake-induced loading.

So, it is the same thing we have mentioned over here also. It is the response of the building, the response to various kinds of structures or buildings to seismic waves, or in general, we call it disturbances which are the actual indication or representation of seismic waves generated from the source to the site. If I am standing over here and some earthquake happens, the wave will propagate; if I am depending upon where the earthquake has happened and where I am located, maybe with some delay, but certainly the wave will propagate through the ground where I am standing. This disturbance will be carried forward by means of seismic waves. So, whenever waves are passing, I will be able to feel some kind of disturbance. If I put a sensor over there, this disturbance will be calibrated in terms of maybe displacement values, how these are changing with respect to time, velocity values with respect to time, how it is varying, or acceleration values with respect to time, how these are changing. Earlier, most of the time, the ground motion records used to be recorded in terms of a rotating drum followed by some pencil which is actually sensing the vibration and marking it on a calibrated sheet. Later on, we are also using different kinds of piezoelectric sensors, so that will sense the vibration and convert it in terms of some values of volts, and depending upon the calibration unit, we can convert it and find out a suitable value of ground vibration. So, it is basically the response of the building to seismic loading which will define whether the building will undergo partial damage or complete collapse and subsequently induced effects. Induced effects mean the effects which were actually not there, but now because there is vibration involved, and this vibration is going to induce additional loading to your structure. The classical example of induced loading is liquefaction.

So, I am interested to find out, like during a particular earthquake, what happened during liquefaction. Initially, there was a ground which was quite levelled, and the ground was also offering significant bearing capacity, but as the same ground was subjected to earthquake loading conditions, there will be an increase in pore water pressure, or there will be development of excess pore pressure, which will actually push the soil particles away from each other. Now, the entire process, whether the soil particles are being moved or pushed away from each other, is primarily happening because of the interaction of seismic waves with respect to the medium or soil particles. So, when such things happen, there will be a loss of shear strength of the material. The material in which the liquefaction phenomenon is triggered will almost transfer from a very stable ground to almost like a liquid-consistency ground. So whatever ground was there, if you have used it as a parking area and parked your vehicle before an earthquake, it was well balanced; your car was parked in a good manner, and then, during the earthquake, the entire ground underwent liquefaction, and then, subsequently, it will undergo sinking, or there will be too much settlement in the building. So, this is called an induced effect. This is not directly the effect caused by the earthquake, but certainly how the earthquake-generated waves have interacted with the medium, so this is an induced effect. It is basically induced by the earthquake but happening in the medium because the medium was not able to withstand the earthquake loading condition. So, the high amount of energy during an earthquake is released in the form of seismic waves or shock waves, similar to the development of ripples in water.

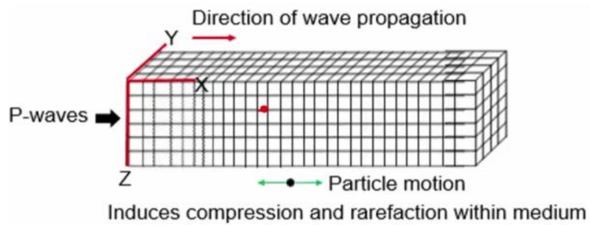
So, as you throw a stone in water, you will see there will be development of ripples. At the same time, if you are having a leaf in the water at a certain distance away from where you drop a pebble, you will see there will be development of ripples, and when these ripples reach the leaf, you will see initially the leaf was more or less in a stable condition, avoiding the minor disturbance which was happening before the dropping of the pebble. Suddenly, when these ripples, which are generated at the place of dropping the stone, reach the leaf, you will see significant upside-down movement, or at times, other times, it may also undergo some kind of rotation. So, this kind of movement which is happening may be because of the combined effect; it is very much similar to seismic waves passing through a particular medium or ripples created by dropping a pebble in water.

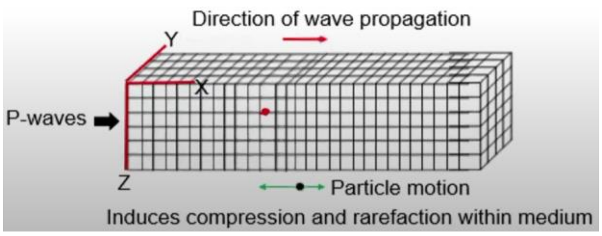
So, kinds of seismic waves. Now, whenever we discuss seismic waves, primarily these are classified into two categories. One is the seismic waves which are generated at the source or the focus, and when these body waves, which are primarily generated deeper at the focus, interact with the surficial or near-surface medium of the earth, how these seismic waves are interacting will then subsequently lead to the development of surface waves. So, as I mentioned, you are having two types of waves. One is the P wave that is called the primary wave or compression wave, primarily because these are the first waves which are reaching a recording station because these are the waves which are the fastest in terms of seismic waves or all seismic waves which we will be discussing over here. So, these are the waves which travel faster, and so this is why it is also called a primary wave. So, if you are having a recording station, these are the waves which are going to reach the recording station at first. After that, there will be a secondary wave. So, your recording station is over there; you waited for some time, some primary wave, some disturbance was there, and then again you will see that the amplitude of the vibration reduces, and suddenly there is a jump in the increase in the amplitude of the vibration, clearly indicating another type of wave has just reached your recording station, indicated by some vibration. So, this is your recording station having ground motion, so you will see initially there was some disturbance, small disturbance, and suddenly reached the peak; then there was some reduction in the disturbance, and again you will see some peak over there. So do not take right now the amplitude in the literal sense of primary and secondary waves. What I am trying to show over here is that firstly, there will be a P wave arrival, followed by an S wave arrival. So, these two things we will be able to differentiate even from the ground motion record, provided the ground motion record is also at a sufficient distance from the source; that arrival of the primary wave and secondary wave can be easily distinguished. If the recording station is very close, then the difference between P and S wave arrival time will be so small that distinguishing between primary wave and secondary wave will be almost impossible. At least by naked eye, you can process it; you can find out other parameters that will help you in identifying where the primary wave is ending, and subsequently, that will help you in identifying where the incoming secondary wave is starting.

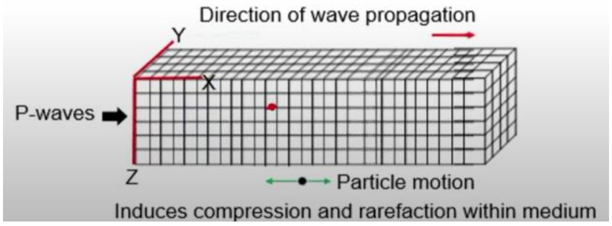
So, the first one is called a primary wave because it is coming first at the recording station; the second one is called a shear wave, which is the second wave reaching a recording station. These are also called shear waves because whenever they are passing through a particular medium, they are also inducing shearing in a particular medium. Both these waves, whether we are talking about the primary wave or secondary wave, are the classes of body waves. As I mentioned sometime back, body waves are the waves which are generated at the source and start propagating through the proper medium, whether it is a propagation medium or the crystal medium, and even at shallower depths, and these get interacted with the near-surface layer of the earth or near-surface soil medium, resulting in the formation of surface waves. As the name says, surface waves mean the waves which you can find dominating closer to the near the surface. So, these are called love waves and Rayleigh waves. These are two kinds of waves which are more prominent near the surface. Primary waves and secondary waves are the waves which are actually generated at the source and are propagating. When they are propagating and interacting with near-surface layers, then we will have love waves and Rayleigh waves coming into the picture. So, as I mentioned, P and S waves are called body waves as these waves can travel through the earth's interior because they are generated at the source and can be recorded even at distant recording stations. So, some recording stations which are even located at larger epicentral distances, you can have a clear signature of primary and secondary waves because these are body waves. In addition, you have love waves and Rayleigh waves. As the name suggests, these two are called surface waves because these are coming into the picture, coming into existence when body waves are interacting with surface or near-surface material. So, these are called surface waves, which can only travel through the near-surface medium or through the crystal medium. Now, the primary wave, if you look into the detail of the primary wave, is also called as compressional wave. As I mentioned, these are also called primary waves because they reach first, and are also called longitudinal waves because whenever these waves are propagating through a particular medium, there will be particle motion in the direction of wave propagation. So, if the wave is propagating in this particular direction, there will be particle motion in the direction of wave propagation. Whatever particles mean particles which are there in the medium, propagation medium, if the wave is passing like this, then there will be particles which are also going to and fro in motion in the direction of wave propagation.

So, we have primary waves, which are called longitudinal waves because they include vibration in the longitudinal direction. At the same time, you are having primary waves also to be called P waves because these are the waves which are reaching first at a recording station. Then these are also called compressional waves because, as I mentioned, particle motion is along the direction of wave propagation; these are called longitudinal waves. These are called primary waves because they reach first at the recording station. They are also called compressional waves because whenever these waves are passing through a particular medium, they actually induce compression and rarefaction in the propagation medium, so identical to sound waves passing through a liquid or gas. So as a sound wave passes through a liquid or gas, there will be compression and rarefaction in the medium; the same is happening with respect to primary waves. Now, in addition to transmitting the seismic energy which was generated at the source by means of compression and rarefaction triggering in the material through which the waves are passing, now compression and rarefaction mean there will be backward and forward movement of the particles, medium propagation particles, whatever is the propagation medium through which primary wave is passing. Always the movement of medium particles will be happening in the backward and forward direction.

Now, here we can make out based on the speed you can see over here; the primary wave can travel at a speed of 5 to 8 kilometers in just one second. So, 5 to 8 kilometers even in one second a wave passes or travels. Now we can understand if there is some earthquake happening maybe 100 kilometers, 200 kilometers away from where I am currently sitting, how much time it will take for a seismic wave, primarily the primary wave, how much time it will take. Even if you are located 500 kilometers away from your epicenter, it will just take 100 seconds; it will take hardly 3 minutes or less than that to reach your recording station, less than even 2 minutes it will take to reach your recording station. Or even if you are sitting over here, it will take significantly less time. So, we are talking about 1 minute, 2 minutes, 3 minutes, like that to feel or to record an earthquake which has happened 500 kilometers radial distance. That too, I am talking about 5 kilometers per second. We are talking about some other earthquake, which is, I mean the wave which is traveling in a medium having primary velocity of 8 kilometers per second, still we can see it will not take complete 2 minutes; it will take less than 2 minutes to reach the primary wave generated at a 500-kilometer distant earthquake to reach your recording station. So, this is the fastest seismic wave, passing through a particular medium, and this is the wave velocity in the earth's crust. It is over 8 kilometers per second in mantle and 1.5 kilometers per second in water and 0.3 kilometers per second in air. So even these waves can travel through water and air. Now, the smaller in the amplitude compared to other types of waves. So that's what I showed in the previous slide also when I was showing the ground motion signature. Do not take amplitude into account; the whole sense there was to indicate that whenever some vibration is there or some waves are reaching your recording station, first you will see some minimum disturbance followed by some peak. The amplitude of the peak might be lower for the primary wave, as mentioned over here, but there will be some increase in the peak again; it will come back to the minimal position, and then after that, once the shear wave reaches your recording station, there will again be an increase in your signature of ground motion. So, the amplitude of these waves is comparatively low with respect to other types of waves. Particle motions wave is passing in this particular direction, so even the particle motion will be happening in the same direction. If you are able to see my hand, so consider this is the particle. When the wave is passing along my hand, even the particle motion is happening in the direction of my hand movement. So, no deformation once the wave leaves a particular medium; there will not be any kind of deformation or even volume change. So whatever volume was there before the wave entered a particular medium, it remains the same once the wave leaves a particular medium, so there will not be any volume change in the medium; there will not be any deformation in the medium itself, so these can pass through liquid as well as through solids.





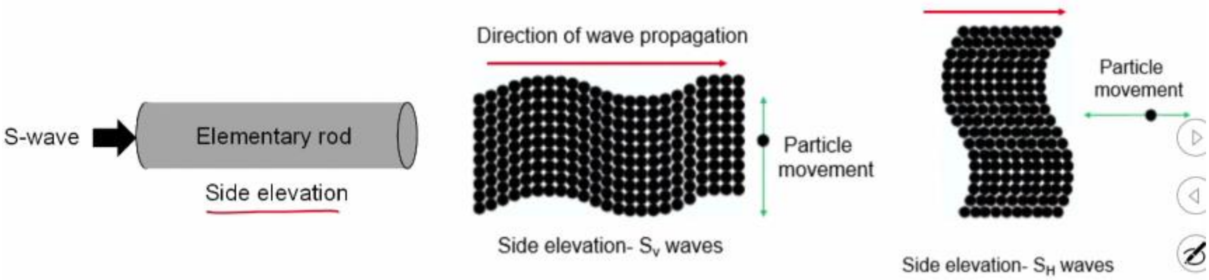


Now here is one animation you can see over here. There is particle motion. Consider even one particular element over here, and then you see once this particular wave is passing through a particular medium, there is to and fro motion, backward-forward movement, and you can see the particle initially underwent compression, rarefaction, and then came back to its original position. So, this is inducing compression and rarefaction in the medium through which the wave is passing. S wave, now some portion of this wave information, I will also discuss in a later section when we will be discussing the one-dimensional equation of motions for primary waves and secondary waves, and then this will be used when we will be discussing ground response analysis in later lectures.

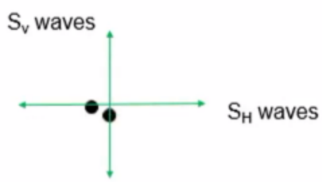
So, shear waves, as I mentioned, these are the waves which are reaching second at the recording station; that is why these are called secondary waves. These are also called transverse waves because whenever a wave is passing through a particular medium, if this is the direction in which the wave is passing, there will be oscillation in the particle in the transverse direction. This is the direction of wave propagation; particles are undergoing movement in the transverse direction, which can be upward-downward movement, or it can be in the direction perpendicular to your screen. So, this direction, if I see in plan, the particle can undergo motion in a direction perpendicular to your wave propagation and also in the horizontal direction. So those two will be indicated by the movement of particles triggered by the propagation of the shear wave. Now, thirdly, it is also called shear waves as the particle is, as the wave is moving, the particle is undergoing movement in the vertical direction. So, consider particles are there in the direction perpendicular to the wave propagation, and the nature of particle movement is like this, which is an example of pure shearing happening in the vertical direction. Same thing, even in the horizontal direction also, there is movement of the particle happening in perpendicular to the direction of wave movement. So, it is inducing shearing in the horizontal direction; the other one was inducing shearing in the vertical direction. So, it causes shear deformation as passed through a particular medium. When the primary wave was passing, it was triggering compression and rarefaction; when the shear wave is passing, it is triggering shearing in a particular medium, that too in two perpendicular directions with respect to the direction of wave propagation. These are also called secondary waves because these are the second waves reaching a recording station. So, when the primary wave is done, there will be a sudden increase in the signature or amplitude of vibration, indicating the arrival of secondary waves or shear waves or transverse waves at your recording station. But usually, these are slower than primary waves.

Material, again very much similar to primary waves. Once the shear wave leaves a particular medium, there will not be any deformation; there will not be any volume change; the material will come back to its original position. So, these can travel through solids but not from liquids because liquids, in general, do not offer resistance to shearing, so there will not be any propagation of shear waves through liquid, and the same is applicable for gas. So, there will not be any propagation of shear waves through liquid or through gas. Whatever shearing is happening, it will only be happening in terms of if the propagation medium is solid. So now here we can see the typical velocity of propagation is 3 to 4 kilometers per second. In the previous case of primary waves, it was 5 to 8 kilometers per second in the Earth's crust; here, it is 3 to 4 kilometers per second. So even after having close to 2 minutes of arrival time of primary waves, there will be shear waves, which are yet to be received at a recording station because the wave propagation velocity here for shear waves is slightly lower than primary wave velocity. So, this is 3 to 4 kilometers per second in Earth's crust, 4.5 kilometers per second in mantle. Particle oscillation happens in a perpendicular direction with respect to wave propagation. As I mentioned, the wave is moving in this particular direction, the particle motion will be happening perpendicular to a board or again along the board in a vertical direction.

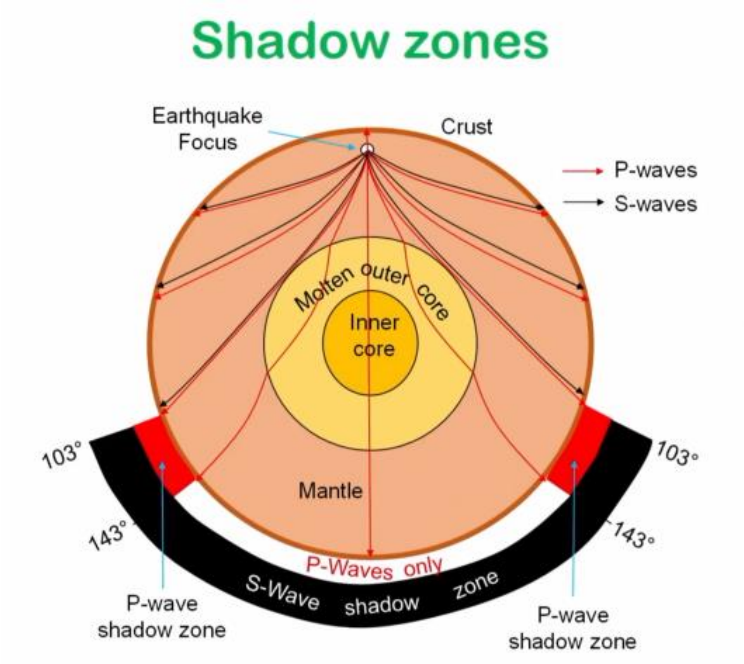
Now, depending upon which type of movement is triggered by the shear wave, you can still call it an SH wave or SV wave. So, the direction in which the particle is moving in the upward and downward direction because of wave propagating in a horizontal direction, you call it an SV particle or SV motion, shearing happening in the vertical direction. The same way with respect to left and right movement with respect to the direction of wave propagation, that will be called SH movement or shearing happening in the horizontal direction because of wave propagation. So, this is the nature in which the shearing will happen.



Consider the shear wave incident on a particular medium; this is an elementary rod, and you are seeing it in side elevation. Now, as the wave moves, the first figure shows elevation or the shearing which is happening in the vertical direction. You can see over here, take any particular cross-section, you can see over here, because of movement of the particle or movement of the wave in the direction which is indicated by an arrow over here, you can see the shearing happening in the vertical direction; this is the way the shearing is happening. Even here also, you can see there is shearing happening in this particular direction. So, this is what you can call as corresponding to SV wave, vertical plane in which the shearing happens because of secondary wave propagation. So, this is because of particle motion in the vertical direction. The same way, here also we can see again the particle motion is happening in the horizontal direction. So, you can see over here, shearing is happening in this particular direction. Consider this particular plane or this particular plane, shearing happening in the horizontal direction, and this is triggering particle motion in the horizontal direction. So, the shear wave is passing through a medium and triggering possibly two types of particle motion, one in the horizontal direction and one in the vertical direction.



Now later on we will also see; now here, one thing which later on we will use is there is one particle or one cross-section is there, which is undergoing shearing in horizontal as well as in vertical direction simultaneously. As a result, the propagation of shear wave through a particular medium is also approximated with respect to application of torque. So, when you are talking about torque, that means it is happening in horizontal as well as in vertical direction, some kind of shearing happening in both the planes, which is an indication of shear wave passing through a particular medium. Now, here also we can see, so it is like the particle remains the same, but movement is happening in horizontal as well as vertical direction simultaneously.



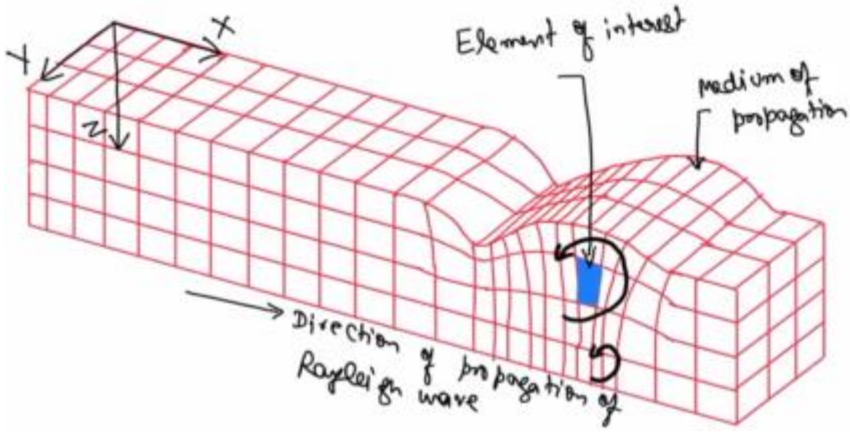
Now, as I mentioned, that during a particular earthquake at the source or at the focus, seismic waves, primarily the body waves, will be generated, and depending upon their inherent properties, depending upon what kind of movement they are generating, and the medium, what sort of resistance the medium is offering, we can see over here that the wave is not able to propagate through a certain medium; certain waves are able to propagate through all the mediums. So, consider over here this was the focus of the earthquake through which P wave and S waves are generated. Now, as we see the characteristics of the medium in terms of its viscosity, in terms of its consistency and physical properties, it is changing as you move from crustal medium to mantle to core. So, if you start from crust, and there is propagation of primary wave within the crust, so this, you can say, this is the recording station which is actually sensing the vibrations in the ground. The primary wave started from your source and reached your recording station, so between the source and the site, it is more or less traveling in a medium of the same physical properties. If you do not take medium heterogeneity at this moment into account, it's propagating more or less in the same medium. So, you will have primary wave and secondary wave both.

Now, consider another example: we have also discussed that in the outer core, the material is in a molten state; that means the physical property of the material with respect to crust and mantle has changed. Taking into account that shear wave cannot pass through liquid or molten state, whatever incident shear waves are there will not be able to propagate through this particular medium. So, whatever shear wave incident over here, the black one, you can see over here from the source, shear wave reached over here; same way, on this particular part also, the shear wave has reached, but after this, in this particular entire range, shear wave is not able to propagate because whatever incident wave is there, it should reach the molten outer core, and further, it cannot propagate because these are characteristics of shear wave; it will not be able to propagate further. So, this entire region, which is located at 103 degrees azimuth on both sides with respect to your focus, all the recording stations which are located at 103 degrees azimuth on either side of the globe will not be able to detect any kind of shear wave generated from the source. It does not mean that the earth did not generate any shear wave; rather, it is the limitation of your location of recording station with respect to the epicenter, which made the condition such that there will not be any shear wave reaching your recording station located between 103 degrees on either side of the globe with respect to the focus. Same thing if we talk about primary wave. The primary wave started from the source, but once it reaches a significant change in physical properties, that means between the mantle and the outer core, because of the change in properties, what we are seeing is it is deflecting from its original path, and again, a second deflection is happening over here when it is again reaching the interface of outer core and mantle. Because of this deflection, the wave otherwise would have reached this particular side, but it is not able to because of the change in the physical properties of the medium. So, because of this deflection, again, you see over here, in this particular red zone, though there was a primary wave generated at the source, it will not be able to get detected by the recording station located between 103 degrees to 143 degrees azimuth on one side, and same way, 103 degrees to 143 degrees on the other side of your recording station.

So, this azimuth will keep on changing if you shift your recording station—not recording station, the focus—if the focus of the earthquake is shifted from here to here, then corresponding to the revised focus or the focus of an earthquake which has happened very recently, 103 degrees on two sides of your earth, and 103 degrees to 143 degrees again on both sides, this will be the range of azimuth in which you will not have secondary wave; you will not have primary wave, respectively. Since these waves are not there, the zones are also called as P wave zones. So, this is called a P wave shadow zone; this is called an S wave shadow zone. So, there is an earthquake which does produce primary and secondary waves, but considering the physical properties change across the depth of the earth, certain waves will be detected at some recording stations but not be detected at other recording stations, and subsequently, that will be applicable to all the recording stations across the globe with respect to the focus of the earthquake target.

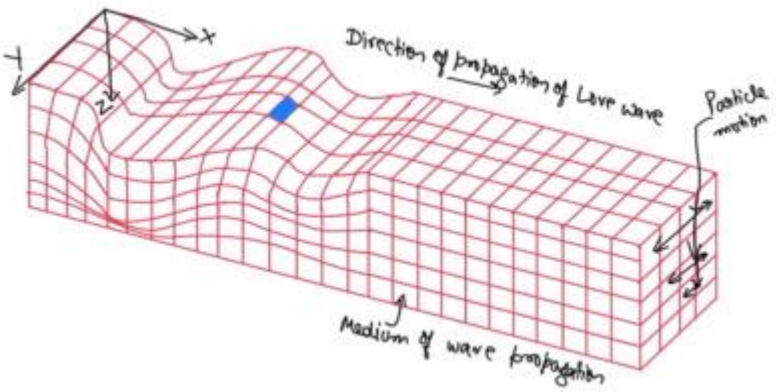
Now, surface waves, as I mentioned, move along the earth's surface, very near to the earth's surface, resulting from the interaction of body waves with the surface and other surficial layers of the earth, whatever layers are available near the surface. When body waves are interacting with those layers, then surface waves come into the picture. The amplitude of surface waves decreases drastically or exponentially with respect to the depth. So, whatever amplitude you are seeing at the surface, there is a significant drop in the amplitude as you go deeper, more prominently like larger distances, usually greater than 1.5 to 2 times the earth's crustal thickness; you may see significant amplitude in the surface waves. At a distance, the thickness of the earth's crust surface wave may cause more damages with respect to body waves. So, these arrive after primary and S waves. Primary and secondary waves reach the recording station, then it will be followed by surface waves. Deep focus earthquakes generally do not produce surface waves. These are further classified into Rayleigh waves and Love waves.

Now, as I mentioned, as we can see over here, Rayleigh wave, which was understood by Lord Rayleigh in 1855, and so after that, these are called Rayleigh waves, also known as Lamb waves. Whenever these waves are passing through a particular motion, whenever these waves are passing through a particular medium, there will be elliptical motion in the particles in longitudinal direction as well as in the transverse direction. So, if the wave is passing like this, there will be movement in the particles in longitudinal as well as transverse direction resembling an elliptical motion. The amplitude decreases exponentially with respect to distance as well as with respect to depth. Rayleigh waves are generally produced by the interaction of S-V waves or the vertical component of shear wave with rest and primary wave with respect to the near-surface medium.



Now, here we can see this is the direction in which the Rayleigh wave is propagating, and as a result of which, you can see over here there is movement in the particle representing an elliptical motion or rolling which is happening in the direction of—I mean, if the wave is propagating like this, then you can see this kind of rolling or elliptical motion both in the longitudinal direction and also in the transverse direction with respect to wave propagation. At the same time, we can also see that the amplitude of these elliptical motions also significantly reduces as we are going deeper with respect to the ground surface. So, the typical speed at which the Rayleigh wave can propagate, it also depends upon the medium involved, so 50 to 300 meters per second. Further, we can go for a denser medium, and then it can also increase to the speed of sound that is approximately 3 kilometers per second. Other sources of Rayleigh wave are basically ocean waves, movement of railway trains, vehicle movements, slash hammer impact. So, these are also additional sources based on which the vibration which will be generated will be dominated by Rayleigh wave content. So, this causes more shaking and damage because of its rolling effect. The intensity of shaking by Rayleigh wave during an earthquake event is a function of the size, focal depth, epicentral distance, and focal mechanism. So, it carries maximum energy released during a particular earthquake. Particle motion will be similar to throwing a stone in ponds; we will see again some ripples, some elliptical motion in water which will show some kind of ripple movement. Slightly slower than S wave depending upon the elastic properties of the medium. The depth of material displacement is equals to the wavelength. So that material which is involved will be equals to the wavelength of the Rayleigh wave which is coming into picture, and that's how one can focus more on what is the depth which one can call it as near surface medium or surficial layers for the development and quantification of Rayleigh wave properties.

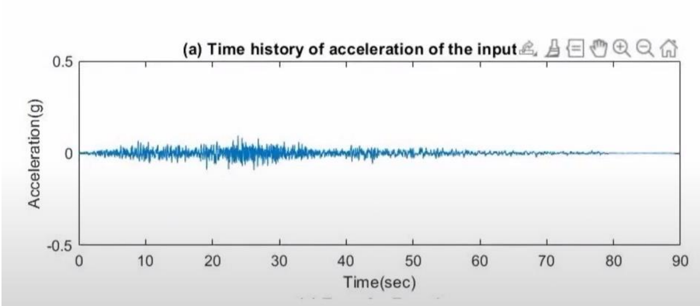
Next comes is the Love waves. It was again named after Augustus Edward Hugh Love, who discovered these kinds of wave in 1911, and as a result of which these are called as Love waves, also known as Q waves, which are primarily responsible for movement in lateral direction. So, these are generated primarily because of the interaction of the horizontal component of shear waves with respect to surficial layers of the earth. There is no vertical movement, so all the movement which are happening because of Love wave passing through a particular medium is primarily happening in horizontal direction or in lateral direction. There is no vertical movement. Again, you can see over here that when Love wave is passing through a particular medium, the movement is happening in lateral direction. Secondly, we can also see over here that the particle amplitude of motion significantly reduces as you move from ground surface to deeper layers. So, the amplitude of the motion is reducing. These always cause lateral movement; there is no component which is triggering movement in vertical direction.



Now, arrival of Love wave happens after primary and secondary wave, but it happens before Rayleigh wave. So, if there is a recording station and we are interested to find out which wave will come first, then there will be primary wave which will be coming first, followed by secondary wave, followed by Love wave, and then Rayleigh wave. This is generally the nature in which the different kinds of wave will reach to a recording station. Again, in addition to the earthquake source, if any other source of vibrations are there, then in your ground motion record, you may also experience some kind of additional noises. If along the propagation path between your focus and your recording station, medium heterogeneities are also available, these will also act as additional source of reflection or refracted waves, which will again reach to your recording station. Depending upon the position of these sources with respect to your recording station and your focus, some of these refracted and reflected component may reach prior to your direct wave. This will again add more complications to your ground motion record.

Again, once it is reaching to a recording station, because it's not that the wave starting from the focus is trying to reach to your recording station, so wave is propagating in the three-dimensional space, and then depending upon the response of your ground, some components of the wave are reaching to your recording station. Now these some component may be reaching directly; some will be undergoing reflection and refraction through a propagation medium. Thirdly, some of the wave which have actually surpassed your recording station and moving further will also have some kind of back-scattered waves, so that will also cause additional vibrations or, at times, delay or increase in the amplitude of the duration of vibration. So, amplitude of the motion in case of Love wave also decreases rapidly with respect to the depth. It attenuates at a rate of 1 by r, where r is the epicentral distance, so 1 by square root r is the rate at which the amplitude of the wave will attenuate, will reduce as you are moving away from your point of origin. Larger earthquakes generally generate Love waves which can travel the earth several times without any kind of dissipation. Travels at a rate of 2 to 4 kilometer per second in earth's surface, depending upon the frequency content of propagating waves. Now, finding an epicentral of an earthquake. See, we are interested to know about the waves because these are finally the waves which are actually generated from the focus, reaching to different, different, whether you call it as recording station, you call it as building, you call it as soil deposit, bridge abutment, tunnels. So, these are the waves which are generated from the source of the earthquake or the focus and then propagating in all the direction. In order to understand the characteristics of the waves, there will be recording station called as seismograph, which will be installed at different, different locations. The guidelines for selecting can be covered in other courses; I am not covering over here, so depending upon the suitability where one can install a recording station, we can go and locate a recording station which will actually sense the characteristics of vibration during a particular earthquake. So, if there has been an earthquake, as a result wave generated from the source, it reached to a recording station and then move further, and this characteristic of vibration which was available at the location where the recording station is located, that will be detected at the recording station.

So usually, it is the disturbance or some sense of ground shaking, how it is changing with respect to time. As I mentioned earlier also, so if you are discussing about some vibration, it's like some rotating drum is there with some pen over there to mark the disturbance. Now when earth undergoes some kind of vibration, this will also be able to mark some vibration. How the vibrations are changing, it should be in vertical direction, actually, how the vibrations are changing in with respect to time. So, I am standing over here, some earthquake comes, I will go back and forth motion. If I am able to sense that particular motion and calibrate in some fashion of expression, then I will be able to develop a ground motion record. Now, whether I am discussing about displacement change with respect to time, or change in velocity values or acceleration values with respect to time, accordingly a particular ground motion record can be called as.



So here, in this particular image, we are able to see one typical acceleration time history record. On x axis you are having time values in second; on y axis you are having acceleration values. So, you can see whenever an earthquake had come, you had a recording station which is actually sensing the ground vibration. Starting from zero, you can see initially there was no disturbance because there was no arrival of wave. Suddenly some disturbance, some vibration from wave started coming, and then you will see a lot of disturbance are there which can be also quantified in terms of acceleration values given over here in terms of g. So, it's basically the how the value of acceleration is changing over a period of time, so this you can call it as the duration of loading which is coming over here as close to 90 second. So, it's like whenever there was an earthquake, almost close to 90 second, there was vibration happening at your recording station. How much vibration this has been calibrated over here in terms of acceleration time history record.

If one is interested to find out the frequency content of the motion, there are ways which will be discussed in terms of when we will be discussing about ground motion characteristics in later lectures. Now, here the purpose of showing this particular earthquake record is there will be some primary waves which are coming or are there in this particular record, there might be some secondary waves also which are there in this particular record. So, wave generated at the focus being detected at the recording station, can we use these signatures to find out where actually the earthquake has happened? Because this is going to give me only the nature of ground vibration at my recording station. I am also interested to know which is the source, or where is the source, which actually triggered earthquake which is leading to these kinds of vibration. So, one is recording station, which is actually recording station which is actually recording the vibration, and there is focus which is called as source of earthquake. So, though vibrations are generated from the source, reaching to a recording station, I will be taking the ground motion recording and try to reach to locate the source of the earthquake where the earthquake has happened. Primarily, we will be interested to locate the epicenter of the earthquake where actually the projection of focus is located on the earth's surface. Now seismic wave arrival sequence, as we discussed, there will be primary wave, secondary wave, Love wave, Rayleigh waves. So based on the arrival time of different kinds of waves, we are able to detect the primary wave, we are able to detect secondary wave, and also, we know what is the wave propagation velocity in those medium. Using this two information, we will be able to locate a particular earthquake's epicenter. So based on the arrival time of primary waves, secondary waves, we will try to find out the distance between recording station and your epicenter, that is, epicenter distance now for the recording station, and that can be used from a particular seismograph. As I mentioned, seismograph is the instrument, and seismogram is this particular record. So whenever 'gram' comes in the end, this we are referring to record; seismograph is the instrument. So, from the instrument, we are taking the ground motion signature, identifying P wave and S wave arrival time, and trying to find out the distance. How will we do that? So, as we mentioned, we have primary wave, we have secondary wave, we have Love wave, and Rayleigh wave. This is the order in which different waves will reach a recording station.

- **S-P formulae**

$$\textbf{Time} = \frac{\textbf{Distance(D)}}{\textbf{Velocity}}$$

Now, we see over here time for time for arrival of shear wave; from the recording station, we can find out what is the time in which the shear wave is coming. We are interested in finding out the distance. We do not know where the earthquake has actually happened, but we have some location of your recording station. We also know what is the wave propagation velocity for shear waves. We know the arrival time of the shear wave based on the record if we are able to distinguish between primary and secondary waves. Remember this, for at this particular level, we will only be able to apply this particular record if in a ground motion record, we are able to distinguish between which is the point, which is the moment at which the primary wave has come, which is the moment at which the second wave has come. Identifying the arrival time of primary and secondary waves, in general, is a complex task which requires much more understanding about how the processing of ground motion can be done, how these can be corrected, and can be treated. So, processing of ground motion record, once it is done, you will be able to distinguish between the arrival of the primary wave and secondary wave. At this stage, those have not been separated as far as we complete this particular derivation.

Time for Shear Wave or S-wave (V_s) Recorded (T_s)

$$T_s = \frac{D}{V_s}$$

So, arrival time of shear wave, we can find out from here. T suffix s is time of arrival of shear wave from an earthquake which is located at d epicentral distance, and the wave is propagating through your propagation medium with the propagation velocity of V suffix s.

Time for Primary Wave or P-wave (V_p) Recorded (T_p)

$$T_p = \frac{D}{V_p}$$

Same way, we can also find out the time of arrival of the primary wave, though we know the primary wave will reach first. So, T suffix p is the time of arrival of the primary wave at a recording station. D again is the epicentral distance with respect to your recording station. V suffix p is the primary wave velocity for a particular medium.

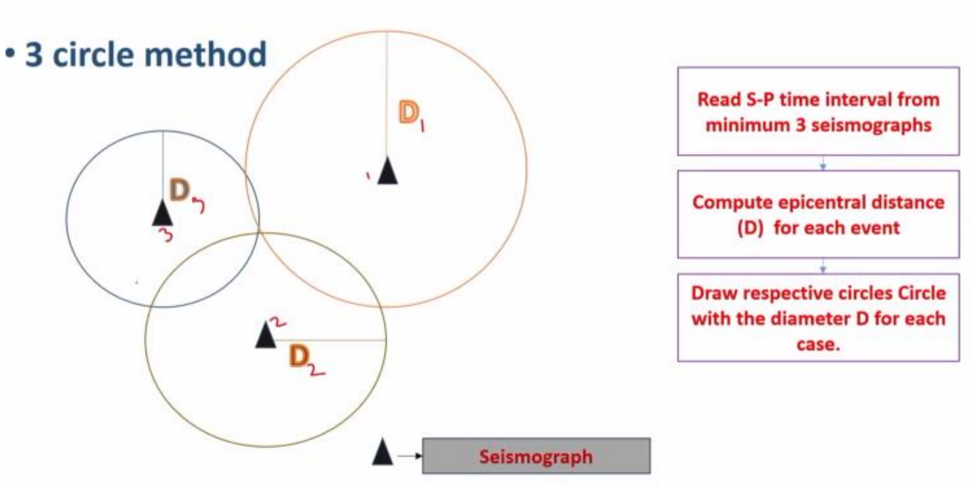
- **Subtracting equation 2 from equation 1**

$$T_s - T_p = D \times \frac{(V_p - V_s)}{(V_p \times V_s)}$$

Now, if we take the difference between the two, that means T_s will be more because the secondary wave is coming late. So, if we start from zero, the secondary wave arrival time will be more. If you take that particular difference between the time of arrival of the shear wave and the primary wave, that's how we can calibrate using the equation which was there in equation one and two.

$$D = \frac{(V_p \times V_s)}{(V_p - V_s)} \times (T_s - T_p)$$

That's how, from this particular equation three, we can determine T, which is the epicentral distance, which is the objective to find out over here. We can determine the value of, I mean, for known value of V_p and V_s, we will be able to determine the value of how much should be the primary velocity, the distance between your recording station and your epicenter. So, we need not have the actual arrival time of the primary wave and secondary wave; rather, the difference in the time of arrival of the primary and secondary wave, if it is there, then we will be able to use it over here because this is simply going to give me the distance between t and s wave. So, you need not worry about absolute time; even when the record is there, looking at the record, if we are able to find out the difference in the time between primary and secondary wave with respect to the record itself, that will help us in finding out T_s minus T_p or the difference in the time between primary and secondary wave arrival. Using this particular equation, that is equation number four, so we have the value of T_s minus T_p, we have the value of V_p, we have the value of V_s, that means material characterization for a particular medium, if it is available. Usually, whenever we are installing a recording station, we'll also try to find out for recording station what is the subsurface profiling so that can also be used in crystal medium, and mantal properties, more or less, one can refer to existing literature to find out this. Okay, so using this, we will be able to determine the value of D. Now, this D is with respect to the epicenter; the earthquake can be any distance located within a radius of capital D all around your recording station because this is going to only give the epicentral distance. It's not going to tell whether it is, you have to move north, you have to move east, west, or south; it's only going to give you a radial distance range within which an earthquake can be located.



So, to do that, what we will do, we will discuss about first method, three circle method. What we will do, depending upon the coordinates of your recording station, we will locate three points. So, these three points are located based on the latitude and longitude of your recording stations or coordinates of your recording station, referring to those coordinates and determining the value. We have taken first recording station; we have determined the value of capital D1, that with respect to recording station one, what is the epicentral distance one, or what is the radial distance from recording station one, which can be referred to in order to develop the radial distance or the circle. Similarly, with respect to recording station two and recording station three also has to be continued. Remember, these are the seismograph or recording stations which I am mentioning over here. So, D for all the three recording stations, you can call it as D1, D2, and D3. So all three recording stations are there; depending upon the formula which was there in equation number four, D1, you have the value of T_s T_p, determine the value of D1, or the radial distance from recording station one, referring to which you can find out the epicentral of the earthquake; same way with respect to D2, which is another recording station, so you will have another value of T_s minus T_p for D3, again there will be another value of T_s minus T_p as a result D1, D2, D3, all three will have different values of epicentral distance. Take those epicentral distances, and keeping the coordinate or the center of your recording station as the center of the circle, draw a circle of radius D1 from point one, so this is point one, this is point two, this is point three, which are basically indications of the coordinate of your recording station. So, take one, mark a circle of radius D1; take two as center, mark a circle of radius D2; three as center, mark a circle of radius D3; draw those circles, and then we will see for this particular circle, this was the radius or range of epicentral distance; for D2, this was the radius; and D3, this was the range of location in the epicentral can be there. Since all these circles are generated corresponding to the same earthquake, the common area now you see over here, this particular point is the common area which I have just drawn. This particular point is basically an indication of a region which is a common location of the epicenter as suggested by the record from station one, suggested by the record from station two, suggested by the record from station three. So, all three records are going to suggest what is the common area from all the three circles which are generated using the record from the same earthquake at three different recording stations. This is called the three-circle method. So more than three also are there, then you will be able to more accurately locate the efficient of the earthquake. So minimum three stations are there; many a time, it may happen like here it is converging to a similar small area; many a time, it may happen that when we draw three circles, rather than a small area, you will end up in getting a larger area. So that means in that particular larger area, the epicenter of the earthquake can be located anywhere. In order to further narrow down to a shorter area, smaller area, we can have maybe a fourth circle, fifth circle, such that it will, every time you draw another circle, it actually reduces the common area to a lesser area. So that's how you can more accurately locate potential locations which are the epicenter of the targeting earthquake. If you do not have any earthquake record, more than three circles, if you are not able to locate, then the common area from all the three circles, you can say, is the potential region where the efficient of the earthquake can be located.

So, with this background, I'll stop here, and in the next class, we will solve one numerical related to this, and we will also discuss about one more. So next class, we'll continue this particular topic, we'll solve one more numerical and see how, based on one particular earthquake record, we will be able to locate the efficient of the earthquake, and we will also discuss further about magnitude and intensity values, and how one can quantify the magnitude of a particular earthquake. So, thank you, and we will continue the numerical related to this topic in lecture number 8. Thank you, everyone.