Advanced Marine Structures

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Lecture - 1
Fluid structure interaction – I

We now, discuss lectures on module 2.In module 1 we discussed about most important parameters in terms of design aspects.As we all understand, in marine structures the important environmental load which contributes to the design is essentially from the waves.Of course,aerodynamic effects are important, because the super structure is having asymmetricity in its geometry and layout.

Therefore, aerodynamic stability or wind forces are important, because we have got very tall mass and cranes etcetera, but the projected area of these arecomparatively less with respect to the submerged volume of members in the marine structures.Because marine structure essentially designed for deep graph system, essentially we talk about floatation systems which are compliant in nature we look for large dimension of bodies, where the diameter of the structure or the members are very large,therefore, it attracts lot of wave forces or current etcetera.

So, fluid structure interaction and fluid induced vibrations or wave structure interaction becomes predominantly of interest for any designer in marine structures, because is one domain which has taken intensive part in terms of numerical, analytical and experimental research in the recent past.So, let us quickly look at a very brief summary of what do we understand,by fluid structure interaction, how to handle them conceptually in the design.

Remember very interestingly, there is no direct application of FSI discussed in this course in this module.If you really want to look, at what would be the fluid structure interaction, how to calculate the forces, we already discussed in module 1 what all the different influence of forces, cost on the marine structure by environmental loads or environmental parameters.You can refer back and try to compute, because we have given you detail equations in spectrums for waves, wind generated forces, etcetera on marine structures.

So, in this specific module we dedicate our discussion only to conceptual understanding of FSI.How fluid and structure interacts, what are the different aspects?Of course, many of you may know few of these discussions, but we already have because as an ocean engineer or as a civil engineer designing hydraulic structuresyou would have encountered these kind of interaction problems in your under graduation level.For the completion sake for the viewers let us discuss this in detail in this course in this module to a greatpossible extent.So, module 2 talks about fluid structure interaction.

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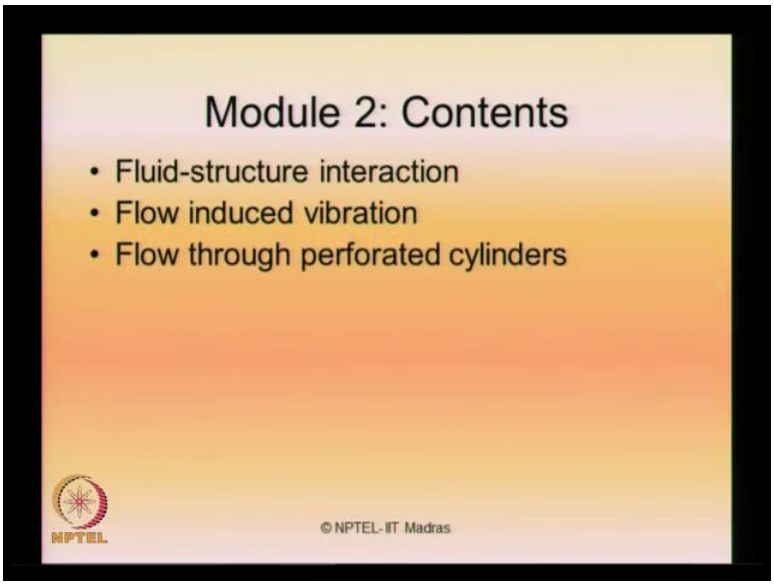

The contents of this moduleare as follows.We will talk about fluid structure interaction in this module.We will talk about flow induced vibration and we (( )) essentially talk about flow through perforated cylinders.These are very important area where people have been using perforation or perforated members in marine structures to reduce the forces on the members essentially.So, this is a modern way of rehabilitating or retrofitting marine structures.You may ask a question, sir, why should attempt to retrofit a marine structure.

Marine structures have been designed for a service life of 20 years,25 years etcetera depending upon the availability of oil deservance specifically state or sea side, but you cannot make the structures to become obsolete on one night or one day because installation, decommissioning are very expensive.So, can I make use of them?So,there are two ways by which, the structure can be strengthened.One, reduce the pay load on the structures.So, relieve the structure of stresses which is practically not possible because the machineries do operate on the same kind of loads, which are exercising on the offshore platform or marine structure.

Therefore, we cannot think of relieving the forces because forces coming from the nature cannot be controlled, cannot be even computed to higher accuracy and forces coming on the platform or in the marine structure because of allied loads like machinery etcetera cannot be controlled because they cannot be relieved of.Then the structure will not have its intended function.Then I have got to strengthen the system, how do we do?I can always adopt a perforated cover over existing member to relieve the forces.We will talk about this in detail in the third point of discussion in this module.

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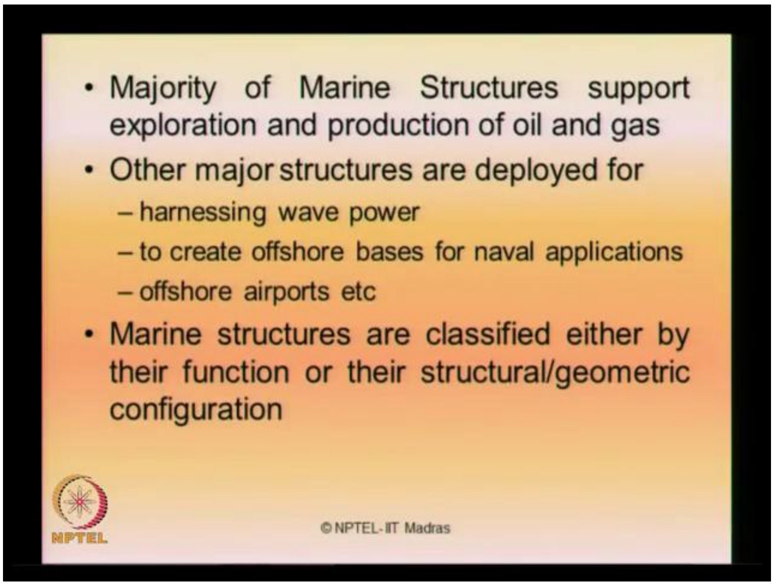

So, in this lecture 1we will discuss in detail about fluid structure interaction.Interestingly majority of the marine structuresdo support exploration and production of oil and gas, that we all know why these structuresare constructed.Other major structures are deployed essentially for harnessing wave power, because renewal energy in terms of wave energy let us say harvesting has become very important aspect on the recent research.

So, people do construct platforms, where wind turbines or wave energy or wave conversion devices are installed, people also use major structures to create offshore base for naval applications which is for strategic importance.Of course, you could have seen in countries like Japan, people have started constructing floating airports, offshore airports because lands scarcity is a very major problem.Marine structures are classified either by their function or by thegeometric configuration.We already seen this in the first module.

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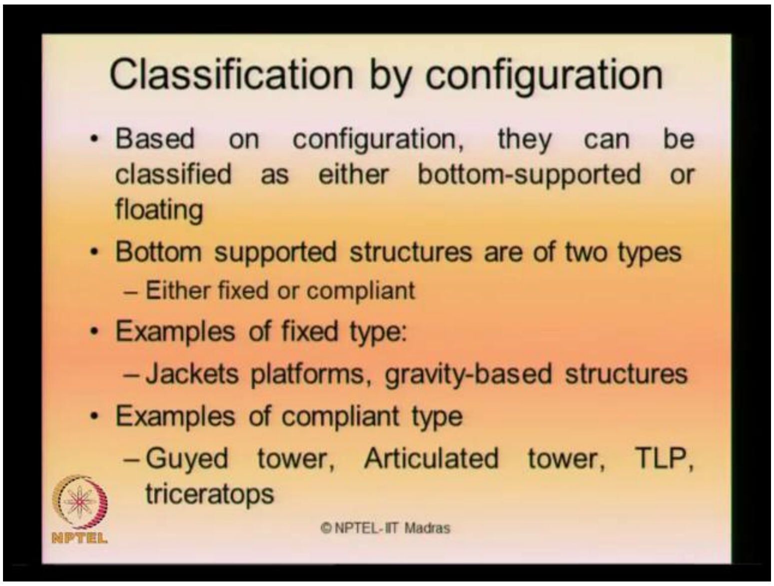

So, if you look at classification of structure by configuration, based on the configuration the structures can be broadly classified as either bottom supported or floating.Bottom supported structures can further be divided as fixed or compliant.Example of fixed type you all know jacket platforms, gravity based structures.Example of compliant type we have understood guyed towers, articulate towers, tension leg platform, triceratops etcetera.

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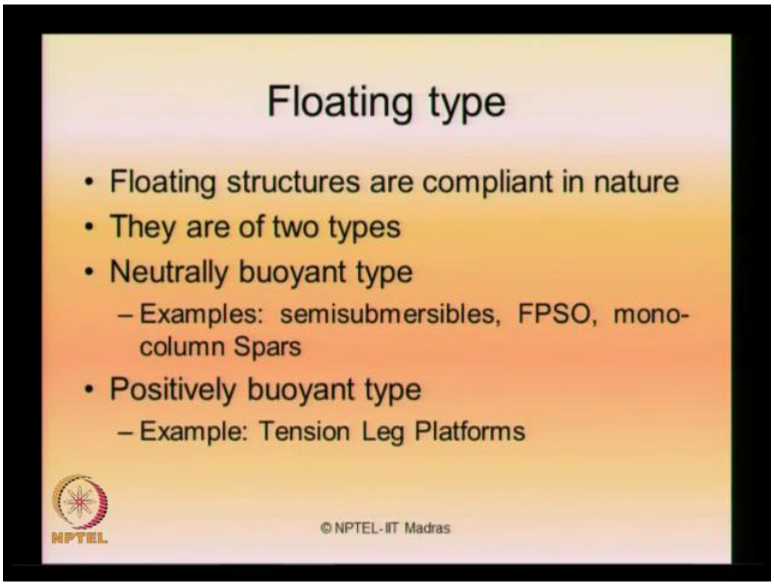

We look at the floating type.Floating structures are compliant in nature.There are again divided into two categories.One is called neutrally buoyant type for example, semisubmersibles,FPSOs, mono-column spars.These are mostly neutrally buoyant type.The positive buoyant type for example, tension leg platform, triceratops etcetera.

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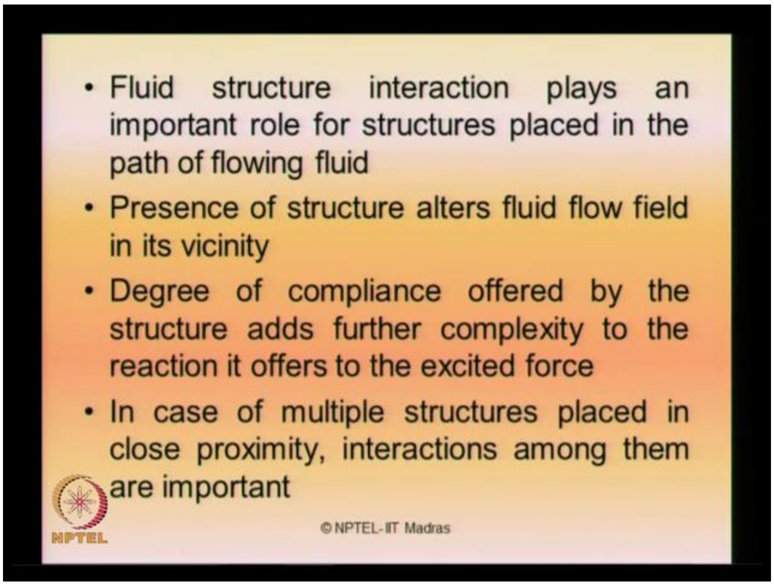

Now, these are the categories of structures available based on either form or based on other structural configuration.We will talk about fluid structure interaction that is interaction between the members of the structures then the fluid flows across thesemembers.FSI becomes very important for structures plays especially in the path of flowing fluid, not in stagnant water.Essentially, if you look at fundamental aspect of influence of the structures in fluid flow, it alters the flow fluid near its vicinity that is very, very important.So, there is a far field disturbance, near field disturbance.

So, essentially we are focusing on the near field disturbance, that is what is the influence of the structure on the fluid flow characteristics in its vicinity?The degree of compliance therefore, plays a very important role because this can add complexity to the reaction it offers to the excited forces.Therefore, it is important for us to understand whether FSI is applied on a fixed structure or a floating structure because if it is floating structure the compliancy, what the structure has also alters the complexity to the reaction it offers to the excited forces.

The other important aspect instead of having one structure in position,if you have got series of structures, series of members which are placed either in parallel or in series under closed proximity then the interactions between themwill alsoaffect the FSI in the fluid flow.So, there are three different aspects here which we must focus.One, what is the structural support system?Is it fixed type or a floating type, becauseif it is a floating type then the mechanism by which the structure generates the force internally to oppose a excited force will add complexity to your interaction in its near vicinity, one.

The second part is, all the structures placed in series, if there are many members placed in close proximity then the interaction between them will also affect the fluid structure interaction in the vicinity of the members.So, then we have to talk about, what is the optimum spacing between the members placed in series, placed in parallel etcetera.

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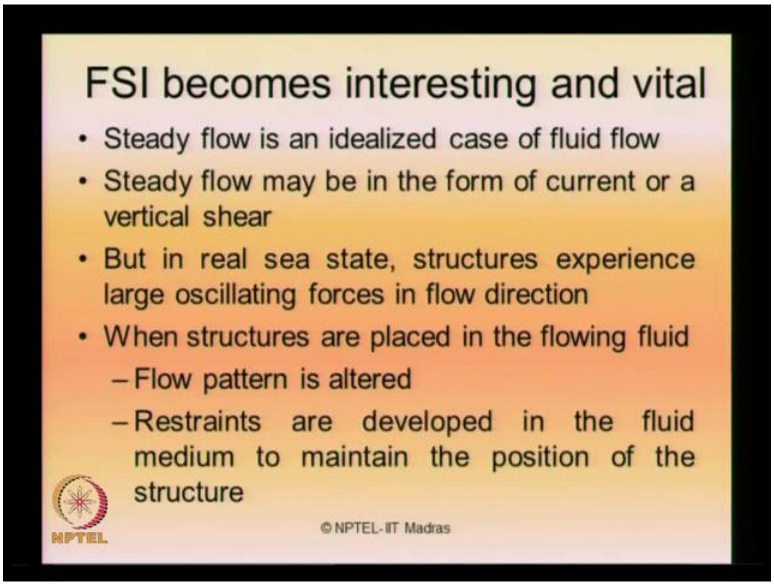

Therefore, in actual fluid structure interaction becomes interesting and sometimes it becomes vital.Now, if you look at some of the idealizations, which are done before we start understanding.FSI, steady flow is an idealized case of fluid flow because the fluid flow is the never remaining steady.It is always turbulent.So, always in a disturbed state, but steady flow it is itself is an idealized state of a fluid flow.Steady flow may be in the form of a current or in the form of causing a vertical shear,but in the real state structures experience large oscillating forces in the flow direction.

So, we are not any way able to really model the FSI in its true sense (( ))..we have to do some idealization in the flow characteristics of the fluid as well as in the structural experience, the response characteristics of the system.So, when the structures are actually placed in fluid domain, on the fluid flow direction, the fluid pattern is seen to be altered significantly, that is the first observation one makes.In a fluid flow if interfere a memberof any diameter the fluid pattern is first altered,number 1.

Number 2, the restraints are developed in the fluid medium to maintain the position of the structure, because you do not want or the structure does not want to get displaced.So, the structure offersrestrain to its disturbance.So,there are two kinds of reactions you can explore in a FSI domain.One is the fluid flow is altered significantly, second because of this the structure, which is offering response or internal resistance to this fluid flow alteration also creates complexity to the FSI behavior.

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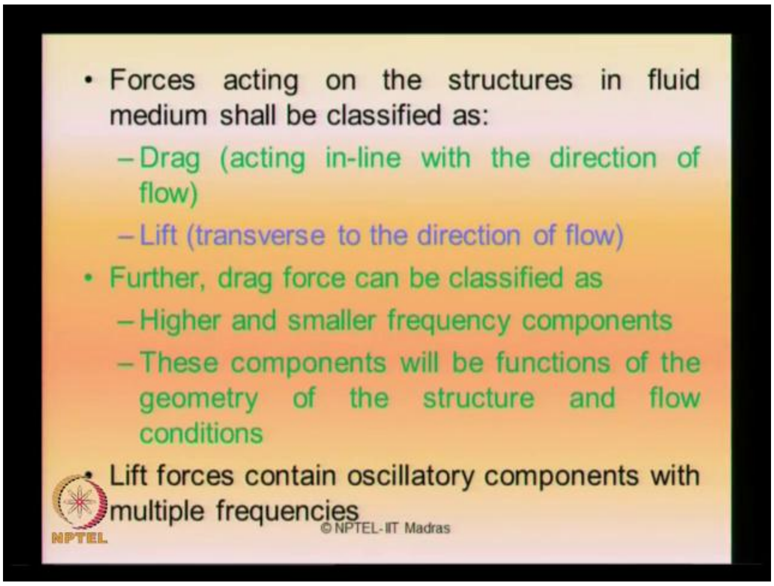

So, the forces acting on structures in the fluid medium can be classified as in two parts,as we all understand.One is a drag which acts in line with the direction of flow, other is the lift which are transverse to the direction of flow.There are two kinds of forceswhich generally act predominantly when a member is interfered in a fluid flow.One is a drag component which acts in line with the fluid direction or fluid flow.The second is lift which act as a transverse direction to the direction of flow.If you look at the drag force in general this can be further classified as higher and smaller frequency components.

Drag has two different distinct components of frequency, one is of higher frequency components,other is lower frequency components.These components of course, will be the functions of geometry of the structures, and they are also influenced by the flow conditions.If you look at the lift force at the hand, lift force contains essentially oscillatory components with multiple frequencies.In drag force you can distinctly identify two frequency contents higher and smaller whereas lift,it is a mixture.

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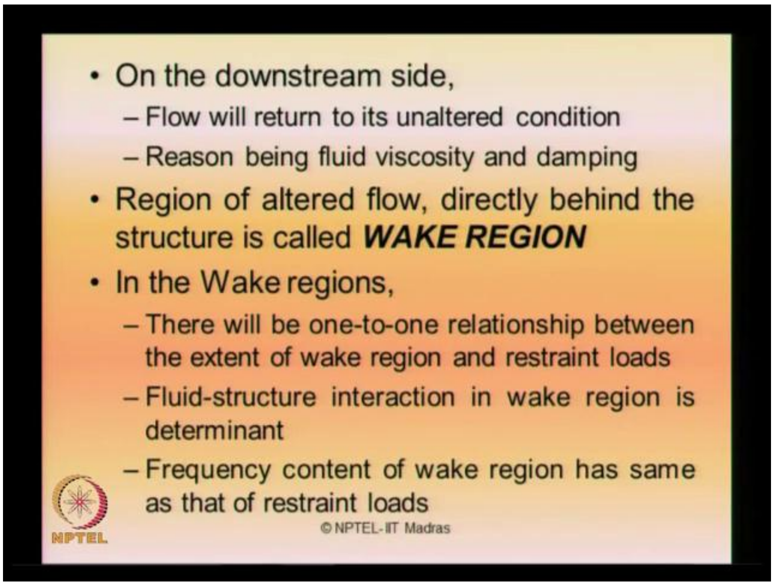

Then again, when you place a body or a member cylindrical member essentially in a fluid flow there are two sections of this.One is the upstream side, other is the downstream side.Upstream side is the direction, where the fluid is hitting the body, downstream side is the direction where the fluid is exiting the body.There are two different sides of looking atthe scenario.On the downstream side flow will return obviously to its unaltered condition because the interference is causedonly because of the presence of the member, that vicinity will have a validity of range, the influence of the member on the fluid flow will not remain for an infinite length.

It has got certain length which is a function of the diameter of the memberbeyond which the influence of the member on the fluid flow can beneglectedbecause the fluid flow can remain unaltered in the downstream side.There are many reasons for this, the literature summarizes this, because of fluid viscosity and fluid damping.These are the two important regions why fluid gets back to its unaltered condition in the downstream side after it leaves the body.It has got a damping phenomenon present in this and of course, fluid as viscosity.

Now, the region of the altered flow behind the structure is indicated in theliterature as a wake region.So, wake region is nothing but,the region of an altered flow which is directly behind the structure.Now, in wake regions there are many important things happening.There will be one to one relationship between the extent of the wake region and the restraint loads.What do you understand by restraint loads?Restraint loadsare generated loads either from the complexity of the geometry of the structure for example, floating, fixed or because of the boundary condition is established by the structure with respect to the sea, sea bed,thier is bottom supported or freely floating.

So, the restraint loads are essentially, these kind of internal reactions which come from the structure either because of fixity or because of its compliance.So, this directly influences the extent of the wake region.How long the wake region extended from the member?One may wonder what is important of wake region, I will show you that in the next slide.So, the wake region is simply a region of an altered flow for the disturbance created because of the presence of the member.Now, how long this system will be created that region,the extent of that region is governed by the restrains which are offered by the structure either because of its compliancy or because of its boundary condition developed by the structure with respect to the sea bed, may be bottom supported, may be compliant, may be floating etcetera.

Now, the fluid structure interaction interestingly the wake region is determinant, it can be easily computed.We can have close form of solution for the interaction of the fluid with the structure essentially in the wake region.Now,one may ask me a question sir why we are interested in discussing only the wake region?I initially said in the previous slide when we talk about fluid structure interaction, we only bother our interest towards what is the interaction of the fluid near the vicinity of the member.So,vicinity is otherwise understood in literature as a wake region.So, the frequency contents of the wake region isthe same as that of the restraint loads.

The restraint loads have higher frequency components, wake regions shows higher frequency content or vice versa.It means there is qualitatively and quantitatively one to one relationship between the wake region which we call as the disturbed region because of the presence of the member in the fluid direction or the fluid field, with that of the restraint offered.So, you can always understand the restraint offered by the structure controls the interaction of the structure with the fluid, that is what we say one to one interaction.

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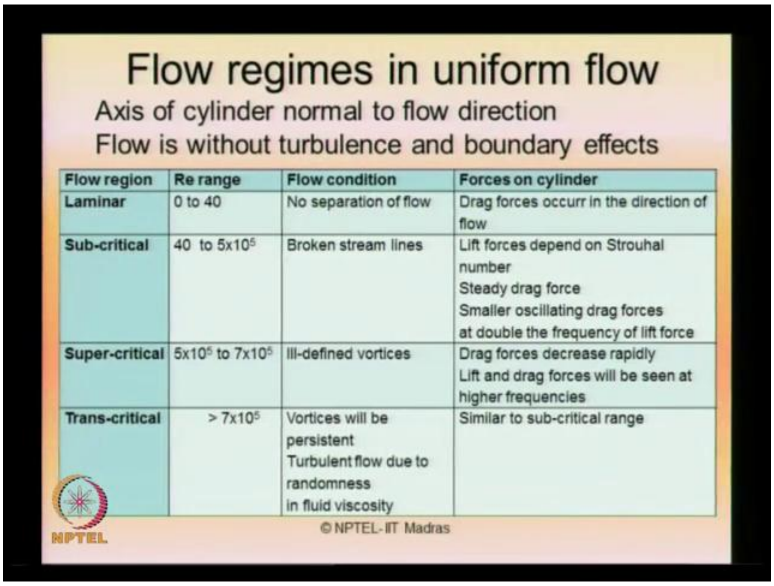

Flow region	Re range	Flow condition	Forces on cylinder
Laminar	0 to 40	No separation of flow	Drag forces occurr in the direction of flow
Sub-critical	40 to $5x10^5$	Broken stream lines	Lift forces depend on Strouhal number Steady drag force Smaller oscillating drag forces at double the frequency of lift force
Super-critical	$5x10^5$ to $7x10^5$	Ill-defined vortices	Drag forces decrease rapidly Lift and drag forces will be seen at higher frequencies
Trans-critical	> $7x10^5$	Vortices will be persistent Turbulent flow due to randomness in fluid viscosity	Similar to sub-critical range

If you look at the flow regimes in an uniform flow,let us say the axis of the cylinder remains normal to the flow direction.The flow direction may be horizontal,the axis cylinder remains normal to the flow direction.The flow is considered to be having without any turbulence and boundary effects,it is a free flow domain.In that case the flow region can be divided into four as laminar, sub critical, super critical and trans critical.How they are classified?They are classified depending upon the Reynolds number.If the Reynolds number varies practically from 0 to 40 or from 40 to 510power5 are as shown in the table column here, we can classify the regions as laminar, sub critical, super critical and trans critical.

Dear, friends very important to understand that there exist a very fine boundary or division between these kinds of regions because, In these regions oncethe fluid starts there continuously transiting from one to the other.So, you really cannot capture a sub critical or super critical region for conducting experiments.Of course, it is very difficult to conduct experiments or experiment investigations in trans critical regions because the Reynolds number needs to be very, very high.So, essentially experimental focus are done mostly on sub critical or super critical regions.

Now, if you look at the distinct difference between these regions in terms of its flow condition, you will obviously notice that there is no separation of flow in the laminar region.The laminar region more or lessremains undisturbed when the body is interfering with a fluid whereas in trans critical you have got well defined vortices.So, the turbulent flow will be essentially due to the randomness of fluid viscosity, can distinctly see this vortices in trans critical region.Ofcourse, in sub critical you can find some broken stream linesand super critical you can see vortices, but they will not be well defined.So, what we can call them as ill defined vortices.

Now, what we are interested as I said in the beginning, my aspect of discussing marine structures will be only on the force exerted on the system or the response given by the system back to counteract these forces.I am not interested in discussing in detail about the hydrodynamic part of the force on the system because, we are talking about marine structures and a structural engineer I would always address this problem in terms of, either the force received by the structure or the response given back by the structure to the environment.So, let us talk about the effect of these regions in terms of the forces on a cylinder whose axis is kept normal to the flow direction.

We look at laminar region, the drag forces are seen to occur in the direction of flow itself whereas in sub critical region lift forces depends on the Strouhal number. You can alwayssee very clearly there is a steady drag force with very small oscillating component of the drag force.The oscillating component of the drag force is very small, more or less the drag force remains steady in sub critical region where Reynolds number is closed to as high as5,10 power 5.Interestingly, these oscillating drag forces occurred at a frequency which is practically double of the lift forces.

Youcan clearly see two distinct differenceof frequency components.One is on lift, one is on drag, you can see this,that is why we can say there are broken stream lines whereas when you move to the super critical region the drag force decrease very rapidly, and lift and drag force seem to occur at higher frequencies.Whereas in trans critical region you can see the behaviors more or less similar to sub critical that is why the validity ofexperiments, what peoplehave conducted in sub critical is extrapolated to some extend to a higher Reynolds number also, because the forces seems to be, the force on cylinder seems to be similar to the top sub critical behavior.

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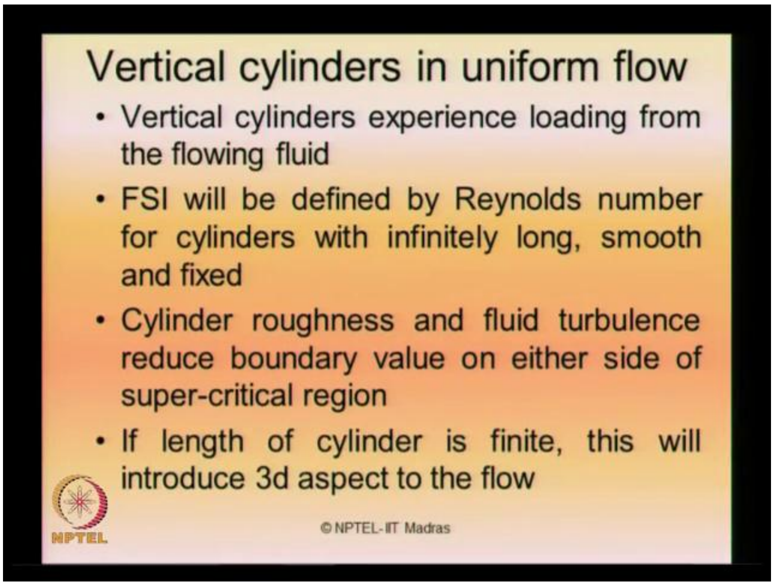

Having understood this, let us see some focus on vertical cylinders kept in uniform flow.The vertical cylinders experience loading from the fluid flowing around it.Therefore, we have just now seen fluid structure interaction on the cylinders essentially is defined by the region which is controlled by a single number which you call as a Reynolds number, but,there is a basic assumption here, that the cylinders are infinitely long and they have a smooth and fixed units.If you have got roughness, if you got theends covered,Ihave got a finite dimension of the cylinder for example, in case of TLP where the pontoon link or the column links are fixed or lesser compared to that of the water depth that we are talking about then all these consort what we talk about will get modified.

The cylinder roughness and fluid turbulence reduces the boundary value on either side of the super critical region,that is very important for us to understand.And of course, as I said the length of the cylinder is finite then a3D aspect also to be studied in terms of the FSI.What we are talking about here is only the 2D aspect of FSI.If the cylinder has got the finite length, then three-dimensionalflow is also very important where people do conduct experiments to understand them in the finite length of the members.

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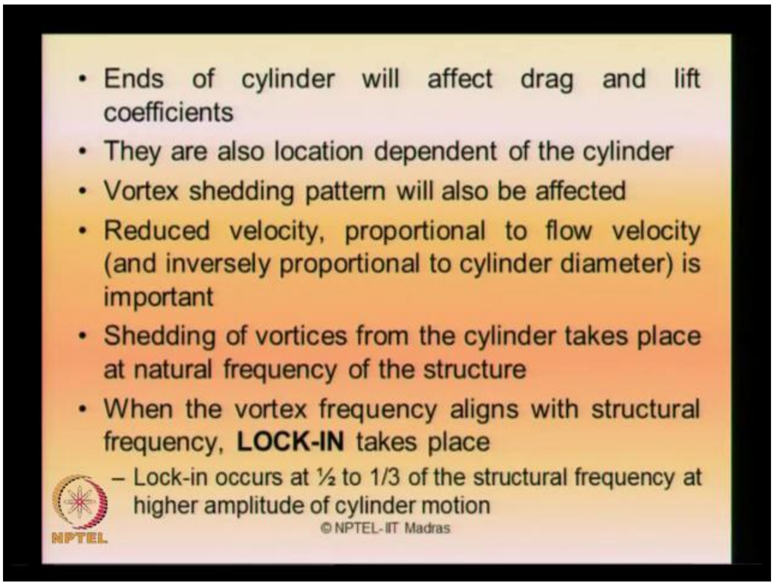

The ends of the cylinder essentially will affect the drag and the lift coefficients which are computed on the membersand of course, very importantly these coefficients (( ))… a location dependent of the cylinder, where are they located?The cylinder is placed near the free surface or mid third of a water depth or closer to the boundary of the sea bed etcetera.And vortex shedding pattern especially in super critical and trans critical region will be significantly affected when the ends of the cylinders are covered, then it can result in what we call reduced velocity.

The velocity will get reduced, it can become proportional to the flow velocity and inversely proportional to the cylinder diameter which is very, very important.So, for larger diameter the reduction can be severe, will be high and shedding of vortices from the cylinder can take place at a natural frequency of the structure which is very dangerous in terms of dynamic response behavior of the structure.Of course, in certain cases capturing this kind of vortices induced by vibration at the natural frequency of the member, can help to generate or harness the maximum power.For example,let us say vortex induced vibration phenomenon in wave energy devices people design or tune the system, such a way that thevibration frequencies on the vortices are captured near frequency to the natural frequency of the structure.

So, that the maximum energy is harnessedor captured by that device for converting it in to a mechanical power.So, depends upon what application looking at, then we can always design the system accordingly, but for an offshore structure where the function is not wave power generation, but oil exploration you not like to have the shedding of vortices very closed to that of the natural frequency structure because this can result in what we call resonating response, which can increase the dynamic amplification factor of the member.Now, when the vortex frequency gets aligns with the structure frequency there is something lock in takes place.

What is a lock in?Lock is actually that occurs at half to one third of the structural frequency and the amplitude of this is very very high.So, it actually starts vibrating in a frequency at above 50 percent to 33 percent of the structure of the frequency.Essentially ladies and gentlemen please understand resonance does not essentially occur only when the forcing frequency matches with the fundamental frequency of the structure.It can also occur at about 30 to 50 percent of the structural frequency, if this occurs because of vortex frequency is what we call as lock in.

Lock in is a very dangerous phenomenon because the amplitude is increased significantly high at these kind of frequencies.So, you can always have an impact caused by have fluid induced vibration on the structure even at a frequency about half the structural of the frequency vibration this is true when the flow remains super critical or trans critical or at very high Reynolds number,where they lift and drag forces or distinctly occurring a different frequencies.So, you have frequencies generated because of vortex shedding which can create what we call lock in phenomenon and there has been instances report in literature, where members have failed because of lock in frequencies occurring in the structures.

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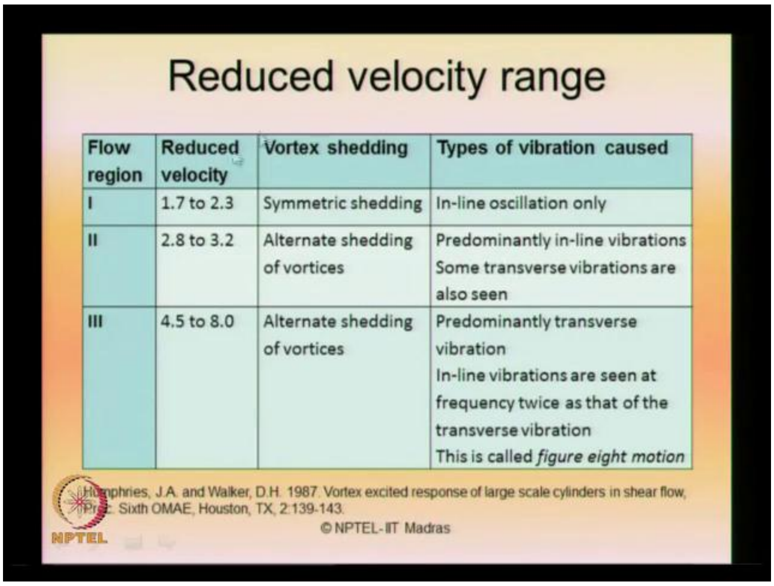

Flow region	Reduced velocity	Vortex shedding	Types of vibration caused
I	1.7 to 2.3	Symmetric shedding	In-line oscillation only
II	2.8 to 3.2	Alternate shedding of vortices	Predominantly in-line vibrations Some transverse vibrations are also seen
III	4.5 to 8.0	Alternate shedding of vortices	Predominantly transverse vibration In-line vibrations are seen at frequency twice as that of the transverse vibration This is called *figure eight motion*

As I said in the previous slide, we have something called reduction in velocity.Let us talk about the reduced velocity and its range as discussed by Humphries and Walker in 1987.They havedivided the flow regions into 1,2and3 depending upon identifying, the vortex shedding phenomenon.If the vortex shedding occurs symmetric or alternate then they divide the flow region into 1,2and3 depending upon the reduction of velocity ranges from 1.7 to as high as 8.0.Now, interestingly let us look at the types of vibration caused because we are interested as a designer how to safeguard the structure underthese kind of lock in phenomenon.

You will see that, when thevelocity is reduced to about let say 2or 2.3the types of vibration is only online oscillation whereas, when there issignificant reduction as high as 8 predominantly will cause transverse vibration and therefore, the failure can be more to dangerous and you will always see the in line vibration are also seenas a frequency twice as that of this vibration.This will result in what we call figure eight motion.So, the failure will get in terms of or the frequency distribution in terms of transverse and in line vibration will cause a resultant response of vibration which we call as a figure eight.

So,this will result in a very dangerous type of failure to the member under flow region.So,do not be happy when, therereduction velocity is as says as8 because the moment you have reduction velocity the amplitude may be low, may be the velocity may be low,but the amplitude of the vibration can become very high, can result in a very specific mode of vibration which can cause disaster to the members.

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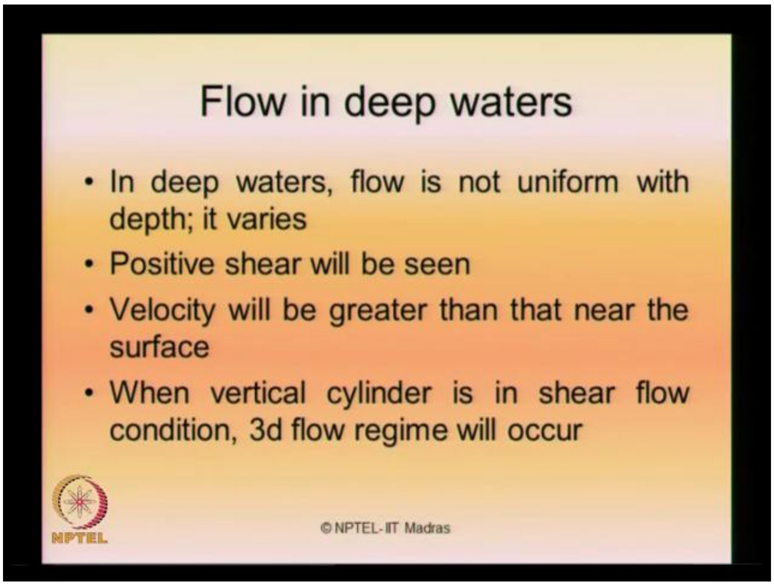

Let us now, understand the FSI in terms of deep waters.Of course,as we understand from the literature in deep waters the flow is not uniform with depth, it varies with depth.There is a positive shear seen in this kind of behavior, the velocity of course, will be greater than the near surface as you move.When the vertical cylinder is in shear flow condition, then you can always envisage what we call as a 3 dimensional flow regime will occur.

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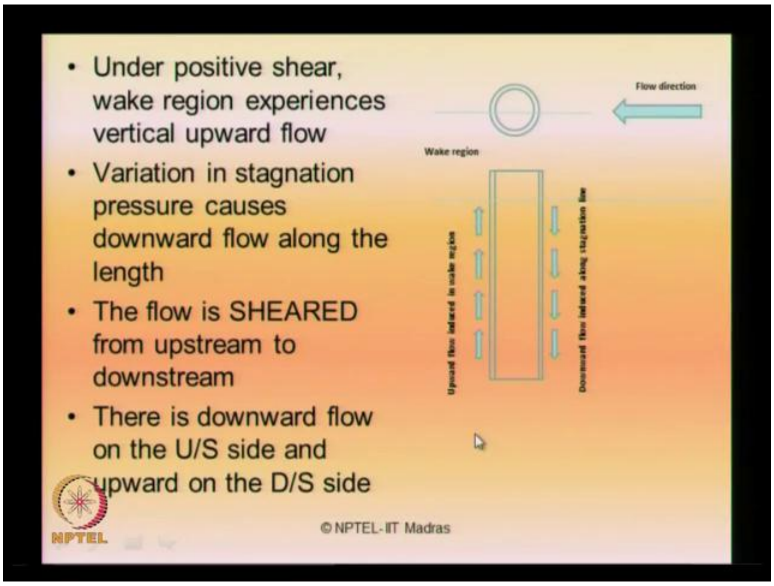

So, as we discussed in the last slide we focused on wake region.Now, we will see in this slide what is the effect of wake region?Under the positive shear this is my wake region as we seen in this figure, this is my cylinder, this is my flow direction as we see from here.Under the positive shear the wake region experience the vertical upward flow,you can see here the wake region, which experience an upward flow whereas the downward flow is induced in the stagnation line.So, the member is subjected to a clear shear.

The variation in stagnation pressure causes downward flow along the length of the cylinder, the flow is sheared from upstream to downstream.That is very,very important thus the member or the structure is subjective to what we call as a shear failure.This is downward flow on the upstream side and upward flow in the downstream side is a very interesting phenomenon, which happens on the wake region because of the flow direction in deep waters.

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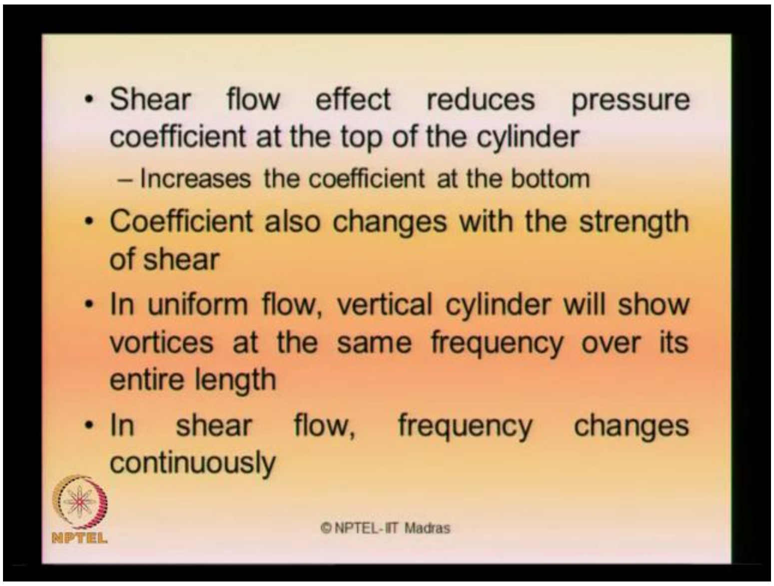

The shear flow effect reduces pressure coefficient of course, at the top of the cylinder, but of course, the coefficient increases at the bottom.The coefficient also changes with the strength of the shear of course, present in the medium.In uniform flow the vertical cylinder will show vortices at the same frequency over its entire length.In the shear flow,of course the frequency changes continuously.

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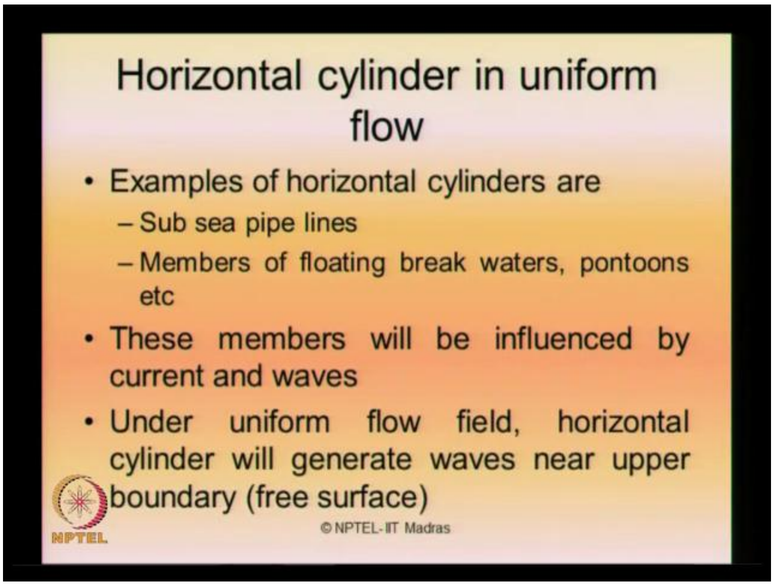

Let us now look at the horizontal cylinder in uniformflow.So far, we are talking about the vertical cylinders.You can quickly look at the cylinders as practical examples.

Youcan see subsea pipe lines, members of floating break waters, pontoons of TLPs etcetera.These members are also influenced by currents and waves.Under uniform flow field the horizontal cylinder will generate waves near the upper boundary which we call as a free surface.

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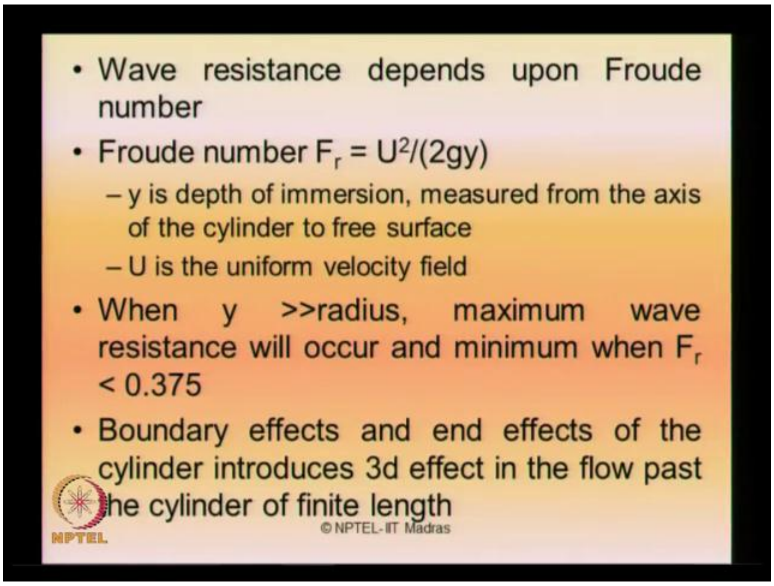

The wave resistanceof course, in this case depends on Froude number.Froude number is given by this equation, where y in this expression, the depth of immersion measured from the axis of the cylinder to the free surface and Uof course, is the uniform velocity present in the field.When y is very, very large compared to the radius of the member maximum wave resistance will occur and it is minimum when the Froude number is less than a number which is 0.375.Therefore, the boundary effects and the end effects of the cylinder will introduced a 3D effect in the flow past cylinder of a finite length which is true in the horizontal cylinders as well as vertical as well.

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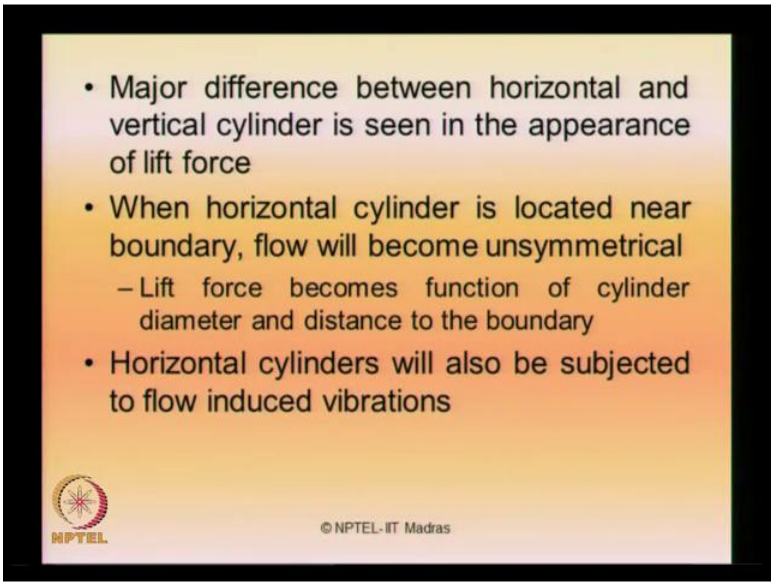

Now, the major deference between the horizontal, vertical cylinder is seen in the appearance of lift force only.When horizontal cylinder is located near the boundary the flow will become unsymmetrical, the lift force becomes function of the cylinder, diameter and the distance to the boundary of the location of the cylinder.Of course, horizontal cylinders will be also subjected to flow induced vibration, which we will see in the successive modules.

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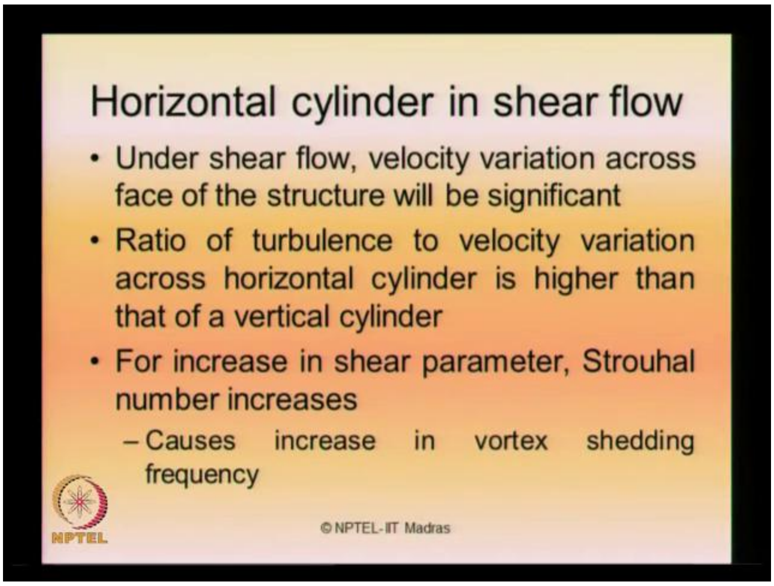

If you look at the horizontal flow cylinder in shear flow, under shear flow the velocity variation across the face of structure will be very significant.The ratio of turbulence to velocity variation across horizontal cylinder is higher than that of a vertical cylinder.So, for increase in shear parameter Strouhals number increasesas we all understand because this increase is caused in vortex shedding frequency of the member.

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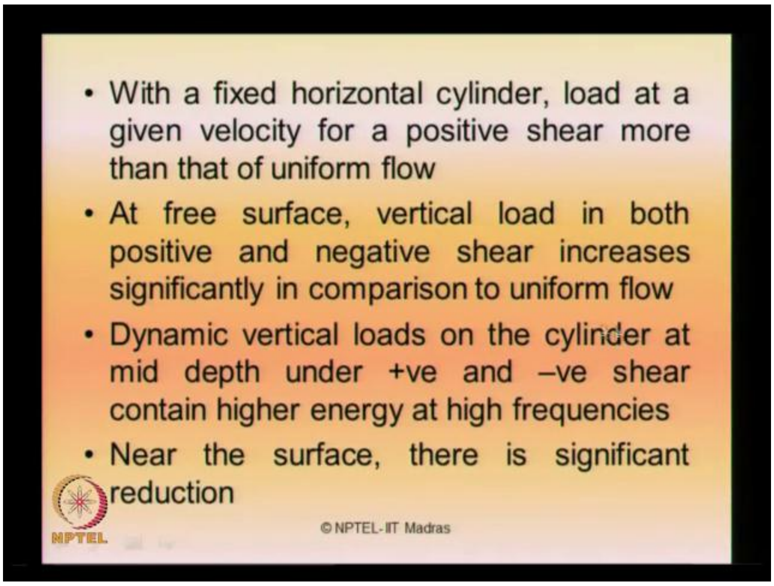

When a fixed horizontal cylinder load at the given velocity for a positive shear is much more than that of uniform flow.At a free surface, the vertical load in both positive and negative shear increases significantly in comparison to uniform flow.Therefore, the dynamic vertical loads on the cylinder at the middle depth under positive and negative shear contains very high energy at varied frequency,that is why you will see generally in case of tuned mass dampers, which are attempted as one of the response control mechanism forarticulated towers you will see the maximum variation occurs near one-third from the MSL of the free surface.

It is because of this because, you will see the dynamic vertical loads on the cylinder at middle depth close to one-third under positive and negative shear has higher energyat higher frequencies.So, people try to attempt this as one of the important parameter to address the unit mass control dampers in case of for example, A Ts or TLPs.Of course, near the surface as we move up there is a significant reduction.So, near the depth at above middle the variation is very severe,as you move up to the free surface there is a significant reduction in this variation.

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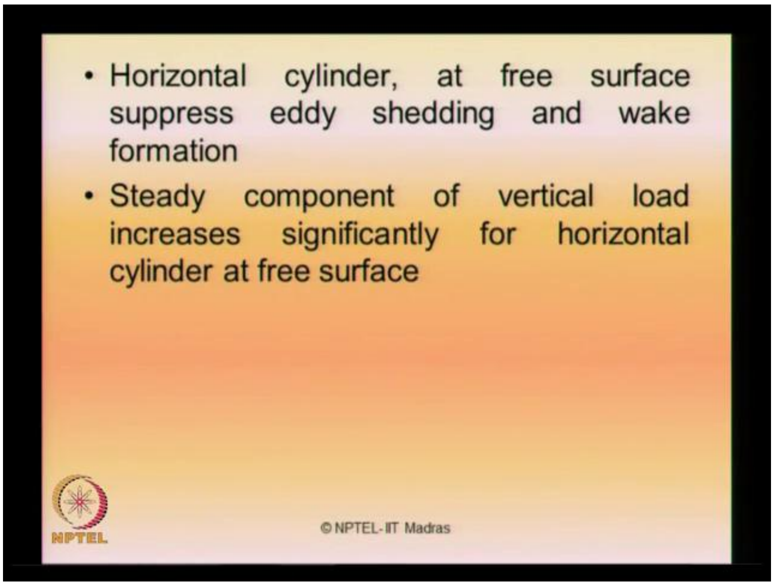

Horizontal cylinders at free surface suppress eddy shedding and the wake formation.Steady component of the vertical load increases significantly for the horizontal cylinder at the free surface.So, as we move towards a free surface horizontal cylinders attract more forces.There is something called blockage factor which is very important in the design which is an important aspect an outcome of a FSI.

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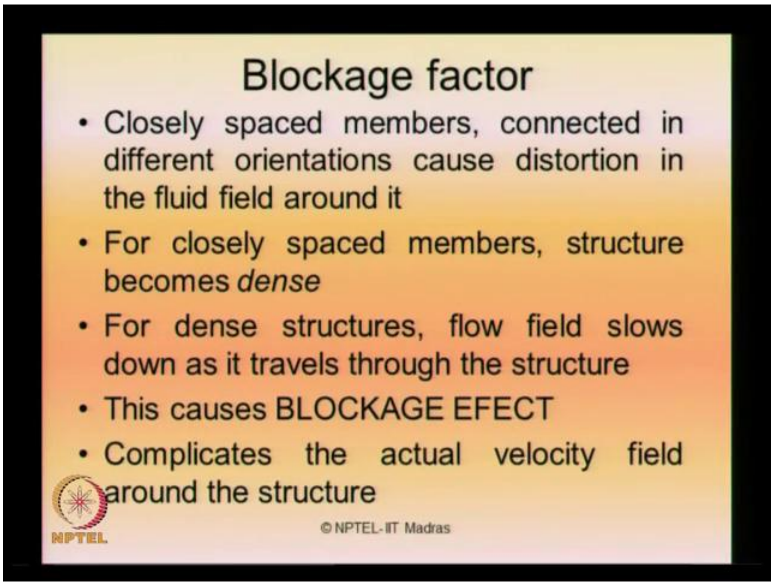

As we saw closelyspaced members interfere with an FSI.Closely space members connected in different orientation, orientation cause distortion in the fluid flow in its vicinity.For,closely spaced members the structures becomes, what we call dense.For dense structures the fluid flow slows down as it travels through the structure, is very important, becomes a cluster, when it becomes a cluster then the fluid flow or the velocity of fluid is retarded, it slows down.

Velocity is slowing down is always not happy we have already seen in the different regions, as expressed with researchers it always causes frequencies at two distinct frequencies, which is affectingthe lift forces in the members.So, in dense structures the fluid flows slows down the velocity as it travels to the structure, which can also be harmful.This is addressedas blockage effect in the literature.This actually complicates the actual velocity field in the vicinity of the member.

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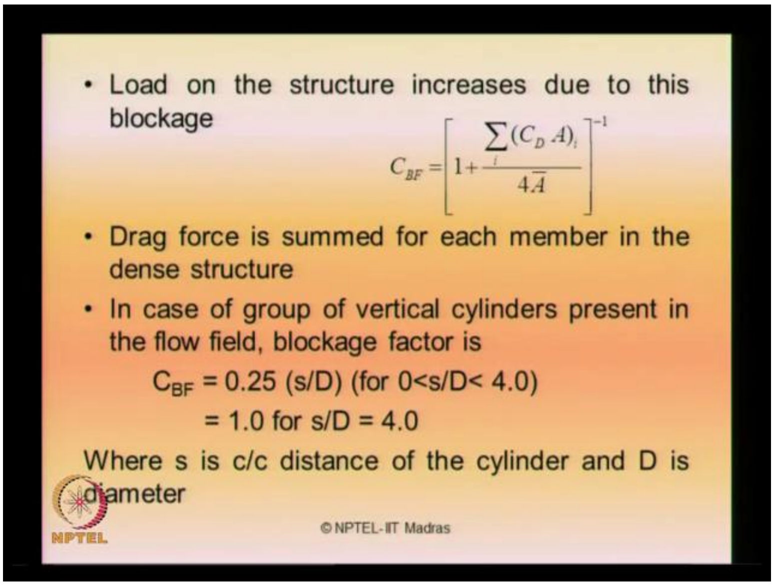

The blockage factor is given by this equation as you see in the slide.The load on the structure increases due to this blockage.This is very important, that when the velocity reduces do not be happy because these depends on what region you are talking about and they will induce lift forces at a different frequency, which is distinctly different from that of the drag forces which in cause complications to the structure, infact it increases the load on the structure.The drag force is summed for each member in the dense structure.In case of group of vertical cylinders present in the flow field blockage factor is given by a factor as you see here, whereas, we are spacing on the member or centered center of distance of the cylinder and Dof course, a diameter of the member.So, it is a function of the spacing or the cylinder distance and of course the diameter.

So, when you talk about cluster of members, let us say costal protection structures or different kinds of marine structures, where we are talking about series of piles driven at a closer proximity, then please take care about the incremental in the load because of the blockage factor caused by FSI, because this is a function of spacing of the member as well as of course, the diameter.This lecture has the following references which I wish to acknowledge is available of course, in open source literature.

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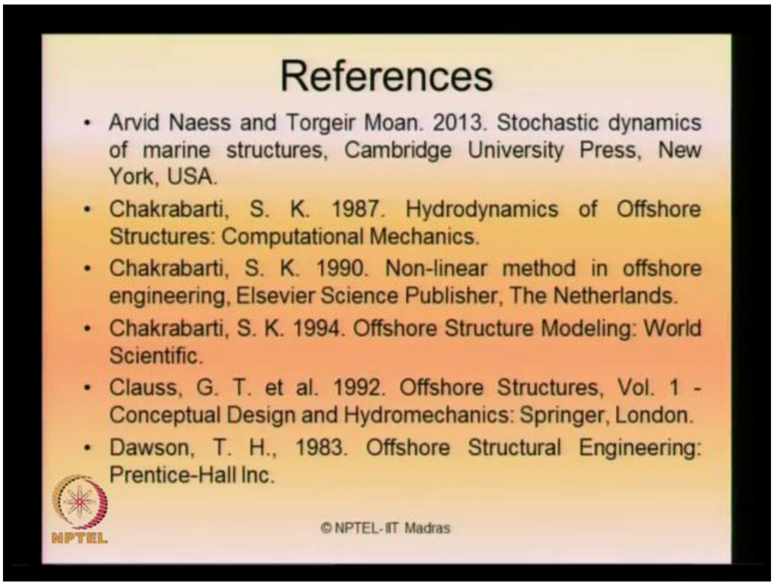

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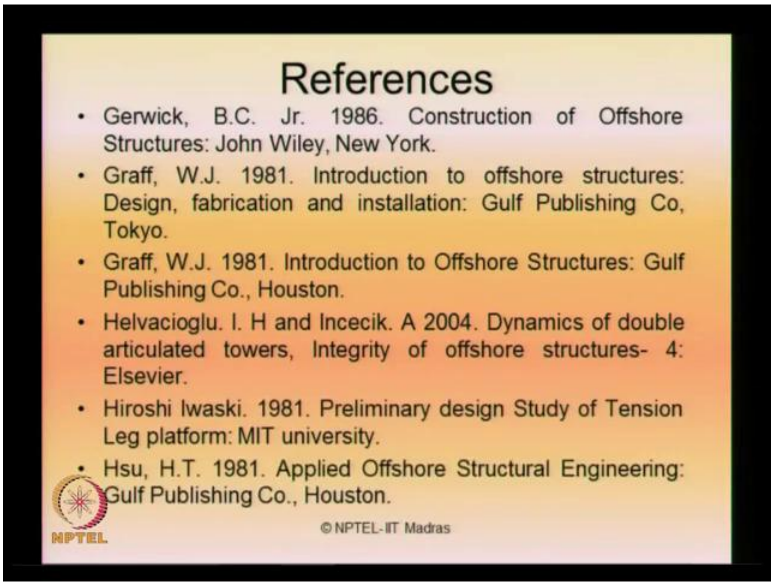

Please, read this text books for more understanding on the points what we covered in this lecture.

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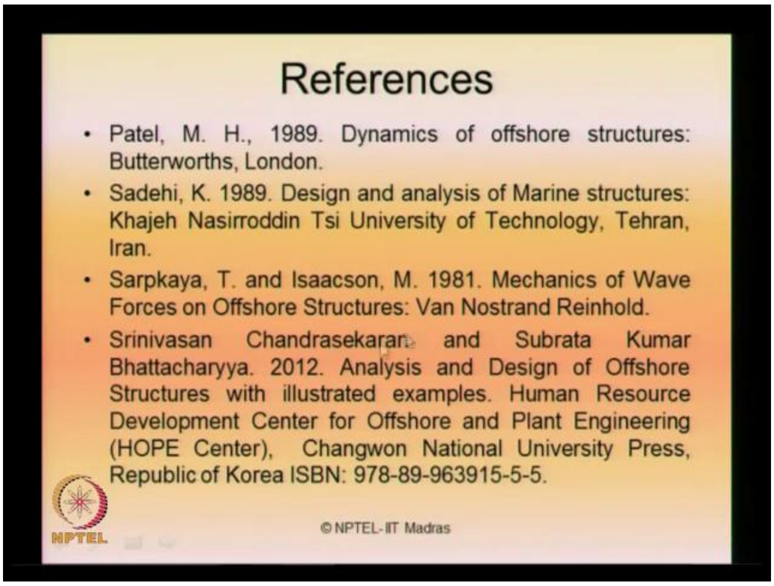

Interestingly youcan also refer to one of my books which is available which also speaks about these kinds of analysis and design aspects in blockage factors,which is written by myself and SKBhattacharyya of department ofocean engineering,IITMadras.All reference are equally important,it is not because I am referring my paper here or my book here.So, my appeal to the viewers will be read this original source of reference.If you find out anything missed out anything in this lecture do write to me at NPTEL,IITMadras.

So, in this lecture to introduce you about FSI, what is the wake region, what is effect of reduction in velocity, how the Reynolds number and Strouhal number can influence distinct frequencies of vibration and as a structure engineer the design of marine structures, we are bothered about the response of the structure to the exertion forces or the force exerted on the structure as a component of FSI, we are not focusing more intensively on the hydrodynamic aspect of FSI on to the members.So, thank you very much, we will discuss FSI continuously in next lecture.