**Dynamics of Ocean Structures**
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**Lecture – 29**
**Fluid Structure Interaction**

So, this is the module 2 lecture which we will talk about FSI fluid structure interaction. Then we will deal with the dynamics of detailed dynamic analysis of offshore structures. We will take up examples of different platforms and will handle both the LHS and RHS of the equation of motion. That is, we will derive the mass matrix stiffness matrix and damping matrices of the given system. We will also talk about how to estimate f of t of course you cannot solve this x of t because it needs lot of iterations. So, we will use numerical solutions for this, and you will show the results from the research proper directly. Before we get into understand how to do a dynamic analysis of offshore platforms directly.

Let us try to talk about in the design perspective, what will be the influence on fluid structure interaction. So, actually if you look at the first module lectures, where we are talking about different kinds of forces acting on structural systems. We have already said the wave force is one of the important contributors, for shore platforms, which is irregular and prescribed and random dynamic loading acting on the structure. There are many theories available in the literature define they what about the water body kinematics sees for salivation which varies with velocity current presence etcetera.

So, we can use different ideal equations, to find out the velocity and acceleration, of the water particle. Then we will also try to know how to get the forces, lateral forces expected on the structural member by these wave interaction. But now I will talk about the design perspective on fluid structure interaction. Where we will say what are those important contributors when in a fluid flow a structure member remains in a fluid rigid. So, what will be the interference effects on structural member on the fluid flow we all know that as long as there is no obstruction, by any member, on any fluid or any domain, no force is excited. For example, wind blows from left to right on this hall and there is no obstruction to the wind flow wind that will not exert any force.

Wind or any lateral force will be excited, on the member only when there is obstruction caused to the fluid flow. So, let us talk about what is that obstruction caused by the presence of member. If the member is vertical, if the member is horizontal, if the member is large diameter, if the member is fixed at the bottom member is floating what would be the interference effects of this. And how design perspective is important in fluid structure interaction. Because it is important to know, that what will be the forces arising from different position of the members, and a different category, if you really wanted to know f of t in equation of motion.

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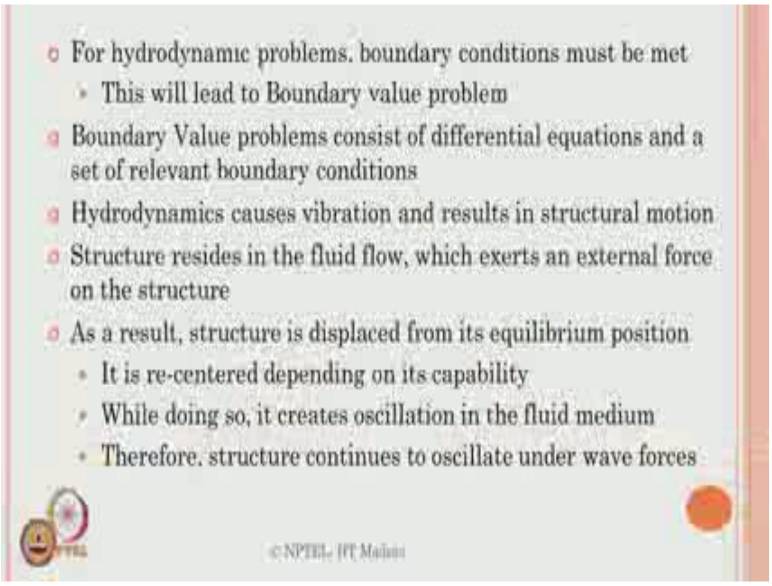


So, it is very clear to understand basically, for a hydrodynamic problem, we all know that boundary conditions must be met. If you look at the boundary condition implementations on a hydrodynamic problem, it will ultimately land up to what we call b v p is which is classified as boundary value problems.

Now, BVP consisting of differential equations, and of course, a set of relevant boundary conditions, which has got to be a met, to solve the boundary value problems. Now we are bothered about this laid, or this point onwards. Hydrodynamics actually causes vibration. The moment it causes vibration, if will result in a structural motion. The moment structures starts moving in the regime of fluid flow, there is external action acting on the member. Now this structure will be displaced whether a structure is fixed, whether structure is floating, complaint there is always at displacement on the structural member which is the result of the external force, acting on this member, which arises essentially from the vibration caused by hydrodynamic effects.

Now, we are not bothered about the boundary value effects. Because the boundary value effects will only modify, the characteristic of hydrodynamic forces. What we are both bothered here is, what is the influence of the structural displacement on the fluid domain. We are important we are looking only this part of it the moment is a structure displaced from it is equilibrium position. We all know for a given design, the structure will always try to re centered it itself. What does not mean is when the structure is displaced from it is equilibrium position, where the natural tendency in a design the structure, will try to come back to it is normal position.

Now, it cannot happen because, the structure can regain it is normal position only in the absence of external loads. Now the external loads in offshore systems are continuously present. There is no absence case considered therefore, re centering will always be an oscillatory motion. This oscillation will again cause a secondary force in the medium itself. Now there are 2 forces oscillated here. One the external force caused by the fluid flow on the member plus the result of the fluid flow, which is causing displacement in the member, which invokes equilibrium movement on the member, by re centering capability, which induce the secondary motion, which call oscillation. So, there are displacements, or causing vibrations, and oscillations. There are 2 important categories of aspects dynamic present, in FSI therefore, ultimately the structural member will continue to oscillate, under the action of wave forces.

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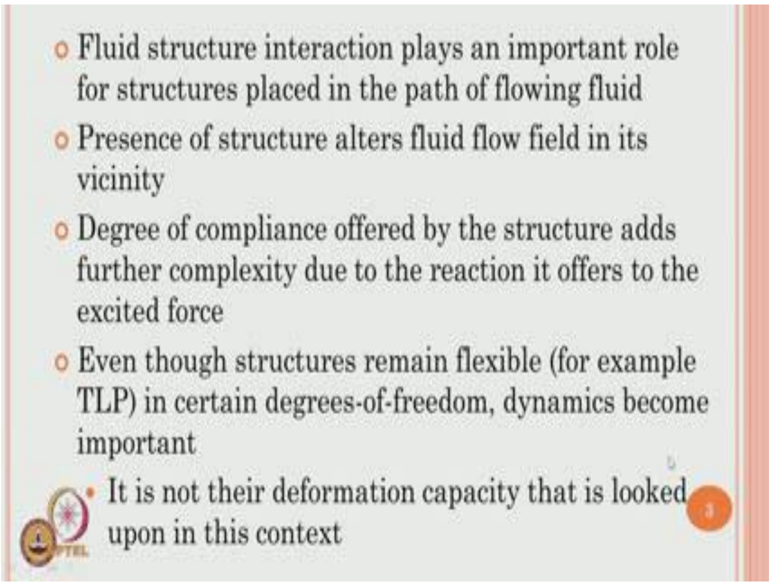


Having said this, we must understand that, fluid structure interaction place a very important role for structures placed in the path of flowing fluid. The presence of structure, significantly alters this flow filed, in it is vicinity. That is very important. Now depending upon the diameter of the member versus, the wave length effect, what we call d by l effect etcetera. The significant alteration of the structure, in the fluid field may not be present. So, what we mean to say is, the structural presence is felt only with in vicinity. So, in the closed regime, it is present. On the other hand if you are got 2 members place at a large distance or spaced as a large distance, the cascading effect of one on the another, caused by the fluid medium may not be influential. So, spacing d by l or the diameter versus wave length, all are important factors, now to understand that what would be the influence on the presence, of structure in the fluid medium.

Adding to it, the degree of compliance offered in the structure because the degree of compliance is nothing, but the support conditions given to the system, by the external boundaries. For example, it can be floating and anchor to the sea bed. It can be completely floating and controlled by a DPS system it can be rigidly fixed to the see bed etcetera. So, what is the boundary effect you are giving to the structural system, to avoid the degree of compliance, or to induce the degree of compliance, to a structural system, adds further complexity? Because this will create additional reaction forces, to the excited force, now even though the structures remained flexible for example, in TLP in certain degrees of freedom, dynamics still become important. Because it is not the deformation capacity that is looked upon it is actually the vibration caused by the medium is looked upon.

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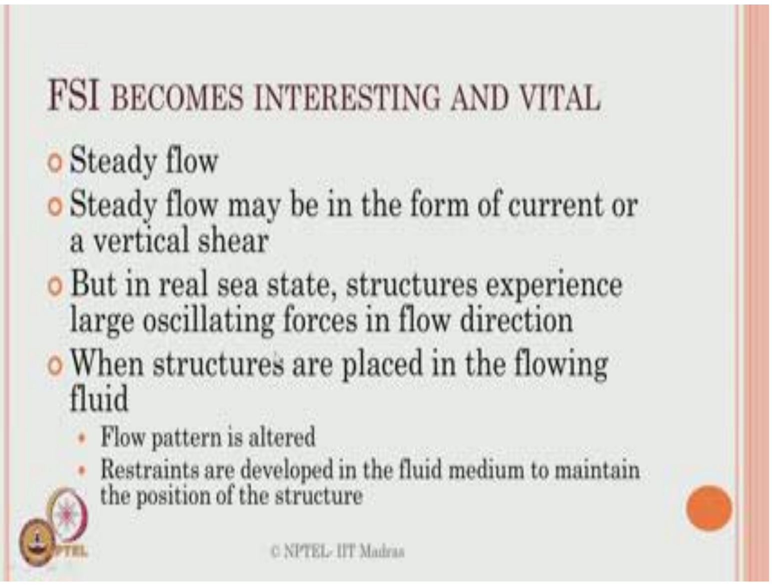


Therefore, fluid structure interaction becomes interesting and becomes vital for structures placed in the fluid medium, because it alters the steady flow steady flow may be in the form of current, or a vertical shear, because it induces vertical shear. It induce the displaced or differential pressure gradient, that is upstream and downstream side, which we will see the next slide, but in the real state structures experience large oscillating forces in the flow direction. Now there are 2 ways here. One is structures experience forces in the direction of flow medium one is in the transverse direction.

Now, when the structures are placed in the flowing fluid flow pattern is significantly altered, restraints are developed in the fluid medium to maintain the position of the structure. Because the moment you try to push the structure may start exerting it is boundary value limitations to the fluid medium itself.

So, that will cause an additional reaction, which will induce force on the medium back and depending upon who is the winner either the structure is effected or the fluid medium is altered.

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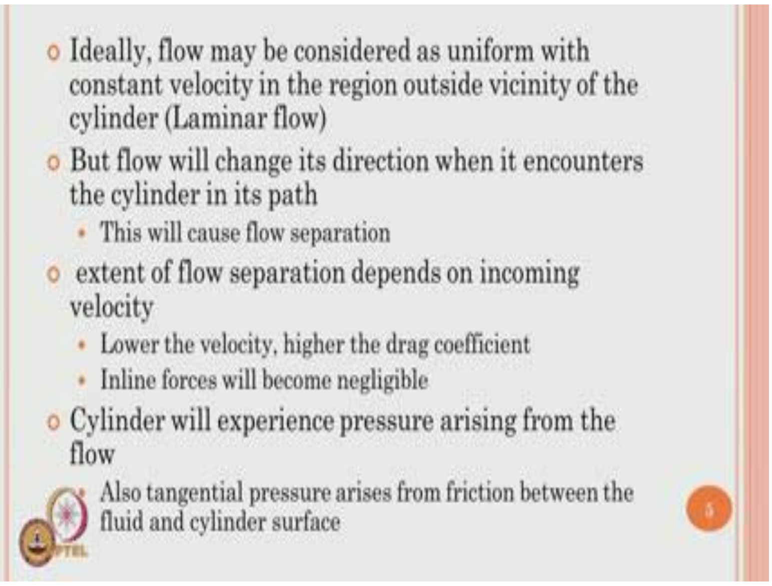


Ideally, flow may be considered as uniform, with constant velocity in the region outside the vicinity. Which we call technically in hydrodynamics as laminar flow, but flow with the change it is direction, when it encounters the cylinder in it is path. This will cause what is call flow separation. Now the extent of flow separation in a given system strictly depends on incoming velocity. Therefore, water body in a kinematics becomes very important. We will talk about this equation slightly later, in the end of the lecture. So, water body in kinematics, becomes very important because the extent of flow separation depends on that. One may ask me a question, what would be the influence on flow separation on the force exerted on the structure.

Once the flow is separated, then they will act as an independent medium there is an interaction between the flow lines. So, the extent of flow separation depends on incoming velocity lower, the velocity higher the drag coefficient. Now the drag coefficient which is called a cd which is very important item, which is now identically argued upon in the research friend, which you call as drag crisis. I will talk about that slightly later in the next slide. So, drag coefficient is enhanced. Inline forces will therefore, become negligible. Now cylinder will experience pressure which arises from this float at one and therefore, it also increases or creates tangential pressure which arises form friction between the fluid medium and the cylinder surface.

Now, the point of interest is here the cylinder surface, does not remain always smooth because of the marine growth deposits on the member. The moment the cylinder surface becomes rougher, it attracts more and more forces and therefore, the drag the initial coefficients keep on changing. Therefore, there is always the constant interaction between the structures even though the structure does not move. Now please understand the structure is or the member is fixed to the bottom. It offers reaction. This interaction interfaces the fluid medium. And that alters of the fluid flow actually. So, if you keep a member, may be fixed or floating, it will alter the fluid medium. The moment the fluid medium is altered it exerts forces. And it is a continuous process. And adding to this complexity the member is also moving, in terms of complaint systems, we are more secondary vibrations introduced a system which we call as oscillatory motion.

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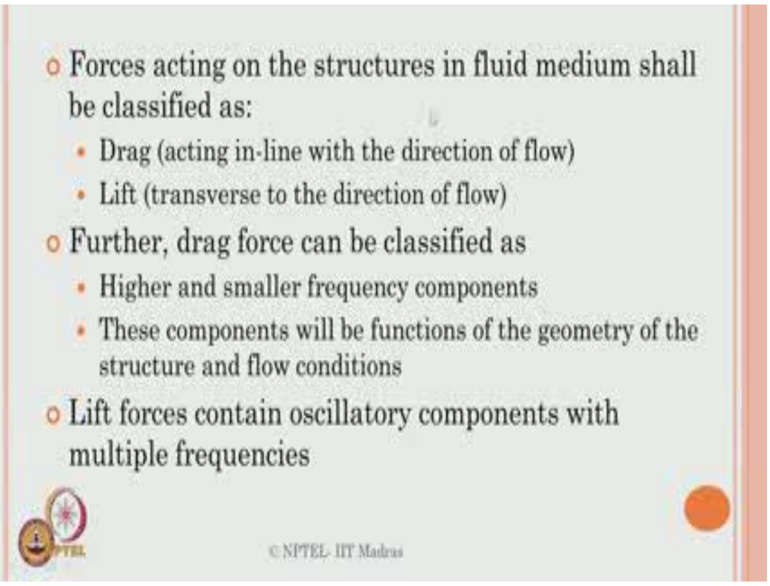


Therefore forces acting on the structures in the fluid medium shall be classified as 2 one is a drag and the lift forces. Drag is what we call in line force acting in the direction of flow. Lift is the transverse to the direction of flow. There are 2 ways here the flow will be characterizing the flows us on the member. Further the drag force can be classified as, higher and smaller frequency components, which we call as premium bringing responses later, in the later part of experiment TLP for dynamic analysis. Therefore, both the frequency components are important higher as well as smaller. These components will be of course, functions of the geometry of the given system and the flow condition. Now here the design becomes important.

If you really wanted to make design interceptive force comparability, in that case the geometry of the system places a very important. So, since the drag force is component of the functions of the geometry, which is the design interception in the force calculations. If the geometry of the system is very large, if we invoked additional forces because of it is size or the design itself. Now interestingly, you will understand in any classical structural design, forces are estimated on the members. And the members are designed for the given forces. Whereas here you see the geometry induces forces on the system itself. Because of it is interaction with the media. Now lift forces which are transverse to the direction of flow, contain oscillatory components, with multiple frequencies, which also important. Now you have a member which is vibrated, or which is vibrating, or which is displaced in the direction of flow because of the drag effect. Which is also be vibrating, with multiple frequencies, in the direction normal to the direction of flow this is transverse motion.

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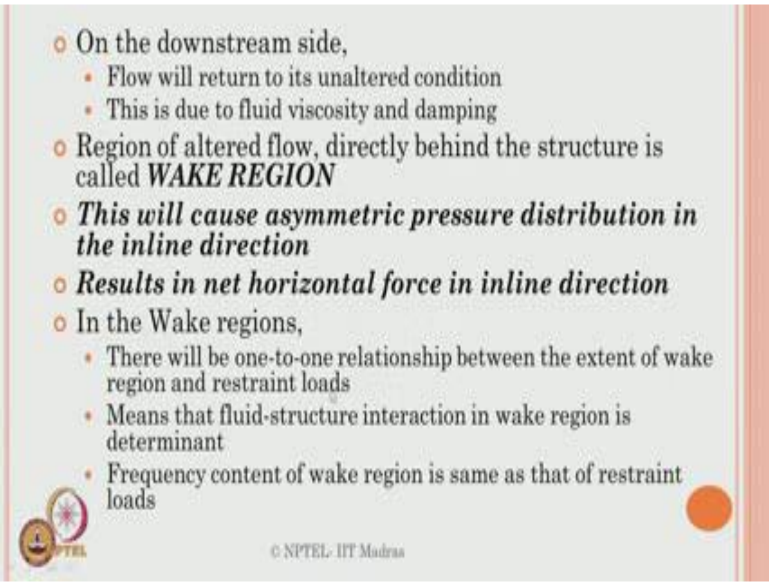


So, now the system or the member is interactive in both the components. Now, let us see what happens in the downstream side. One can understand or ask a question what we mean by a downstream side - let say I have a member.

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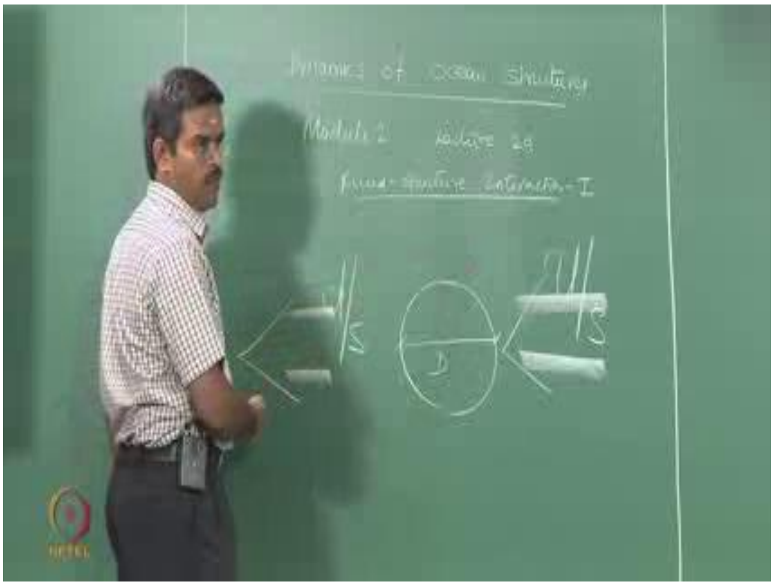

Let say we have the cylindrical member, maybe of a specific diameter d; the wave is approaching the system, in it is direction. And the wave leaves the platform or the member in this manner. Here hypothetically considering a unidirectional wave of course, we know that the direction of wave is not in unidirectional, it is multidirectional hypothetical if a laminar flow, let say it is a unidirectional wave. We call this has upstream side this has downstream side, for a unidirectional flow.

Now, on the downstream side, flow will return to it is unaltered condition because it leaves the member and then becomes unaltered after specific distance. This is due to the fluid viscosity. And a damping effect present in the media. Now the region of altered flow directly behind the structure is what we call as wake region. This is very important because this will cause asymmetric pressure distribution, in the inline direction of forces. This results in net horizontal force in inline direction. In the wake regions, there will be one to one relationship between the extent of wake region and restraint loads which means that fluid structure interaction in the wake region, is becoming determinant we can calculate this very in the closed form solution.

Frequency content, of the wake region is said same as that of the restraint loads. So, on the other hand you see here, the frequency content of the force component remains and assimilates a similar value as that of the restraint loads. It means you will see that, the wake region invoked forces, or in resonance with that of the restraint loads. So, this induces though in a multiple frequency, a kind of an additional force on the wake region which is on the downstream side only for a specific sector. Beyond which the flow becomes unaltered back again. So, it is not only the flow direction important. In line is not only the transverse direction. It is also the downstream side sectors this disturbing the flow medium which causes forces on the member.

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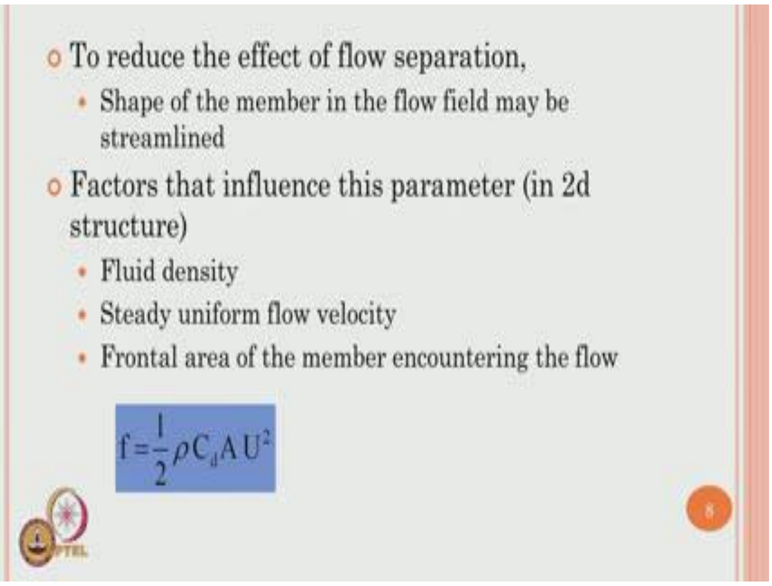


Now, one can ask me a question. I want to reduce the effect of flow separation. What should i. Do to reduce the effect, of flow separation in design people use to adopt shape of the member is one of the important parameter, to streamlined flow. Now one asks me a question what are the factors which influences this parameter in a 2 dimensional frame. Fluid density, steady uniform flow velocity, and the frontal area of the member encountering the flow, which is given by this equation where rho of courses sea water density, series the drag coefficient, a is the frontal area of the member, and use the uniform steady uniform flow velocity.

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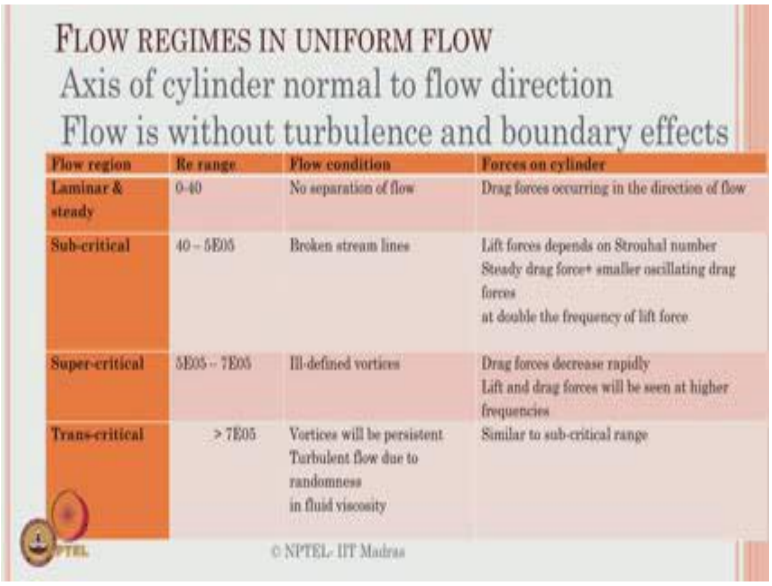


If you look at the flow regimes in uniform flow; let us consider axis of cylinder normal to the flow direction. Flow is without turbulence and boundary effects. Now when you talk about this hydro dynamics, people generally look at one important parameter, which we call as Reynolds number which is indicated as re here. Depending upon the range of the Reynolds number one classifies the flow conditions, and assimilates what are the kinds of forces which can come on the strain cylinder. For example, if the flow region remains laminar and steady, for which the verification is the Reynolds number should lie between 0 and 40, the flow condition shows there is no separation of flow.

If there is no separation of flow, the drag forces occurring in the direction of flow will be a predominant force, acting on a cylinder. On the other hand if the flow becomes sub critical. Which can be verified with Reynolds number ranging from 40 to 5 10 power 5 you will see that there are broken streamline generated in the flow field which induces lift forces. Which also of course, depends on Strouhal's number a steady drag force, plus small oscillating drag forces at double the frequency, of lift force will be now acting on the structure.

When the flow becomes super critical, where the Reynolds number ranges from 5 10 power 5 to 7 10 power 5. Then it will develop what we call ill defined vertices now drag forces decrease rapidly in the situation. Lift and drag forces will be seen at higher frequencies now. Now there is an extreme shift of the frequency, from the direction of regular to that of small frequency to that of double of the frequency of lift force to that of the higher frequency. Now one can see here depending upon the flow field, and flow condition, you will see that all components of the drag forces in lower and higher frequencies, and double the frequency are also present in the given system. If the flow becomes further trans critical where the Reynolds number exceeds 7 10 e power 5, in that case vertices will be present. The flow will come turbulent due to randomness in fluid viscosity, which results in sub critical range as that of you see here.

So, the lift forces we again created. So, depending upon the flow field mannerism, flosses or induced in the member, when the member interferes with the flow field.

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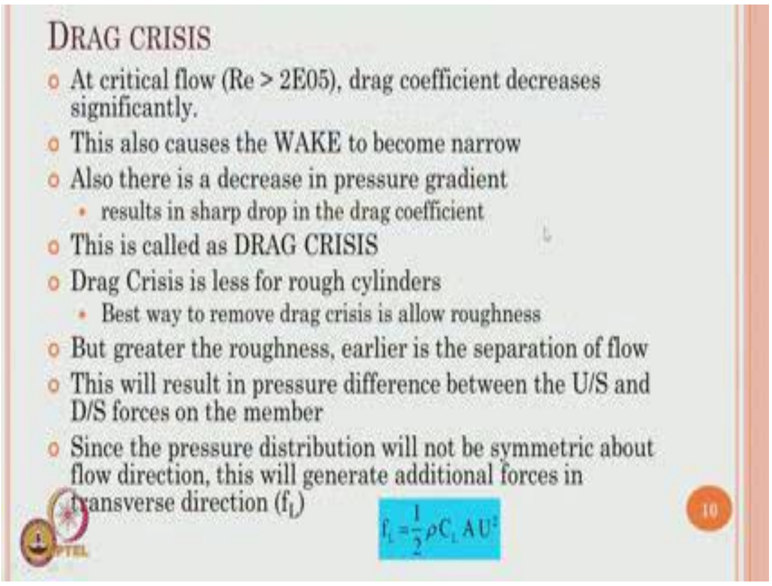


There is something called drag crisis in the literature which is very important for drag dominant structures in offshore platforms. At critical flow for example, the Reynolds number exceeds 2 e power 5, then the drag coefficient decreases phenomenally. This also causes a wake to become very narrow.

When the wake becomes narrow this causes a decrease in pressure gradient. These decrease in pressure gradient, will results in sharp dropped in the drag coefficient. This is what we called as drag crisis. Now crisis is less for of course, rough cylinders therefore, as for the design people induced roughness in the cylinder surface. That is way you will say there are perforated members, or there are stampered members, or there are stripes placed on the members, which will induce surface roughness, which will decrease or the drag coefficient in the given system. Which is one of the design methodology for doing this, but greater the roughness the separation of the flow is earlier, when the flow get separated you will have the lift forces induce in the system automatically. So, one benefit creates one more demerit in the given system. So, this will result in pressure difference between upstream and downstream force in the member.

Since the pressure distribution is not symmetric about the flow direction, this will now generate additional forces what we call lift forces, which is given by the equation on the slide now. Where c l it is a lift coefficient and of course, a rho and u or as same as defined in the previous slide

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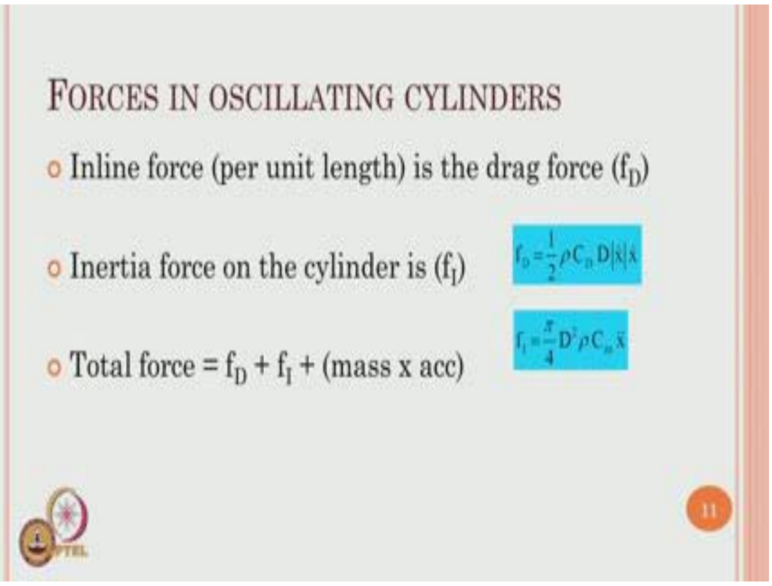


Now when you talk about oscillating cylinders, which I am not fix to the sea bed, there are 3 kinds of force generated one is what we call inline forces, what otherwise we call as drag force given by the equation available here. Other is the inertia force and the cylinder given by the equation available here again f I and fD. Now the total force in a given system the right hand side of the equation of motion, the summation of the drag force per unit length of the system, plus inertia force per unit length of the system, plus of course, the mass of the platform into acceleration of the structural system itself.

Now, there are 2 components here. Please understand f D and f I have of course, the velocity and oscillation components which arise from the flow field and this acceleration components from the structural system because structure is now oscillating. So, there are 2 components inherently represent in the system. One because the structural motion itself, one because of the oscillatory motion induced, by the interference of the system on the flow field. So, now, it is very interesting to know all of us that, the f of d is dimension protected by having one of the system modular here. So, that it can also cause reverse effects.

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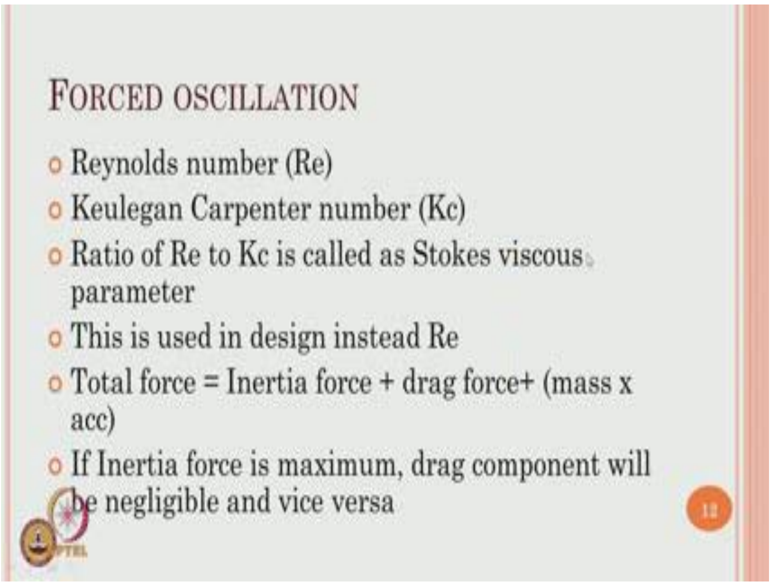


Now, we will talk about what we call forced oscillation which slowly depends on Reynolds number, and Keulegan carpenter number. But interestingly in design of offshore structures, people need the looks at this number independently, if you look at the ratio of this number. Which you call stokes viscous parameter. Which is ratio of re to kc this is actually used in the design in subsequent Reynolds number.

Now, the total force as you saw in the last slide, if the inertia force is arising from the system, plus drag force arising from the system, plus mass into acceleration, of the system itself. So, these 2 are from the medium. This is from the structural component. Of course, when the structural component does not move, this component becomes inefficient of course; this will be linearly present in the given system. Therefore, the right hand side of equation of motion, in the given dynamic system offshore structures will never be set to zero, if inertia of force is maximum interestingly, drag component will be negligible, and because vice versa that is what you seen in the research in the literature.

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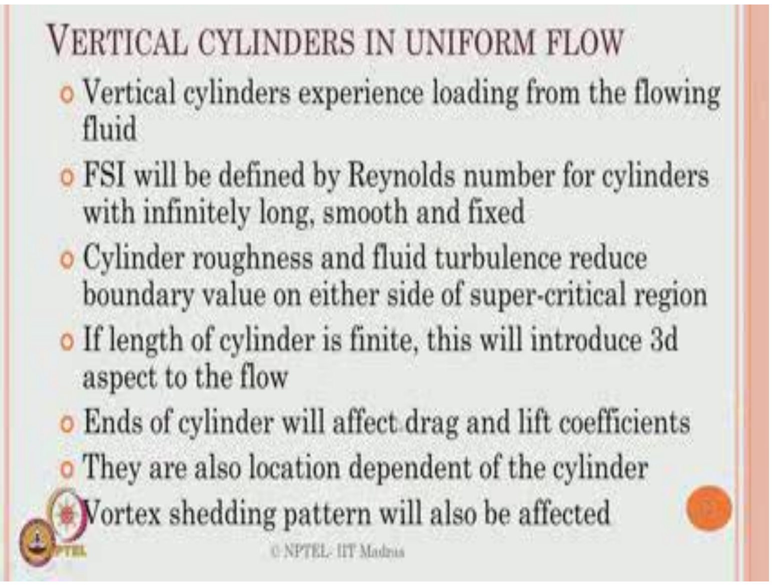


Now, let us talk about vertical cylinders in uniform flow. Vertical cylinders experience different kind of loading, from the flow in fluid. Fluid structure interaction will be different by Reynolds number for cylinders, with infinitely long smooth, and fixed at the bottom. The cylinder roughness and fluid turbulence reduce boundary value on either side of the sub critical region. If of course, the length of cylinder is finite, this will introduce 3 dimensional aspects, to the flow field. Ends of the cylinder will of course, significant affect on the drag and lift coefficients. Because your considered to be covered, in the original design. They are also location dependent of the cylinder. Therefore, the coordinate of the cylinder, or the coordinate of the cg of the cylinder, with respect to that of it is a boundary, because the important role to estimate these kinds of forces on the given system. Vortex shedding pattern will also be altered, depending upon the flow field surrounding the vertical cylinder.

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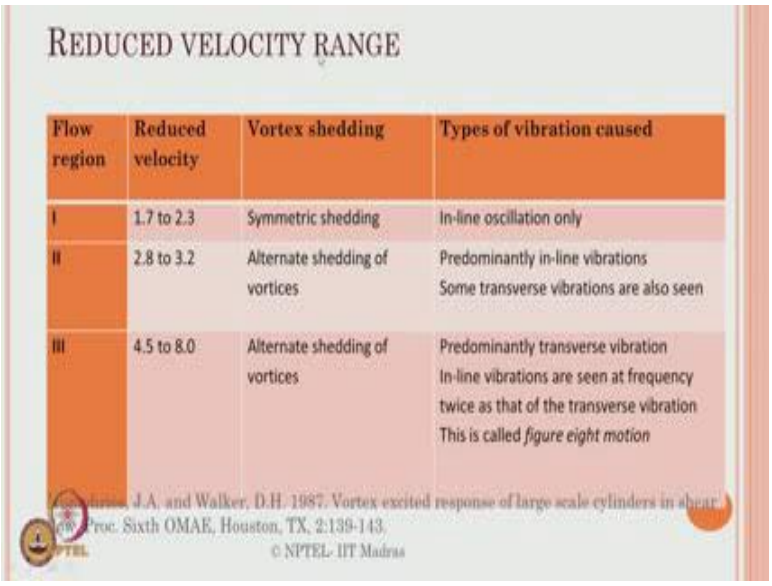


| Flow region | Reduced velocity | Vortex shedding | Types of vibration caused |
|---|---|---|---|
| I | 1.7 to 2.3 | Symmetric shedding | In-line oscillation only |
| II | 2.8 to 3.2 | Alternate shedding of vortices | Predominantly in-line vibrations<br>Some transverse vibrations are also seen |
| III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

Like in the case of horizontal cylinders, reduced velocity can also be seen for different ranges, for different flow regions categorize cd 1 2 and 3, has given by Hampshire’s and walker in 1987. The reduced velocity ranges from 1.7 to that of 8.0 which causes vortex shedding effect in the case of 1.7 to 2.3, where the flow regime is calculated as classical value 1 as given by Hampshire’s and walker. The vortex shedding becomes symmetric, which will result in inline oscillations only. Please understand we will talk about design of a given system, we must understand what frequency we must approach, for calculating the response of the system.

So, when your flow region is only, with the reduced velocity of 1 to 1.7 to 2.3 which causes symmetric shedding, it will result only in inline oscillation. Where as in flow region 3, where the reduced velocity can go as high as 8.0 it causes alternate shedding of vertices which you will cause transverse vibration. And inline vibrations are seen at frequency twice that of the transverse vibration which will result in what we called figure 8 motion of the structural system. So, here the stability of the system will be challenged.

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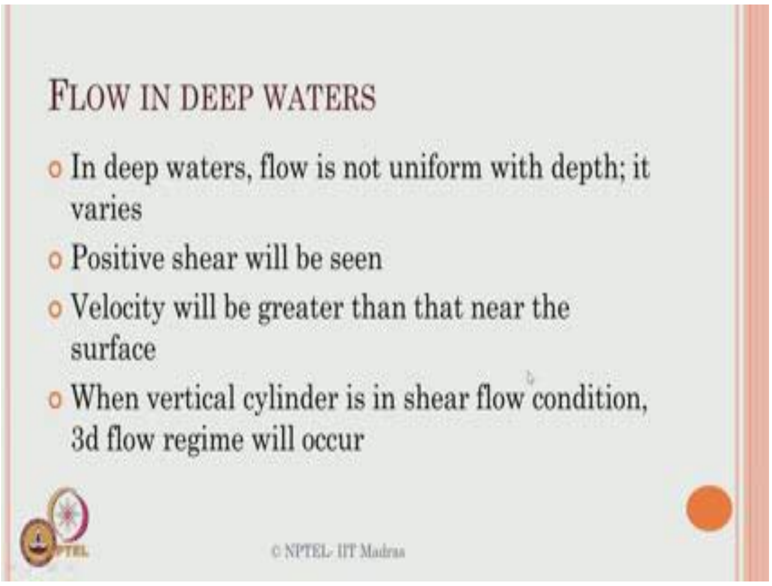


When we move on to shallow medium to deep waters, then the flow field slightly gets altered. In deep waters the flow is not uniform with the depth. It varies. We all know that because a water body is velocity in acceleration, keeps on challenging with respect to depth. It is maximum at the mean sea. And it is practically 0 when it goes through the sea bed.

Positive shear will be generated. Now interestingly shear is always a force, this try to divide the member in it is characterical strength. So, positive shear will be seen. I will show you the next slide how the shear is generated. Velocity will become greater than the near the surface, when the vertical cylinder is in shear flow condition, a 3d flow regime will now occur.

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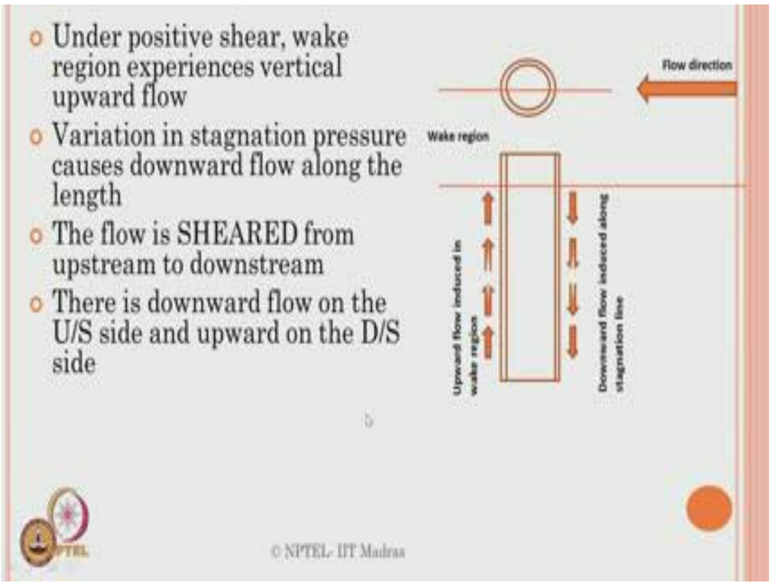


Now, let us quickly see under positive shear the wake region. We all know the wake region is the flow pass the cylinder. If this is my cylinder, placed in the flow region if this is this my elevation, and this is my flow direction. We all know the wake region is on the flow pass cylinder here. Under positive shear the wake region experiences vertical upward flow. It will try to lift the member you see here. There is a downward flow induce along the stagnation line in the upstream side. Where as in the downstream side it is going to create an upward induce flow in the wake region.

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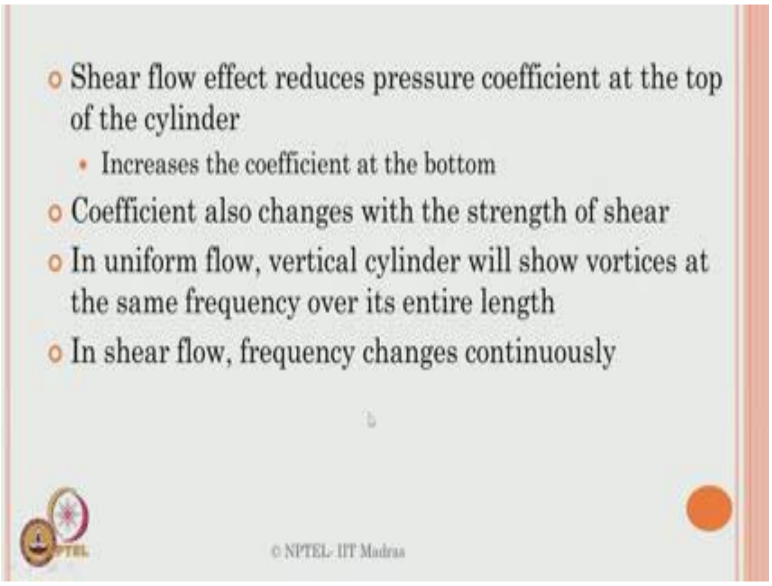


This is will result in, what we call as the sheared motion between the upstream and downstream. There is down flow downward flow on the upstream side, and upward from the downstream side which will cause a shear effect on the given member in the wake region. This shear flow effect reduces the pressure coefficient at the top of the cylinder. And of course, increases the coefficient at the bottom. Usually it is vice versa, where this effect is absent coefficient also changes, with the strength of the shear value. In uniform flow the vertical cylinder will show vertices at the same frequency, over it are entire length. It means the entire member will now become critical.

In shear flow frequencies changes continuously therefore, it can enter and exit the resonance domain of the member very frequently which results in what we call fatigue damage to the members.

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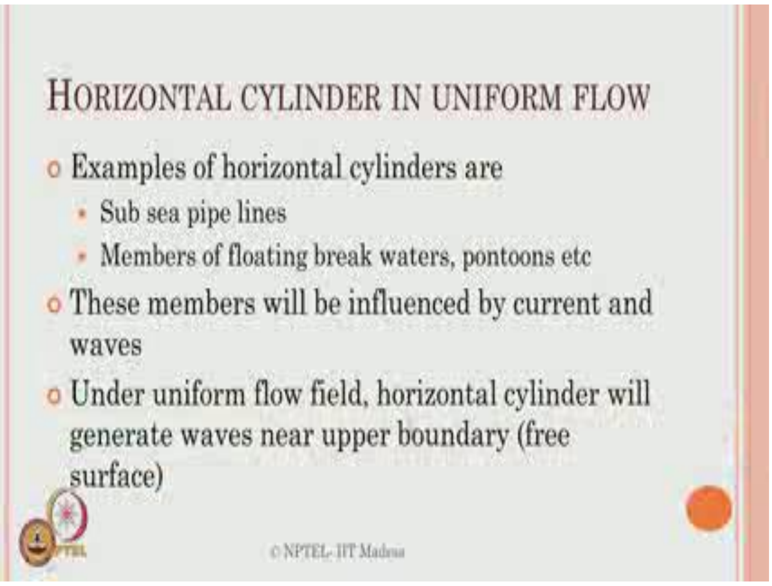


When we now place the cylinder horizontally for example, pontoon members in uniform flow, like subsea pipe lines pontoon members of floating break waters etcetera, in such cases these members will be influenced by the current and the waves together. Under uniform flow field horizontal cylinder will generate waves near the upper boundary, what we call as free surface effects.

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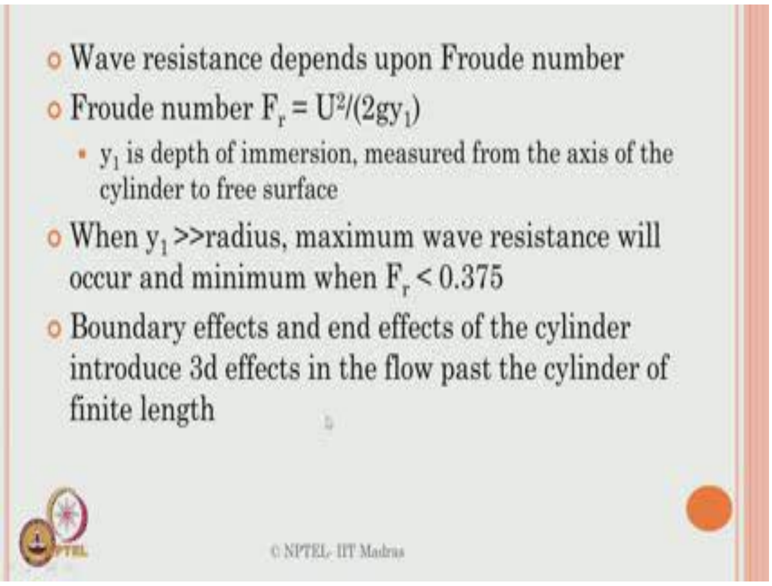

In such situation wave resistance, purely depends on the Froude's number as given in the equation here. Where y one is the depth of immersion of the member, measured from the axis of the cylinder, to the free surface. When this member or this value exceeds the radius of the member, the maximum wave resistance will occur and the minimum, when f r is less than 0.37 5 as see in the literature.

Now, the boundary effects and end effects of the cylinder introduce 3d effects in the flow past the cylinder, in the entire length of the member.

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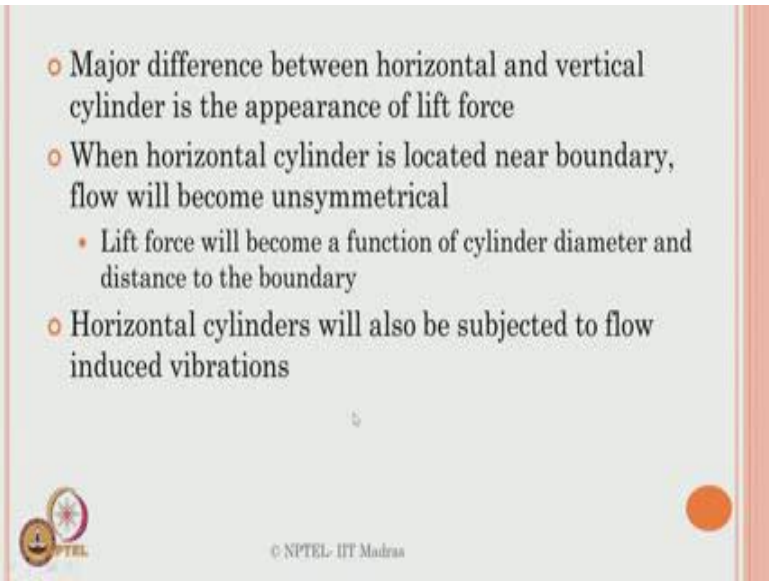


Which result in major difference between the horizontal and vertical cylinder is the appearance of lift force. When the horizontal cylinder is located near the boundary flow will become unsymmetric. Lift forces will become a function of cylinder diameter, and distance to that of the boundary from the axis of the member horizontal cylinders will also be subjected to flow induced vibrations which will cause secondary oscillation to the given system.

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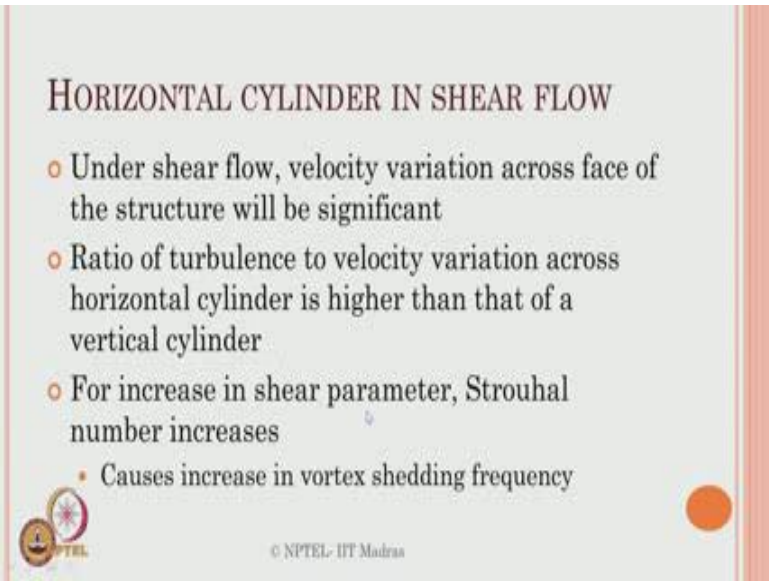


Horizontal cylinders, like vertical are also subjected to shear flow. Under shear flow the velocity variation across face of the structure will become significant. Ratio of turbulence to velocity variation across the cylinder is higher, than that of a vertical cylinder. So, therefore, now you see in a given system, like a TLP where the column members and pontoon members, one kind of member is having different kinds of shear flow compared to the other. It means the member has got disagreement in the pressure variation the upstream and downstream side whether the member is oriented vertically, or horizontally. For increase in shear parameter stochastic number therefore, increases.

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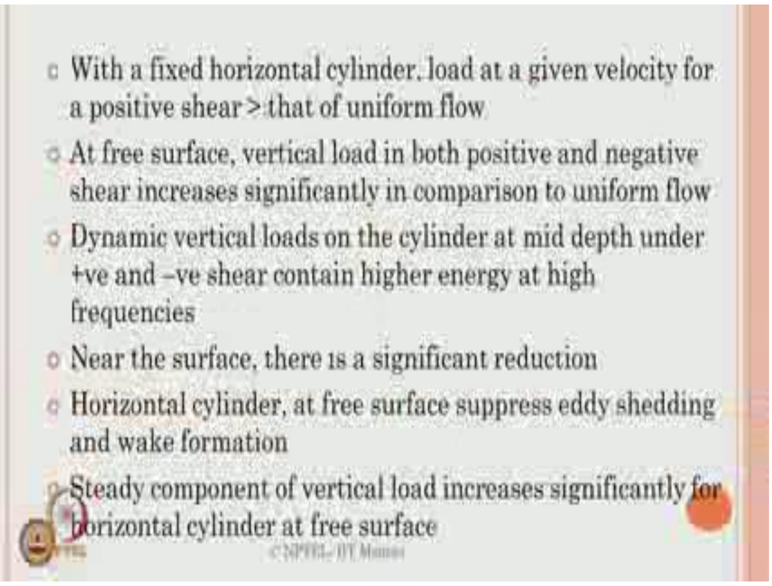


Now, when the stochastic number increases, this result in water shaded frequency, which will cause secondary vibration to the horizontal members. With a fixed horizontal cylinder, load at a given velocity for a positive shear, is generally seen more for an uniform flow. At a free surface the vertical load in both positive and negative shear increases significantly, in comparison to the uniform flow. The dynamic vertical loads on the cylinder at mid depth under positive and negative shear contain higher energy, at high frequencies. So, therefore, the near the surface, this effect is significantly reduced horizontal cylinder therefore, at free surface suppress eddy shedding effects, and wake formation is not see for members, on the free surface. The steady component of the vertical load increases significantly, for the horizontal cylinder at free surface.

So, there are 2 type of component. One is the vertical component which is called the lift component, or is the horizontal component in and force called drag component. So, depending upon the orientation of the member, how do we place the member y one from the free surface effect, you will have the difference in these kind of floats are also created in the given member.

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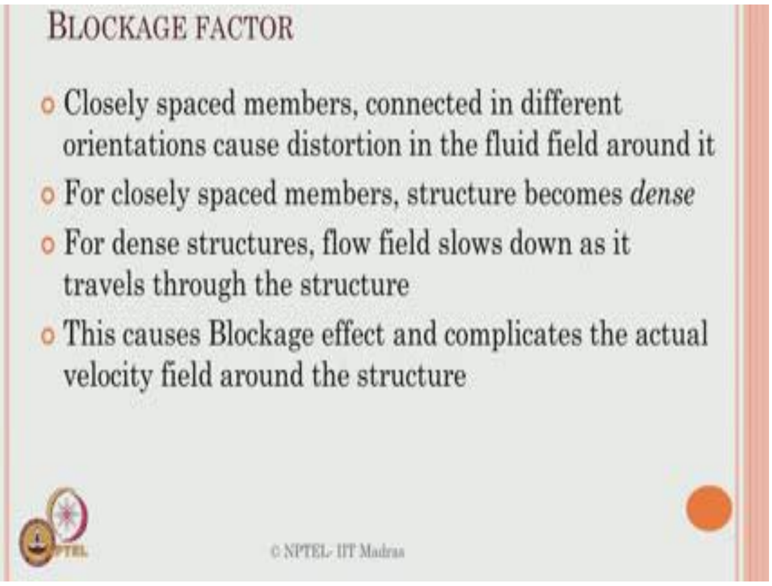


More interestingly, we also something called blockage factor. Now with this blockage factor become significant when I got closely spaced members. When the closely spaced members connected in different orientation, this causes distortion in the fluid field around it. For closely spaced members the structure is considered to be dense for a dense structures literature, flow filed slows down as it travels through the structure. When the flow field slows down this is what we call as blockage effect. This complicates the actual velocity field around the structure. Velocity is reduced by the flows increases.

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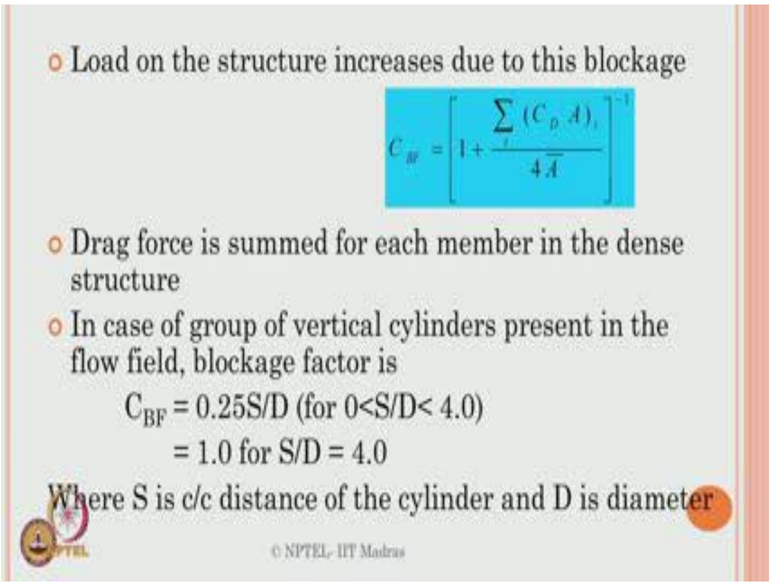


Now, let us coming back to the point or the load on the structure increases due to this blockage effect which is given by this equation where C BF is given by the blockage factor. Which is given by this equation are in case of group of vertical cylinders present in the flow filed you can also calculate C BF using this relationship where s is a center distance of the cylinder, and where d is the diameter of the cylinder.

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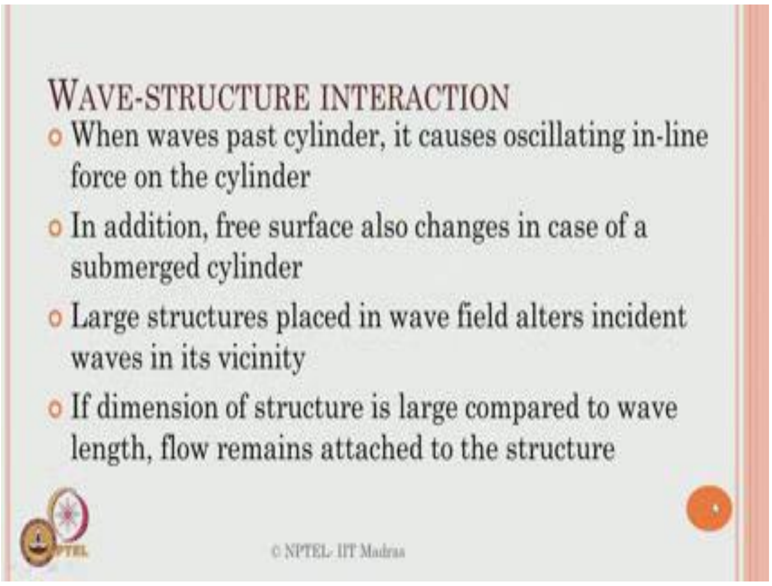

When we talk about wave structure interaction, is very important to know that, when the waves pass the cylinder it causes oscillating inline forces on the cylinder. In addition to that the free surface also changes in case of a submerged cylinder, because of the variables buoyancy or variables submergence effects, large structures place in wave filed alters incident waves in it is vicinity itself. The dimension of the structure is too large compared to the wave length, flow remains attached to the structure.

So, the flow remains attached means, when the flow is from left to right it has tendency it to take back the structural along the same direction. Therefore, the resonance after the structure will go null and wide.

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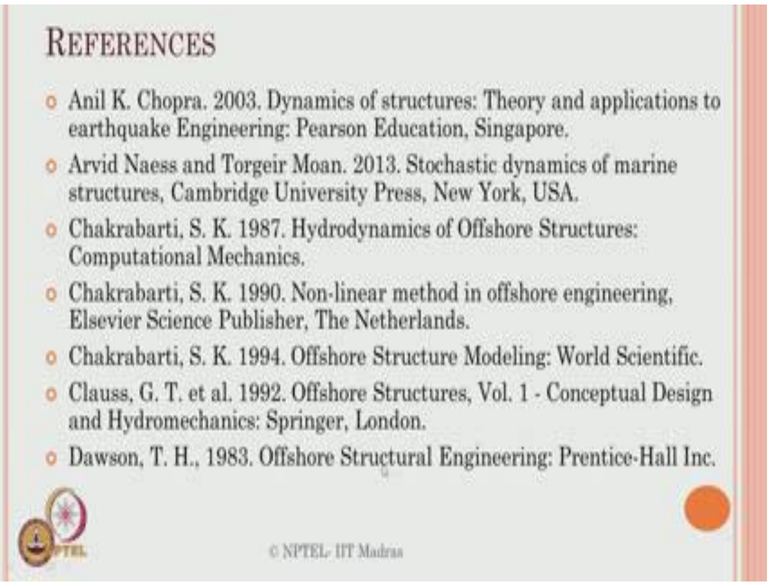


Of course the important components present in the structure in this lecture or given by these references are you see here which include some of the important components as we discussed in the design perspective given by me and Bhattacharya.

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Given by me in 2 of the recent books in Springer and CRC press which will be now coming up, now, adding to having a summary of the forces ,will act on the cylinder will give us to important non dimensional numbers, and some of the important effects of this forces in the summary as a table now.

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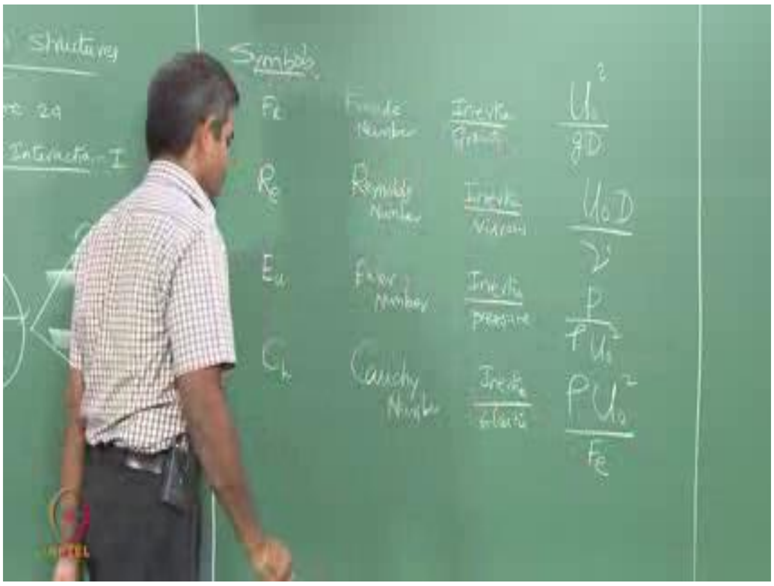

So, let us talk about some of the important symbols, and u forces used in terms of relationships. Let us say Froude's number which is given by fr which is ratio of inertia to gravity, the equation of course, of fr we all know that u 0 square by gd, x one is of course, the Reynolds number, given by re you already seen in force the Reynolds number in a given system is the ratio of inertia to viscous force, given by the relationship u 0 d by nu I will talk about these concepts slightly later. Next is important is an Euler number, given by Eu ratio of inertia to pressure.

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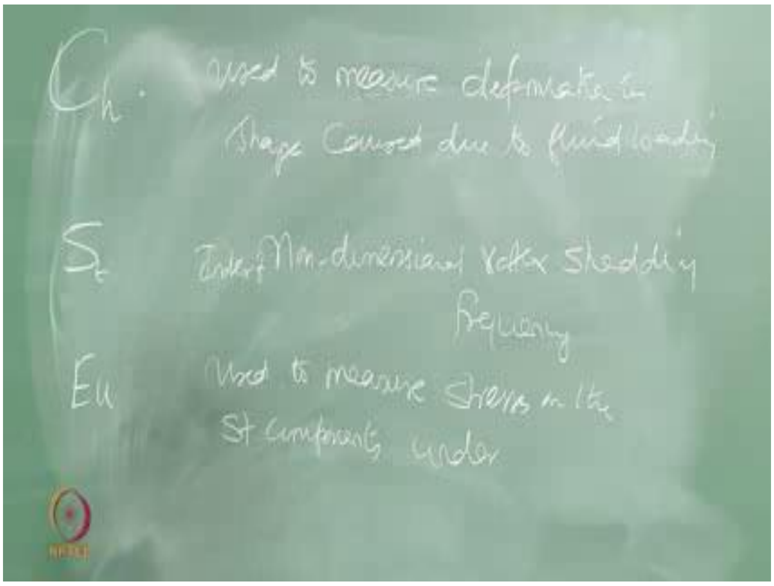


Cauchy number Ch inertia of to elastic Keulegan carpenter number k c. Drag to inertia , Strouhals number, given by St by u naught, where d diameter of the member, u naught flow velocity, out of this. Let us talk about these 3 numbers which are important for us. One is the Cauchy's number, or is Strouhals number. Euler's number talk about Cauchy's number, it is used to measure deformation in shape caused due to fluid in.

Strouhals number see index of non dimensional. Vortex shedding frequency Euler's number use to measure stresses on the structural components, under pressure load. In dynamic analysis of offshore platforms you normally come across, lot of non dimensional variants. Let us look at the summary of non dimensional variables.

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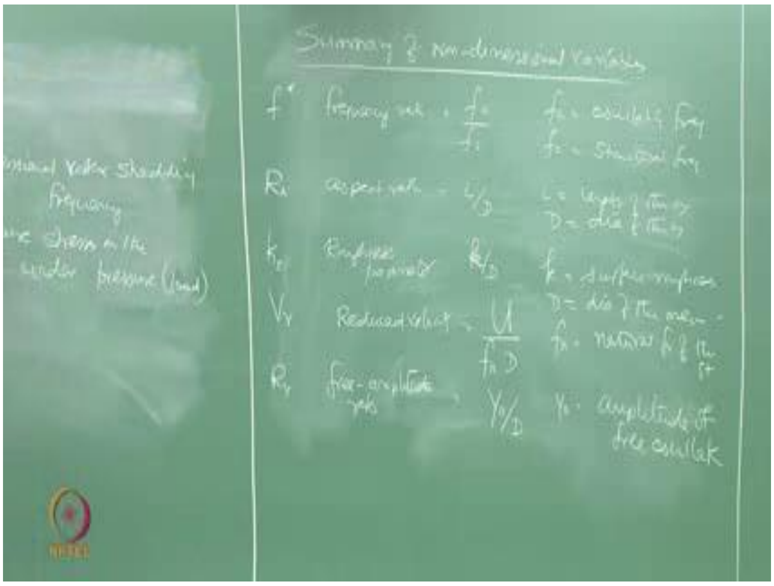


Which is important for us to understand because they will have it is an important role to play, frequency ratio, is actually oscillating frequency, to structural frequency. Or it is called aspect ratio which is the design parameter, which is R a, which is l over, d l length of the cylinder if d dia of it is a geometric parameter. The other one is roughness parameter, which is given as k s is given by k by d I think is small k plus male k is called surface roughness. And of course, d is the diameter. Of the something called reduced velocity which we talked about in the presentation recently which we call as v which is given by u by f and d. Where fn is a natural frequency of the structure R y called free amplitude ratio, which is given by y naught by d. Amplitude of free oscillation you are; obviously, see in most of the cases in these non dimensional variables are connecting the behavior of the flow field to that of the diameter.

Let say they are called design parameters also, because most of them connecting the diameter, you see elevation ratio.

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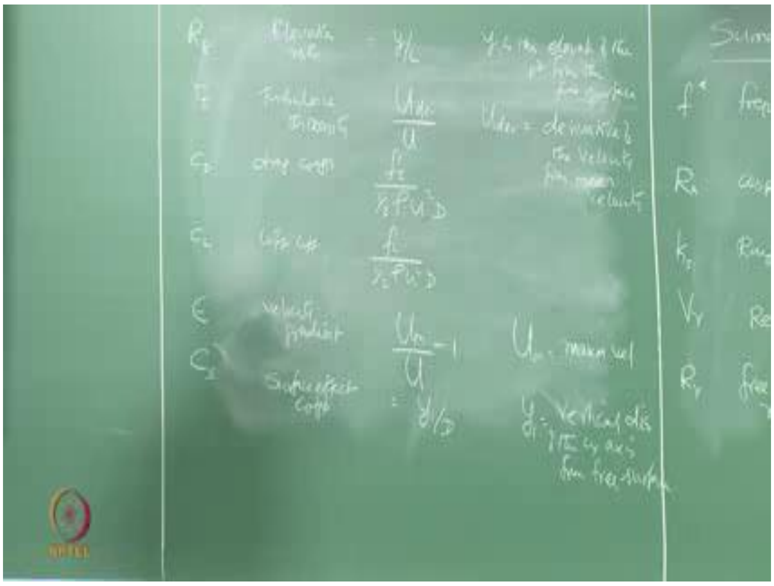

Which is re of course, this way confused a Reynolds number - y by l where y is the elevation of the point from the free surface. Turbulence intensity, u develops by u by u, where u developed is a derivative of the velocity, from mu velocity. Drag coefficient fi by half flow u square d we already saw the equation earlier. Lift coefficient fl by half rho u square d. Velocity gradient indicated by epsilon, which is um by u minus one where u m is a maximum velocity. Surface effect coefficient which is given as Cs it is given by y 1 by d, where y 1 is the vertical distance of the cylinder axis from the free surface.

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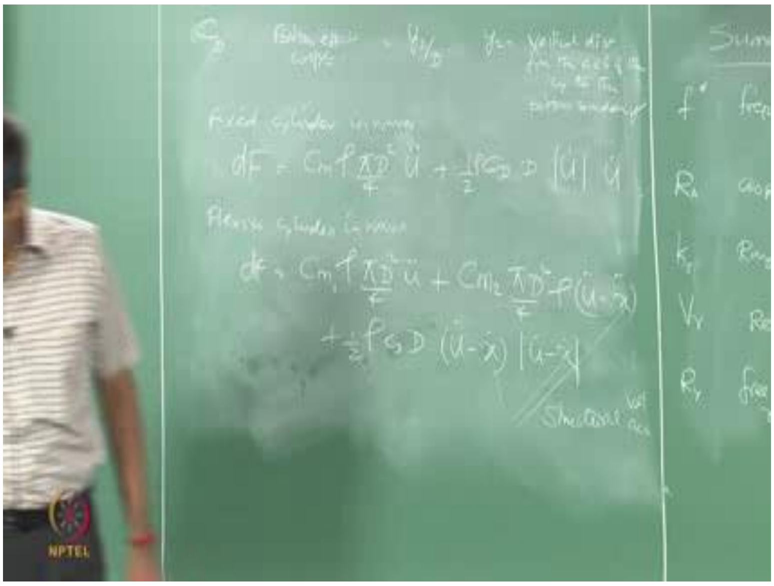

Bottom effect coefficient cb which is given by y 2 by d where y 2 the vertical distance from the cylinder will axis to the bottom boundary. This was a summary of this lecture. Ric from FSI fixes cylinder in waves will develop for experienced forces which are given by d f the elemental force on unit increment length of the member. Cm rho pi d square by 4. Flexible cylinders in waves will experience forces where the term v or let us say x. Please make it to x the term x relates to structural components may be velocity and exploration respectively whereas the term u refers to water particle. Now design one as interested to know what is the maximum force coming on the member f D max which is cd d relate.

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Similarly, inertia of force maximum expressed by the member, the small d indicates water depth of course, the capital d indicates diameter of the member. Maximum wave stiffness it is given by h by l. 0.14 tan hyperbolic kb now of course, k is a wave number. Which is given by 2 pi by l where, l is the wave length and so on. So, this will be a thumb rule for you just glossary of terms looking at different non dimensional variables, which are often seen in the right hand side of the equation motion we are solved we for the different kinds of forces. People used these terminologies or one must know how to compute them, and what is the influence on different kinds of numbers the variations and the participation when a fluid medium, is interfered by a member depending upon it is orientation. Vertical horizontal fixed floating etcetera. Just now we have seen in this lecture. So, this lecture summarizes the fluid structure and wave structure interaction, in terms of brief understanding, how the forces can be estimated on the members.

Thank you.