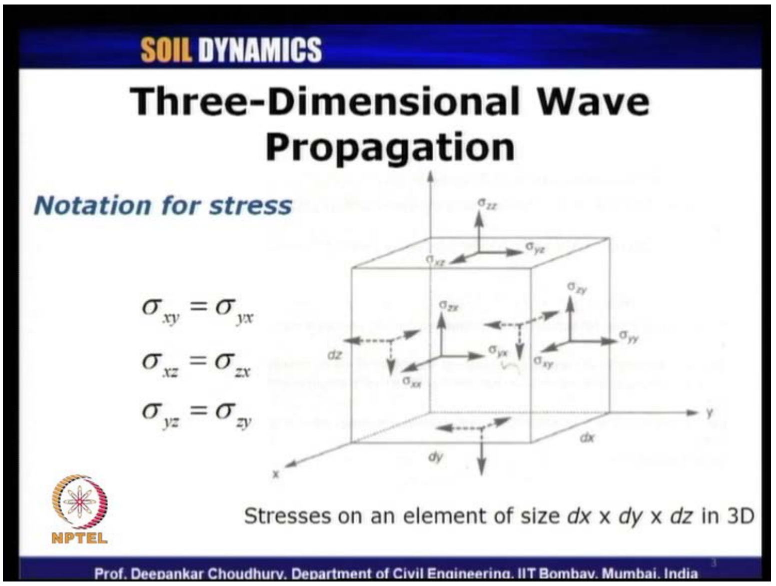
Soil Dynamics
Prof. Deepankar Choudhury
Department of Civil Engineering
Indian Institute of Technology, Bombay

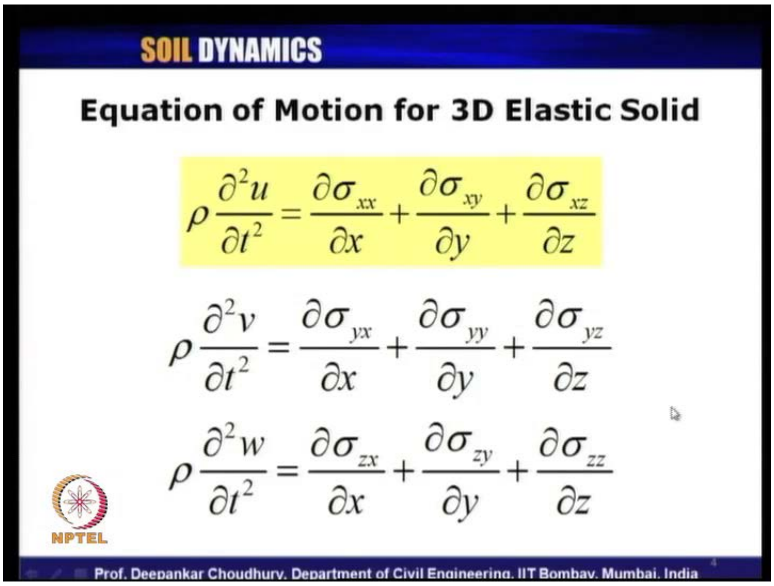
Module - 3
Wave Propagation
Lecture - 16
Love Wave, Waves in layered medium, 3D Case-lnclined wave, Earthquake Waves

(Refer Slide Time: 00:37)



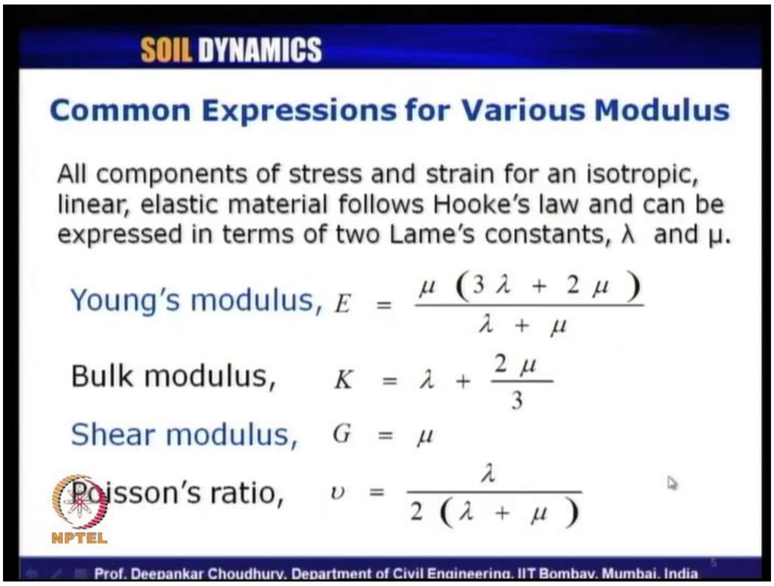
Let us start today's lecture of our soil dynamics course. We are continuing with our module three, that is on wave propagation. So, a quick recap what we have studied in the previous lecture. We have seen how to formulate the equation of motion for three-dimensional wave propagation.

(Refer Slide Time: 00:47)



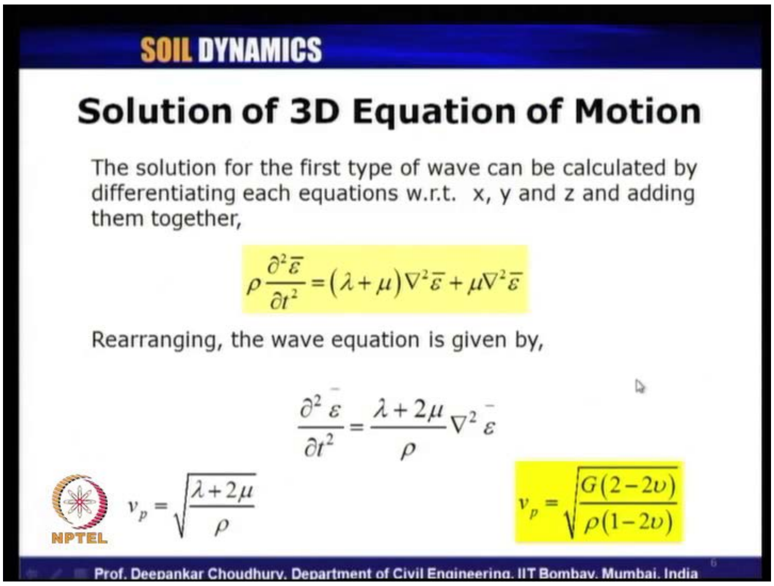
And these are the basic three-dimensional equation of motion for a 3D elastic solid in x direction, y direction, and z direction.

(Refer Slide Time: 00:58)



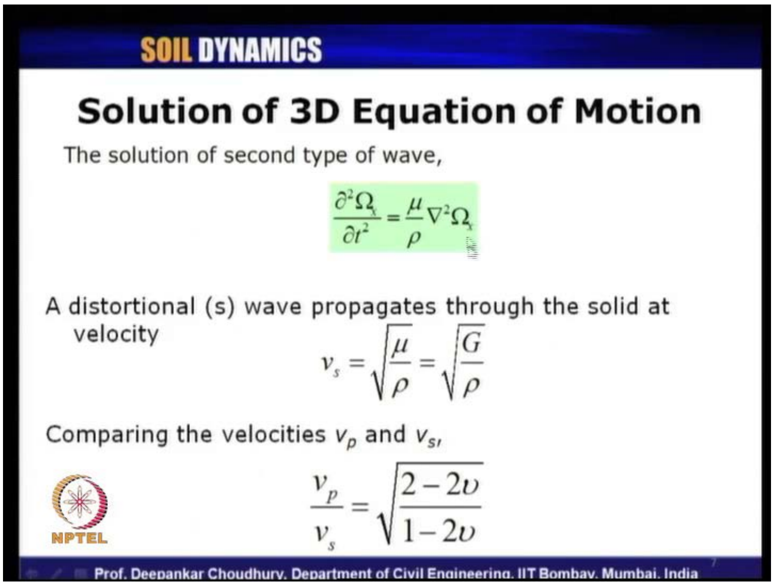
Then, we have just brush up our memories on common expressions for various modulus in terms of two Lame's constant that is, lambda and mu. So, how young's modulus, bulk modulus, shear modulus and Poisson's ratio, these are expressed in terms of these two Lame's constant, we have seen that.

(Refer Slide Time: 01:19)



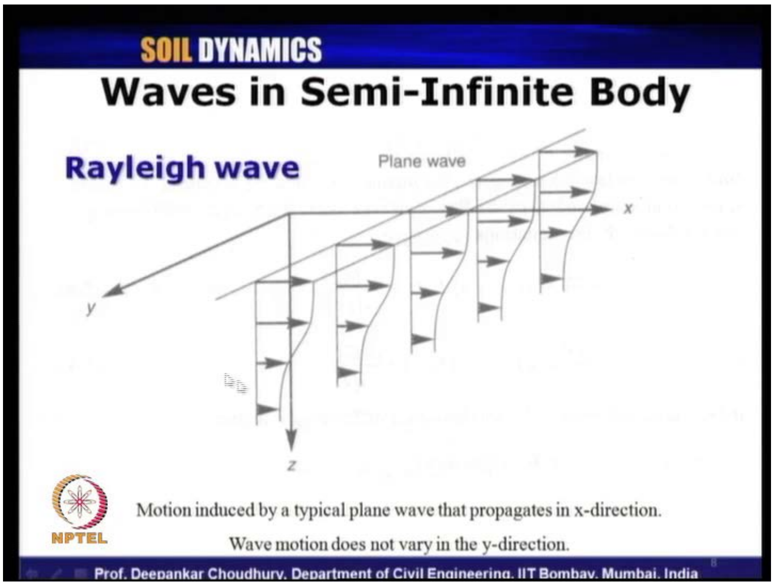
Then to obtain the solution for the 3D equation of motion, what we had obtained in the first slide today I have shown. So, the same thing for the first type of wave we have obtained, what is the wave equation and in that, we have expressed the primary wave velocity v p in terms of two Lame's constant and density of the media like this, and in terms of shear modulus and Poisson's ratio and density of the material, the v p is expressed by this expression.

(Refer Slide Time: 01:56)



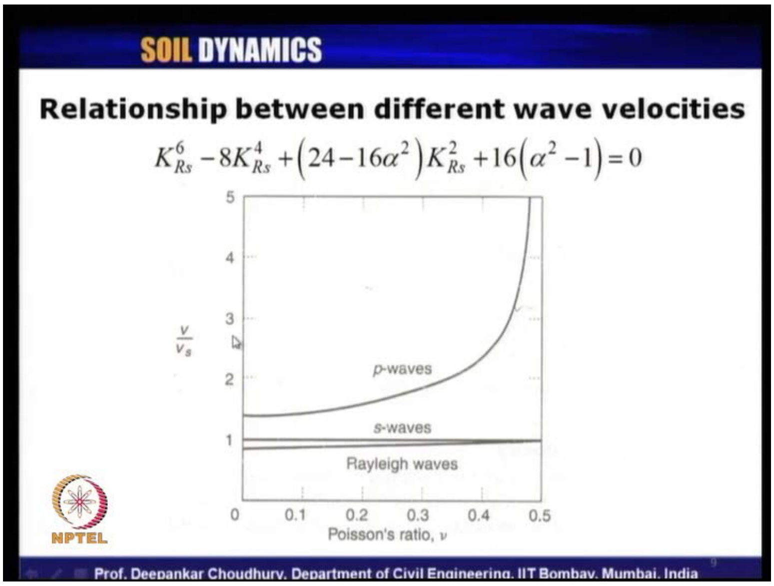
Then, for the second type of wave equation, we have seen this is the form of the equation, and the secondary wave or s wave is expressed in terms of Lame's constant like this which if we expressed in terms of shear modulus, it comes out to be root over G by rho. And comparing the expression for velocities of primary and secondary wave, we obtain the ratio of primary velocity to secondary wave velocity is just a function of Poisson's ratio of the material and expressed by this expression.

(Refer Slide Time: 02:29)



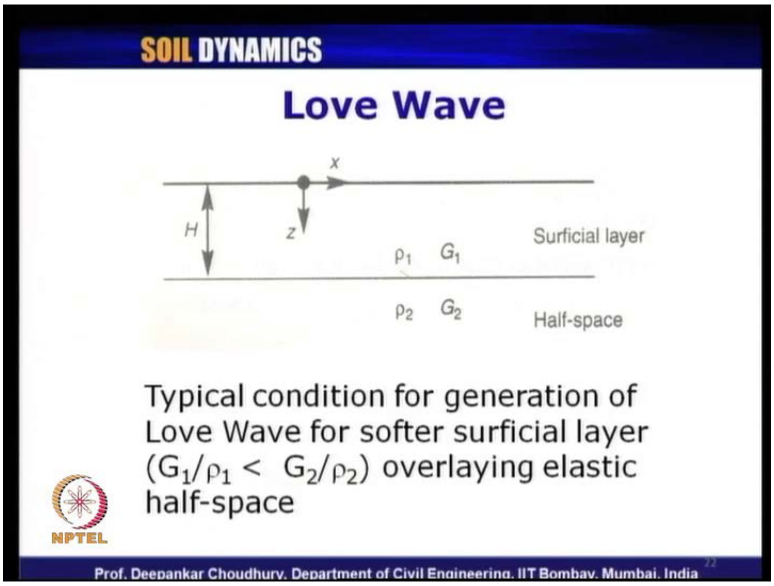
Then we have seen waves in semi-infinite body that is very close to the ground surface and with depth, it is decreasing drastically, we call that as Rayleigh wave. It moves in x direction and with increase in depth z, it decreases drastically as I said, but there is no variation in the other direction of y.

(Refer Slide Time: 02:52)



And the relationship of that Rayleigh wave, how to compute the Rayleigh wave with respect to the shear wave we have seen, this is the equation, we have to solve. And the relationship between the p wave, s wave and Rayleigh wave, with respect to s wave for different values of Poisson's ratio, how it varies, I was shown.

(Refer Slide Time: 03:14)

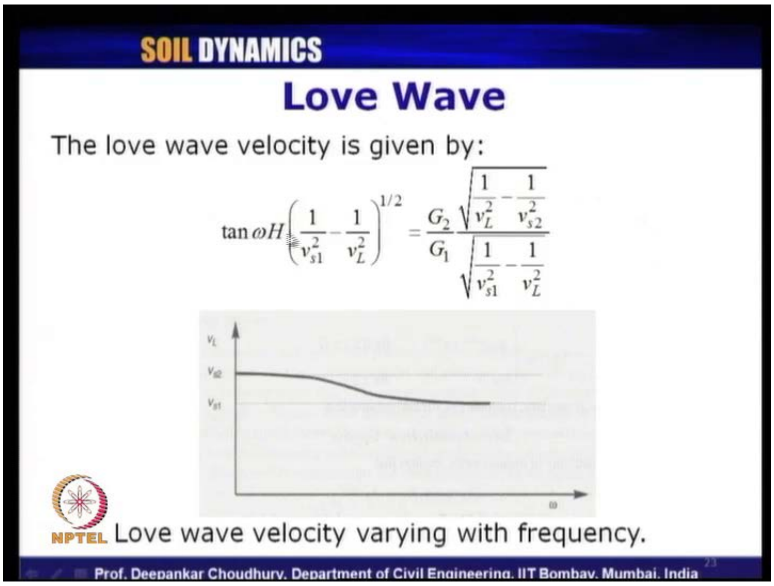


Now, coming to the, another category of wave which is called love wave. When this kind of wave is getting generated, what is the condition for that wave to get generated?

Typical condition for generation of love wave is that for softer surficial layer overlying elastic half space. So, if there is an elastic half space with property rho 2 and G 2, that is density and shear modulus, on top of which if we have a very soft surface layer, a very thin surface layer which is soft in nature, soft means in terms of strain, that is G 1 will be very much lower than G 2, or in other words, it is defined like ratio of G 1 by rho 1 should be very much less than G 2 by rho 2. What we can say in other terms of shear wave velocity? That is the shear wave velocity of this surficial layer will be much lower than the shear wave velocity of this elastic half space.

So, the common examples of this kind of practical cases are like if we have some loose field material and below which we have a very stiff old geological material, say very dense, and or very stiff clay, or even sometimes bedrock. In that case, the love wave can get generated. So, if their difference is, if they if their values are pretty different in the two layers, then it is a good form to get generated love waves in the surface layer, in the surficial layer.

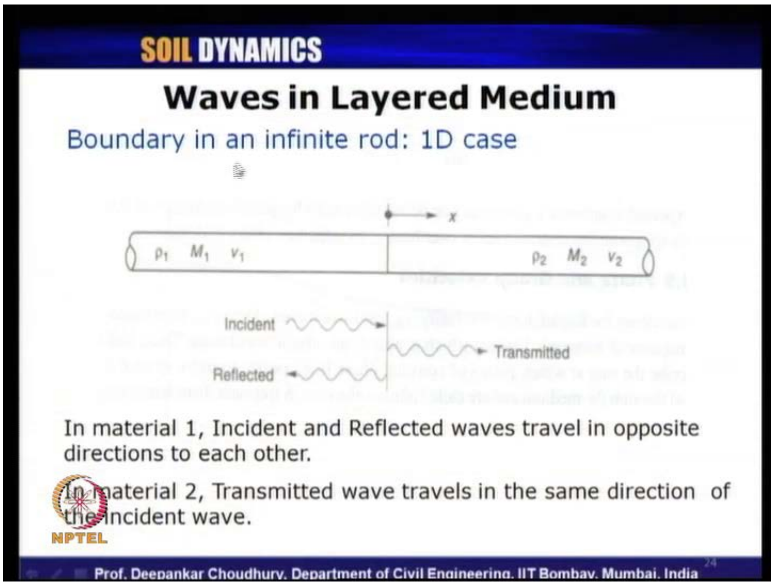
(Refer Slide Time: 05:09)



And how this is related? Love wave velocity varying with respect to frequency, the (( )) is shown, frequency and this is the love wave velocity in the two media, v s 1 and v s 2, these are shear wave. How they are changing with respect to frequency, in terms of love wave and how we can compute the value of love wave v l. v l is the value of love wave, and v s one and v s 2 at the shear wave velocity in that media one and media two, what I have shown. h is the thickness of the media, if h is pretty small enough then we will get a reasonable value of love wave velocity, and omega is the frequency of excitation travelling through the media, and G 2 and G 1 are the corresponding shear modulus in the two layers 1 and 2. So, layer two means the elastic half space or the stiff or rigid or old geological material and one indicates the very soft surficial layer. So, using this expression, anyone can easily compute the love wave velocity in terms of shear wave velocity.

So again we have seen for this fourth type of wave also, what is the main wave velocity? The main wave velocity from which we can compute the love wave velocity is again the shear wave velocity. So, if we can determine the shear wave velocity in laboratorial field very accurately, then using all the three expressions we can get all the other three wave velocities, that is primary wave velocity, Rayleigh wave velocity and love wave velocity, by knowing the other parameters of the soil like Poisson's ratio of the soil and the shear modulus of the soil.

(Refer Slide Time: 07:07)

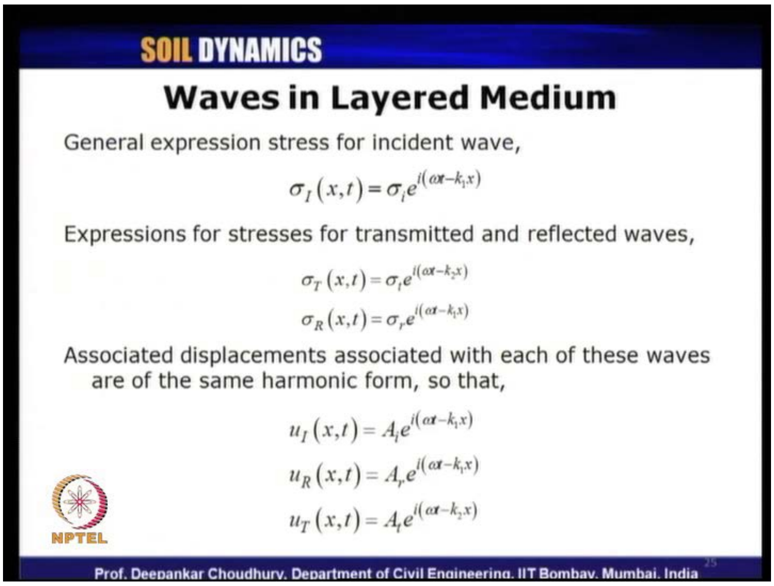


Now, let us come to waves travelling in layered medium. Till now, we have talked about waves travelling in a single media; now, we are using waves when it is travelling in two different media. So suppose, first let us take one dimensional case. The simplified case, there is an boundary in this infinitely long rod, again we are considering infinitely long rod with material properties like rho 1 m 1 v 2, or rather I should say this is nu 1 actually, this is rho 2 m 2 nu 2; rho 1 is the density of this material; m 1 is the constraint modulus of this material; and nu 1 is the Poisson's ratio of the material. We have another different material here with density rho 2, constraint modulus m 2 and Poisson's ratio nu 2. So, the boundary between the two different material or two different medium is this one. From where we are measuring the distance x like this. So, this point, we are defining as our origin point with x equals to 0; this side, x we are considering negative, this side we are considering x as positive.

Now, when a wave is travelling through this infinitely long rod from this medium 1 and then it is striking at this boundary of the two media, what happens? The incident wave initially travels in this direction, it faces this boundary, it faces this boundary, incident waves travels in this direction, it heats at this boundary between the two materials, what happens? A portion of heat will get transmitted in the second media, which is called transmitted wave. So, this is incident wave, this is transmitted wave, and some of the component of the incident wave will get reflected back at this boundary between the two materials, that is called reflected wave. So, any wave travelling in a particular media if it heat surfaces, a boundary of another material, it will produce two different types of waves. One is transmitted wave and other one is reflected wave.

So, what it is written? In material one, incident and reflected waves travel in opposite directions to each other, you can easily see, it is quite obvious from the point of physics or what we have considered just now. Incident wave travels here, strikes here some portion get transmitted in second media and some got reflected back to the first media. So, that is why their traveling directions are opposite to each other in material one; whereas, in material two, we have transmitted wave which is traveling in the same direction of the incident wave.

(Refer Slide Time: 10:24)

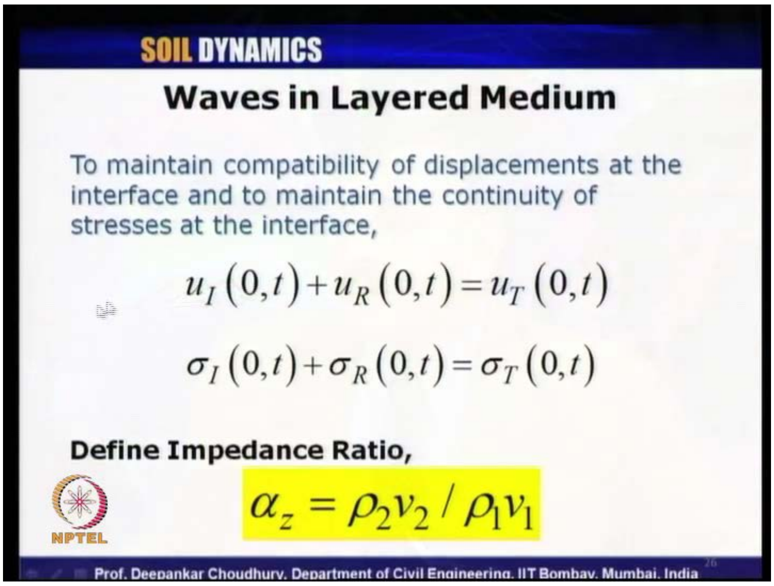


Now, if we considered the general expression for the stress, for the incident wave, we can write the stress expression for incident wave. So, sigma i, i indicates the incident wave, as the function of x of t, x and t which we can write in this form, or let us assume the stress function for incident wave, we are writing in this form, that is sigma i is the amplitude, sigma i is the amplitude of the incident wave, that is stress amplitude of the incident wave. e to the power i times omega t minus k 1 x. What is k 1? k 1 is the wave number in material one, x is the distance traveling, it is minus sign because the media one, when it is traveling as per our chosen access system, it is in the other direction. Our in other sense, I should say this is the more generalized equation what we have considered earlier for the stress, the form of the stress expression.

Now, expressions for stress for transmitted and reflected wave can be written like this, sigma t, t denotes the transmitted wave as a function of x of t can be given as sigma t, this is the stress amplitude of the transmitted waves times this e to the power i times omega t minus k 2 x, where k 2 is the wave number in material two and sigma r, that is the reflected wave stress function is given as the function of x or t as equals to sigma r which sigma r is nothing but amplitude of stress of reflected wave times e to the power i times omega t minus k 1 x, it is again in material one, so k 1. And the corresponding displacements to these incident transmitted and reflected waves, let us say, they are also expressed in terms of harmonic form and given by this. So, u i is nothing but the displacement function of the incident wave which is expressed in harmonic form with amplitude of incident wave as a i. So, these are the just form of the solutions, what earlier we have considered for a single layered media, single media.

Now, for layered media, we have considering u r, that is the reflected wave displacement amplitude, what we are considering? This is equals to the amplitude of the reflected wave a r times e to the power i omega t minus k 1 x and the transmitted wave displacement function u t x of t is given as a t, a t is nothing but amplitude of the displacement function of the transmitted wave times e to the power i omega t minus k 2 x. Now, these are our assumed form of equations in terms of harmonic form of equation for stresses and then the solutions are corresponding displacement. So, stress and displacement. Now, what is the condition, we should maintain at the interface? At the interface, we have to maintain the stress compatibility, so stress compatibility at the interface between material one and material two has to be maintained and the displacement function also, it should maintain continuity.

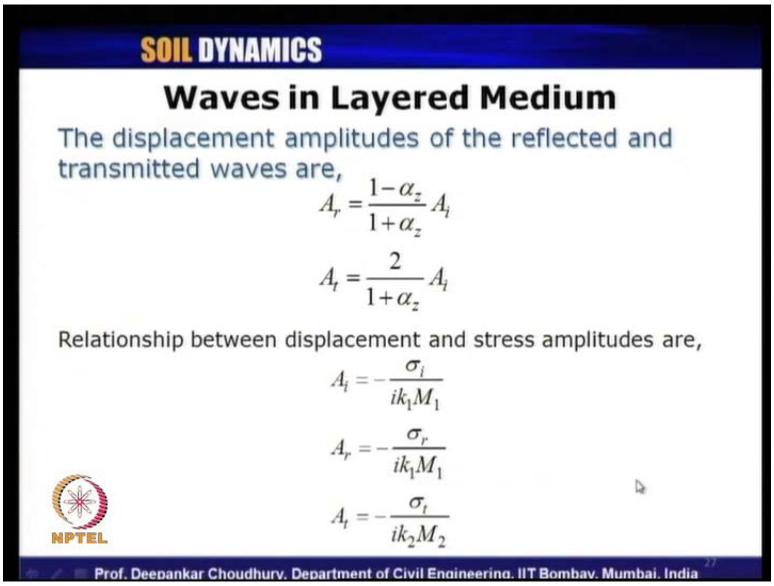
(Refer Slide Time: 14:28)



So, what we can write to maintain the compatibility of displacement at the interface and to maintain the continuity of stresses at the interface, what we can write at interface as per our chosen access system x is 0, am I right? So, what we can say, the displacement function for incident wave that is u i 0 t plus the displacement function of reflected wave u r 0 t should be equals to the displacement function of transmitted wave u t of 0 t, then the displacement compatibility will be maintained at the interface. Similarly, to maintain the continuity of stress, what we can write? The incident wave stress at interface that is sigma i at x equals to 0 t plus reflected wave stress, sigma r at 0 t should be equals to the transmitted wave stress, sigma t at x equals to 0 t, then this compatibility and continuity will be maintained.

Now, let us define one new parameter, which is known as impedance ratio. What is impedance ratio? Impedance ratio is nothing but the ratio of the product of the density and the velocity of the wave in one material to the other material; and how this impedance ratio is expressed? One material to other material means always the incident wave is in which media should be in denominator, say in when we express the impedance ratio of any media, it is showing a kind of relative velocity and density relation between the two materials, where this numerator should be for the material in which the wave gets transmitted and the denominator should be for the material in which the incident wave travels. So, that defines our impedance ratio.

(Refer Slide Time: 17:03)

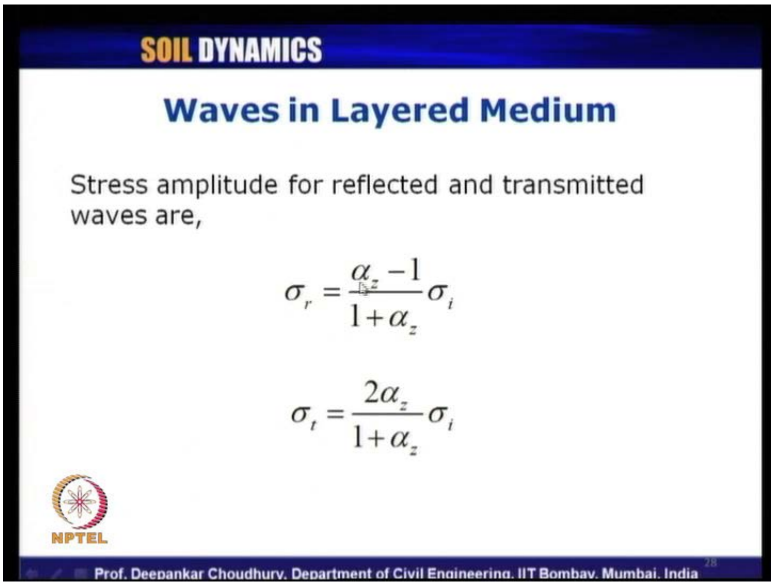


Now, why this impedance ratio is useful? Let us see, how we can express. Without going into all mathematical details, what I can give here for this course on soil dynamics that what are the amplitude of various displacement and stresses in reflected transmitted and incident wave, reflected and transmitted waves in terms of incident wave; because truly speaking, this details of the wave propagation again comes in another course of geotechnical earthquake engineering. So, just to touch the main aspects of the wave propagation in single and layered media for use of this course of soil dynamics, I am giving this final expressions which are useful for our geotechnical practices in this soil dynamics design. So, the displacement amplitude of the reflected wave A r can be computed as 1 minus alpha z by 1 plus alpha z times A i, where A i is the displacement amplitude of incident wave; and the displacement amplitude of transmitted wave A t is computed using this expression 2 by 1 plus alpha z times A i, again A i is the displacement amplitude of incident wave.

So, if we know the material property of two media and if we know the amplitude of displacement of an incident wave, what we know? We can easily compute what are the amplitude of reflected and transmitted wave. So, as an engineer or as a geotechnical engineer, we are more concerned about this transmitted wave, because finally, when earthquake or any vibration at very underground strata, it occurs, the incident wave from a very deep strata will slowly travel, the wave will slowly travel and finally reach to our near ground surface. So, near ground surface, what are the displacement amplitude through this transmitted wave? We are interested in, also we are interested to know the stresses. So, let us see what are the relations? Relationship between the displacement and stress amplitude, they are express like this A i, that is incident wave displacement amplitude can be computed as minus, sigma i is the stress amplitude of incident wave by i is the complex number, k 1 is the wave number m one is the constraints modulus of material one.

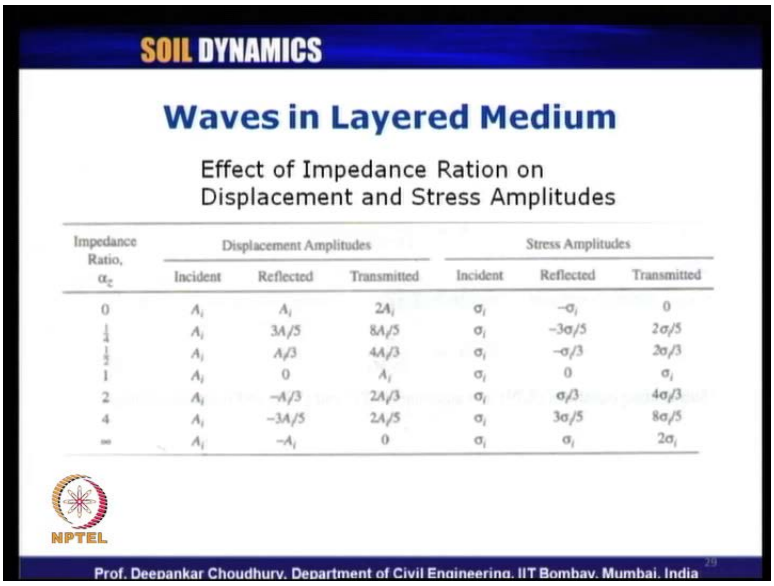
Similarly, a r is expressed as minus sigma r by i times k 1 m 1, and a t is computed as minus sigma t by i times k 2 m 2. So, when we are computing the values remember, this complex number does not come into picture, you have to just take the modulus of the values. So, these are the complete expressions coming from mathematical derivations. So, that is why I said, I am not going into the detail of this derivations, but to know the value of as a designer, once you are given, or you know, the displacement amplitude at a particular point at a very low strata, then from that incident wave displacement amplitude, you can compute stress amplitude or vice versa, if you can measure the stress, you can compute the displacement amplitude, and then corresponding reflect and transmitted wave displacement and stress amplitude, you can easily compute using the knowledge of the material property through this impedance ratio function.

(Refer Slide Time: 21:16)



So, the reflected and transmitted wave stress amplitudes can be expressed in terms of incident wave stress amplitude in terms of impedance ratio like this. So, whatever we have seen, let us see in a gist form, that is how for different values of impedance ratio, this displacement amplitude and stress amplitudes varies.

(Refer Slide Time: 21:45)



Impedance Ratio, α_z	Displacement Amplitudes			Stress Amplitudes		
	Incident	Reflected	Transmitted	Incident	Reflected	Transmitted
0	A_i	A_i	$2A_i$	σ_i	$-\sigma_i$	0
$\frac{1}{4}$	A_i	$3A_i/5$	$8A_i/5$	σ_i	$-3\sigma_i/5$	$2\sigma_i/5$
$\frac{1}{2}$	A_i	$A_i/3$	$4A_i/3$	σ_i	$-\sigma_i/3$	$2\sigma_i/3$
1	A_i	0	A_i	σ_i	0	σ_i
2	A_i	$-A_i/3$	$2A_i/3$	σ_i	$\sigma_i/3$	$4\sigma_i/3$
4	A_i	$-3A_i/5$	$2A_i/5$	σ_i	$3\sigma_i/5$	$8\sigma_i/5$
∞	A_i	$-A_i$	0	σ_i	σ_i	$2\sigma_i$

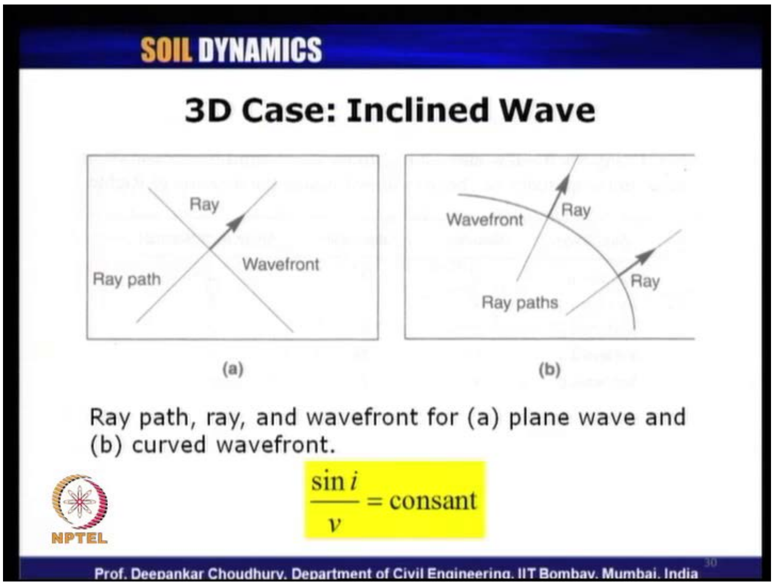
So, this table shows effect of impedance ratio on displacement and stress amplitudes for various impedance ratio. If it 0 means, what does 0 means? We do not have any different material, right? Also infinity means, what does infinity means? The material one has to be 0, and in case of impedance ratio 0 means, material two has to be 0. So, it is basically a single layer. So, whether it is a soft media or a very stiff media, that is why it is showing.

So, let us look at this value, 0 means, this can be 0 or this can be infinity, right? And infinity means this can be 0. So, material one, can it be 0? No, because material one is the material where incident wave is traveling. So, material one always exists. So, 0 and infinity value of impedance ratio is decided based on this rho 2 v 2 basically. So, if second material is not present, rho become 0 then we will get 0, and when we will get infinity? Because this cannot be 0. When this material is very small compare to this one, we will get very high value, is it not? So, in that case, this layer will be extremely soft material. Let us see some values in between, when impedance ratio one, one means basically same material, impedance ratio one means basically same media means, if incident wave is there everything gets transmitted, there is no question of reflected. There assume boundary is null in this case.

Similarly, the stress incident stress is nothing but entirely gets transmitted, but if you see the other values of impedance ratio, that is if we take rho 1 v 1 for a practical situation in most of the cases, what will happen? This value through which incident wave is traveling will be higher than this value, because as we go up and close to the ground surface, this value of v 2 will decrease, right? Material will be softer and softer, I am just telling you the generalized case, it can be other ways also, we can have in between a soft layer and then again a stiff layer, those are possible. So, in that way, we have to do the computation, but generally what I am telling, these value will be higher than this value. So, impedance ratio less than one is most of the common cases, right?

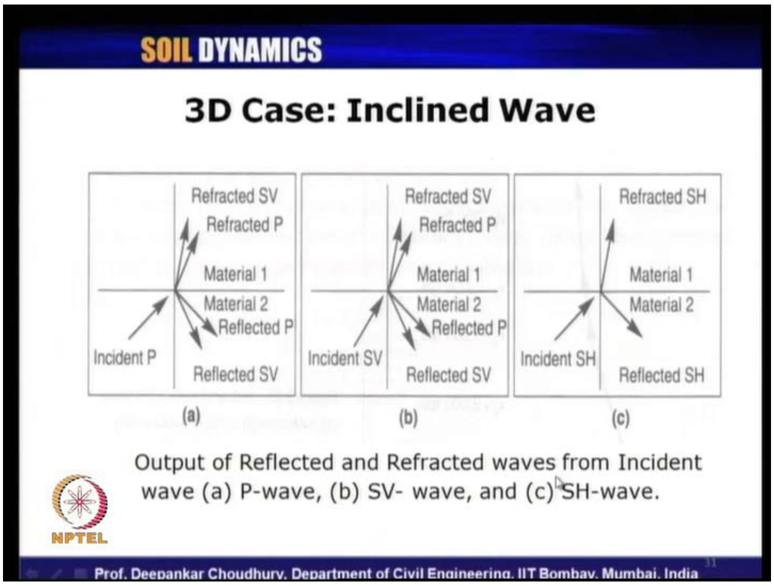
So, if it is most of the common cases less than one, say half, what happens, if the impedance ratio is 0.5? The displacement amplitude A i that is in your material 1, that is lower strata of the soil, when it gets transmitted to the higher strata of the soil are in material 2, how much is the amplitude of the displacement transmitted? That is four by three times A i; what does it mean? The displacement amplitude has been magnified, has been increased. So, what we can expect, when a wave is traveling through the media from a stiffer to a softer layer then the chances of increasing in the amplitude of stress and displacement will increase. So, that is the final conclusion or the main thing as a designer or as an engineer, we should looked into, that is how much increase it has occurred because of the travel of the wave from a stiffer to a softer layer. In the other way, if we have a in between soft layer and then above that, if we have a stiff layer, suppose impedance ratio value is greater than one, say two, what happens? Incident wave stress, displacement amplitude is A i, the transmitted wave's displacement amplitude is two third of A i. So, it decreases. So, which is good for us as a designer, fine.

(Refer Slide Time: 27:18)



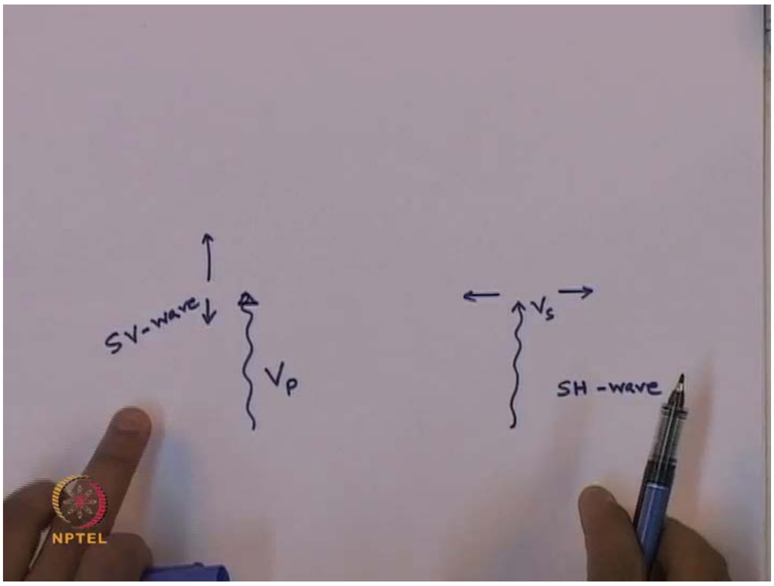
Now, let us see the three-dimensional case. Till now, we had talked about as one-dimensional case only, if three-dimensional case we consider, and there can be inclined wave. So, this is the ray path and wave front. Ray path, ray and wave front for a plane wave and on curved, wave front has been shown. How the wave follows the equation with respect to the incidence angle that is the angle which respect to the normal to the surface on which it is striking is called an incidence angle, right? In our high school physics also, we have studied in optics and in other physics course that they follow the conventional snell's law. So, here also, this waves follows snell's law, when it transfers to one layer to other layer; that is why this equation is valid here, that is the sin of i, i is the angle which respect to the vertical normal taken on the surface to the actual direction of the wave by v is the velocity of the corresponding wave, remains constant in different media.

(Refer Slide Time: 28:43)



And what are the different outputs it can generate, if there is an interface of two materials, say material one and material two, like this, if incident wave is P wave which is traveling in an inclined fashion like this, and if it is strikes the boundary of the two material, what it will generate? It will generate transmitted wave and reflected wave, this refracted wave is nothing but the transmitted wave, what we have studied just now. So, the P wave, inclined P wave will result in transmitted P wave, reflected P wave, and also they will result refracted SV wave, that is transmitted SV, what is SV? Shear wave propagating in the vertical direction, that is the notation for SV wave and reflected SV wave also will get created. What does it mean? Let me show here.

(Refer Slide Time: 30:00)

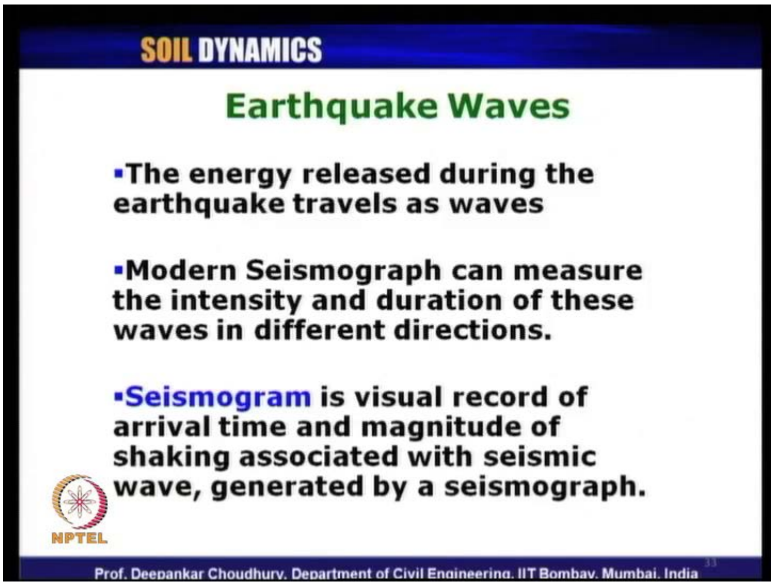


So, when P wave travels, if this is a direction of say V p. So, particle also moves along this direction; whereas, when S wave travels, V s, the particle movement will be in this direction; that is for what kind of S wave? S that is called, S H wave, that is shear wave in horizontal direction and V s means most of the time major component we talk about S H wave, but there can be, as these are not perpendicular, we are considering the inclined waves, there can be some component in the other direction also which exciting the particles in this vertical direction also; that kind of shear wave which is making the particle to excite in the vertical direction is called SV wave.

So, shear wave basically have two types, one is called S H wave and another is called S V wave. S V wave creates or makes the particle to vibrate in the vertical direction, or in other words in the direction of the propagation of the wave; whereas, S H wave is that type of shear wave which makes particle to vibrate in the orthogonal direction to its direction of propagation, and as I said once again, the major component of S wave is considered as S H wave not SV wave, but there will be definitely some component of SV wave also. So, that is how you can see here, this P wave finally, when it strikes between two material. So, suppose when P wave travels, generated due to some dynamic event say for example, earthquake it travels to different layers, it will finally result as in this upper layer some P wave and some SV wave.

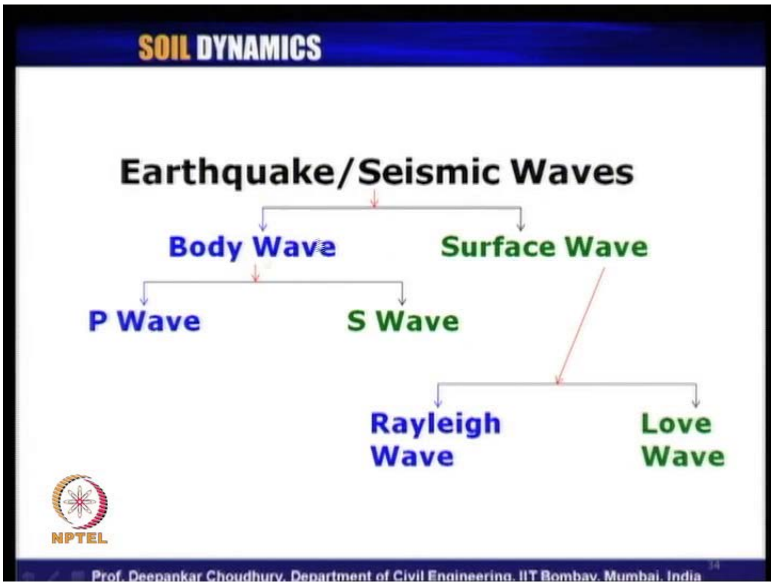
Now, let us look at the second figure. When an incident SV wave strikes this material boundary, what happens? Some of them got transmitted in the other material as SV wave, and some got transmitted as P wave. So, P and SV waves are interchangeable, why? Because of their nature of the direction of propagation as well as the direction of the particle movements, and in second material some will get reflected as a p wave and some will get reflected as a SV wave; whereas, if we consider the incident wave as a S H wave, if it strikes the two boundary what it will result finally, some transmitted wave S H and some reflected wave S H in these two media like this; here, no question arises of generation of p or SV, why? Because their characteristics of S H wave as I have explained is completely different, they excite the particles to the perpendicular direction to their direction of wave propagation. So, these are the different waves which we will come across.

(Refer Slide Time: 34:00)



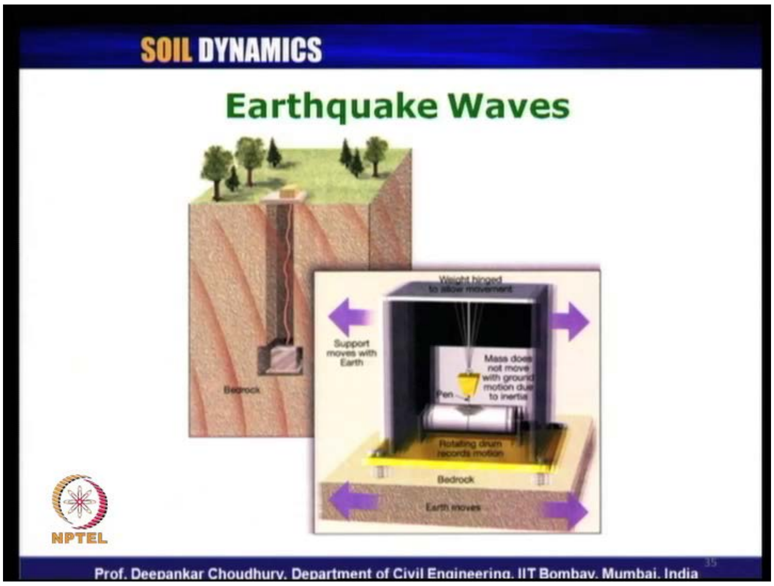
Now, let us comes to the specific wave getting generated because of the dynamic event or earthquake event, that is seismic waves, how they are getting generated and what are their characteristics, let us look into those aspects now. So, earthquake waves, the energy released during the earthquake travels as waves. That we know; that is during an earthquake, it is nothing but an event of release of lots of energy, huge energy stored in the earth crust or in very deep layer of earth. So, that gets released and because of that waves get generated and it travels. So, when it travels the modern seismograph which measures the velocity of this various waves can measure the intensity and duration of these waves in different directions, and seismogram is the visual record of the arrival time and magnitude of shaking associated with seismic wave generated by a seismograph. So, seismograph is the equipment which records this and seismogram is the data sheet on which we got this record, that is arrival time of this wave, magnitude of the wave, etcetera.

(Refer Slide Time: 35:43)



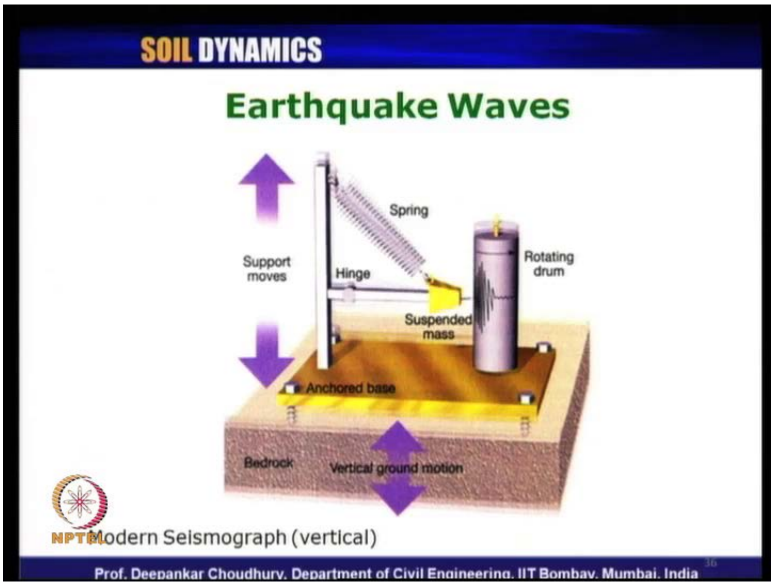
So, if we see the broad classification of earthquake or seismic waves, what are the basic classification? Let us look at here. It can be classified into two major classes, one is called body wave and another is called surface wave. As the name suggest, the body wave travels within the body or within the layer or within the earth body or different layers of earth, and surface waves, as the name suggest there are very close to the ground surface. So, it is valid for that semi-infinite media, what we have studied just few minutes back. Now again some sub classification, the body wave can be sub classified into two categories, one is called P wave, or primary wave, or longitudinal wave, or compressional wave. So, these are the names we have learned; the another type of body wave is S wave, or secondary wave, or tortional wave or distortional wave. So, these are the names we have learned. The surface wave, it can also be classified into two sub categories, one is called Rayleigh wave, and another one is called love wave.

(Refer Slide Time: 36:53)



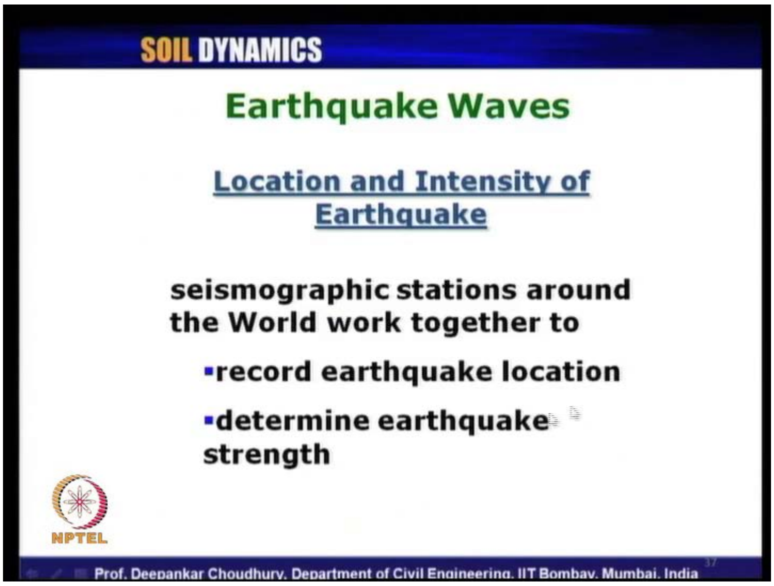
So, this is just pictorial representation, when in a bed rock, the excitation occurs, how it gets notified on a ground surface through use of these seismograph.

(Refer Slide Time: 37:11)



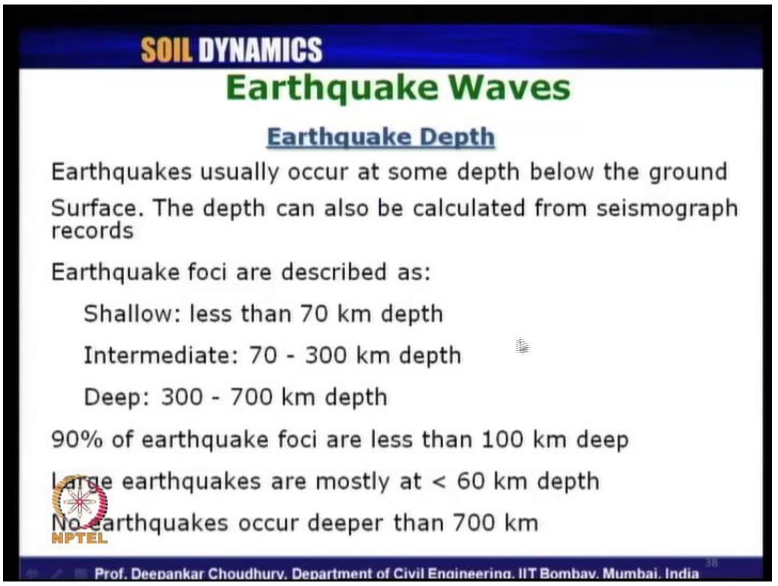
And another modern seismograph, it records the vertical ground motion. So, that is why you can see, here there is an needle spring connection, here is the hinge connection, this is suspended mass ,what will happen if the it shakes in the vertical direction? The drum is rotating in this direction with a paper on it and this pencil will keep on vibrating on this. So, it is recording the vertical vibration, like this; whereas, the previous one what I have shown here, it records the horizontal direction, whatever acceleration occurs. So, here through this support, this mass is hanging and in the front of this mass, there is pen or pencil, this is the rotating dram on surface of which the graph sheets or papers are attached, then it records in this direction. So, automatically it records the vibration in the horizontal direction. So, this way, the seismograph works which will finally give us this graph sheet as seismogram.

(Refer Slide Time: 38:21)



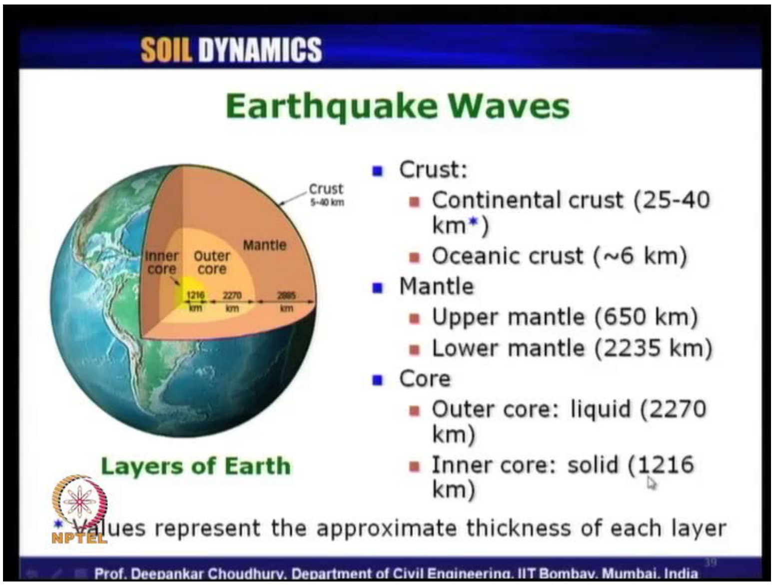
How it means about location or intensity of earthquake? The seismographic stations around the world, they work together to record the earthquake location and to determine the earthquake strength. How they work together? That is suppose if an earthquake occurs at any part of the world, say in Chile, some earthquake occurs; that earthquake if a get recorded in several parts of the world in US, in Japan in India, in Chile also if the equipment is not completely damaged, and like that the whole world records, this seismographic station can record, because of the travel of the waves. Then to find out the actual epicenter of the earthquake and things like that, the strength of the earthquake, we will see how it can be done.

(Refer Slide Time: 39:23)



So, some other basic information like earthquake depth; earthquakes usually occur; usually, note this term, usually occur at some depth below the ground surface and the depths can also be calculated from the seismograph records, and it occurs usually as I said in shallow depth, what do we mean by shallow earthquake? When the depth of the earthquake is within 70 kilo-meter below the ground surface, that is referred as shallow depth earthquake; whereas, the intermediate depth earthquake is known as 70 to 300 kilo-meter depth, if the earthquake gets generated, it is called intermediate earthquake; and deep earthquake is called, when it is between 300 to 700 kilo-meter depth. And as I have just now mentioned, 90 percent of earthquake foci, that is whatever earlier historical data, we have they occurred within 100 kilo meter-depth. So, that is why most of our major earthquakes are shallow depth in nature, and large earthquake, they occur even less than that depth, even less than 60 kilo meter of depth. And no earthquake occurs deeper than this 700 kilo-meter of depth, because then the crustal change of earth properties will come into picture. So, I will show that soon.

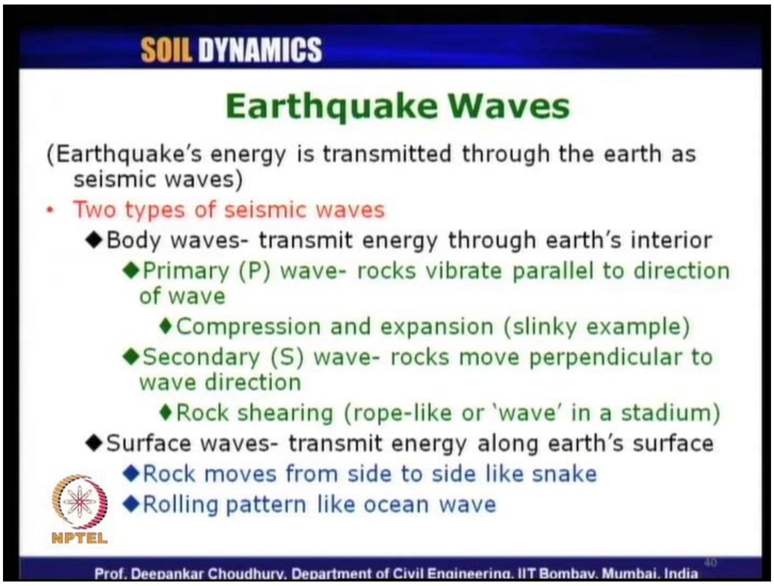
(Refer Slide Time: 41:01)



Look at here. So, these slide shows us different layers of earth, if we cut the earth section like this, and look at the inside, all of us must have studied this in our standard geologic course. So, once again to reiterate it, earth is basically composed of three units, what are those? One is crust, another mantle and another one is core of the earth, in terms of geologic. So crust, there can be two sub division, one is called continental crust and another one is oceanic crust. Continental crust are generally depth about 25 to 40 kilo-mater below the ground surface; whereas, oceanic crust about 6 kilo-meter of depth below the main sea-level. Whereas, the mantle, this is the section mantle. So, this surficial portion is crust, below that we have mantle, mantle also classified into two parts, one is upper mantle, that is which one is close to crust is called upper mantle which is of depth of about 650 kilo-meter; and then the lower one is called lower mantle, which is away from the crust and close to the core of the earth which is of depth about 2235 kilo-meter.

So, you can see, as it is mentioned, most of the major earthquake, those are shallow depth earthquake means, they occur mostly within the crust. If not, some within the very surficial part of the mantle, upper mantle section, because beyond that, as it is mentioned beyond 700 kilo-meter, no earthquakes will occur. The property of earth excreta will completely change, a very heavy dense material will be present there. Then the inner part of the earth is called core, which is again sub classified into two components, one is called outer core, which is totally liquid or molten phase. So, that outer core in molten phase, or liquid phase, or fluid phase, or fluid state; and the inner core is very heavy solid material and these are the, it means typical depth of outer core and inner core. So, these are the major layers of the earth.

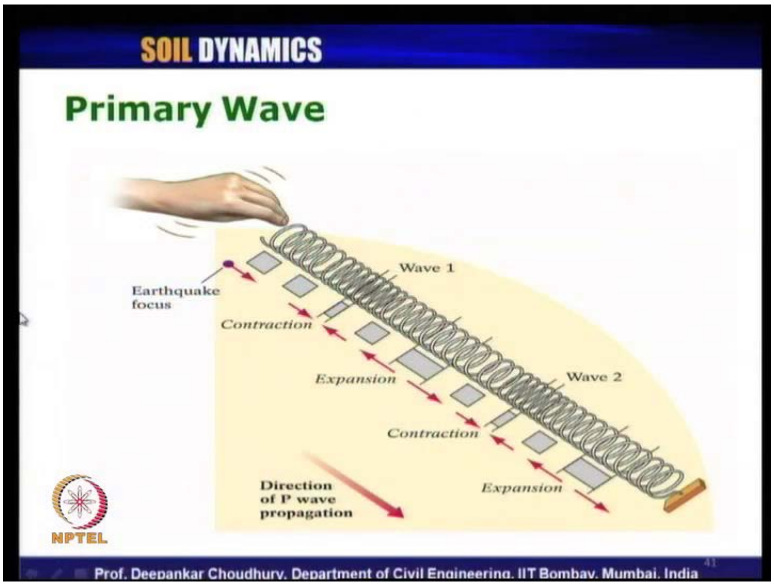
(Refer Slide Time: 43:48)



So, when earthquake occurs, as I have mentioned it is nothing but the energy gets transmitted through the earth in forms of seismic waves or earthquake waves. As I have already mentioned, two types of seismic waves, body waves and surface waves; within body waves, what we called body waves? It transmit energy through earth's interior, there are two types, primary wave, what is the characteristics of primary wave? The rocks vibrate parallel to the direction of the wave, and compression and expansion is the type of nature for this P wave when it travels, right? Because it occurs in the parallel direction of the direction of the wave; whereas, the secondary wave, it rocks move perpendicular to the wave direction.

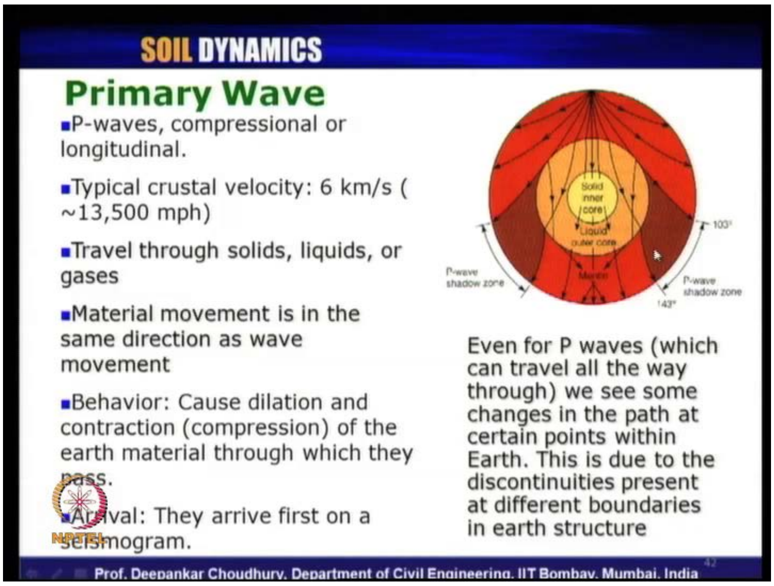
So, rock shearing, it is giving a rope like behavior or a wave in a stadium like a feature, and remember this is S wave, what it is mentioned? It is mostly for S H wave, that is why I said major component of S wave is S H wave, SV wave will have a similar characteristics of P wave, though it is a tortional or shearing, but still the movement will be in the direction parallel to the direction of the wave. And what are the surface wave that transmit energy along earth's surface only? And there can be two features, one is a rock moves from side to side like a snake, and another one is rolling pattern like ocean wave

(Refer Slide Time: 45:34)



Let us look at the pictorial form of these waves. So, it will be very easy for us to understand. So, when primary wave travels in a media, you can see this is the earthquake focus, this is the direction of P wave propagation, and continuous contraction and expansion will occur, and particle direction also movement in this direction. So, if you think about a vibration of a spring that will give you the idea how the primary wave travels during this seismic event.

(Refer Slide Time: 46:12)



What are the major characteristics of the primary wave? As we have already mentioned, Primary waves, P waves, compressional wave, longitudinal wave, these are the various terminology used for the same type of wave. They occur within the crustal depth, and their crustal velocity, that is when they travel through the crust media, I am not talking about very shallow depth of soil, what we consider, I am talking about it is crustal velocity is approximately about 6 kilo-meter per second.

And what are the other characteristics of primary wave? It can travel through solid, liquid, or gas, it means it can travel through any media, all the three phases it can travel through; and material movement occurs in the same direction as the wave movement, that I have explained clearly. What is the final behavior? Final result of this will be it causes dilation and contraction that is compression, it means continuous tension and compression of the earth material through which they pass, and when the arrival time for this P wave? They arrive first on the seismogram, that is if any earthquake occurs in the seismogram, the first record what we will record for a velocity that will give you the velocity of the P wave, because it arrives fast, because of its very high typical crustal velocity. So, what I said, if earth occurs at Chile, if we are measuring in India, in US, in Japan, the first wave will travel through all these distance and get noticed is the P wave velocity, in the corresponding area seismogram.

Now, look at this picture, what it says? Even for P waves which can travel all the way through, that is because in solid, liquid, gas, all media because earth inner is composed of several phases, as I said molten liquid, gaseous phases, also at present, we see some changes in the path and at certain points within earth, this is due to the discontinuities present at different boundaries in the earth structure. So, what it says, suppose earthquake is getting generated at this point. So, our earthquake focus is here. So, because of that, the waves, P waves we are only considering now, P waves are traveling like this, what happens? This is one side on earth at one place, we have hundreds of places, thousands of places all around the world with seismograms which are recording these earthquake, because these waves are traveling and reaching this stations also, fine?

So, if you see, they are traveling here, the same media and no problem; but when it travels in this path, in this direction, it heats this boundary that is crust after crust, this is mantle layer, we are considering and after that we have a core, outer core and inner core, Outer core is liquid and inner core is completely solid. So, when it heats a different boundary, definitely some will get transmitted, some reflected and all those things will happen, what we have learn just now in the wave theory. So, it travels in a different direction inclination followings snell's law and thing like that, and again it gets heat at this boundary of two material and some of them get further transmitted here. So, if you look at this picture, which it shows the corresponding degrees are given, hundred and three degree, hundred and three degree, this is given as one forty three degree. So, if you say this is as 0, this as 180, this is 143, and this is 103, similarly on other side.

And this zone between 103 degree to 143 degree on this earth surface is called P wave shadow zone, what does it mean? On this zone of earth, if we have some seismograph, they cannot receive any P wave, because of the earth different layers, their properties and P waves travelling through this layers, because of the discontinuities of this layers, this zone is called shadow zone means, in that zone no P wave is finally arriving. So, no P wave is finally arriving means, in this zone, that is those who are staying or the seismogram which are stationed between angle 103 to 143, in that range considering the earthquake epicentral point as a 0 degree point, they cannot feel that earthquake has happened, means their stations cannot record any waves, because nothing reaches them, that is why the name is P wave shadow zone. So, with this, we will end today’s lecture with this primary wave characteristics or P wave characteristics. We will continue our lecture in the next class with other waves, with their characteristics behavior and finally, we will try to find out the locate the other earthquake epicenter how we do in practice actually by using several seismogram data collected throughout the world for a particular earthquake.