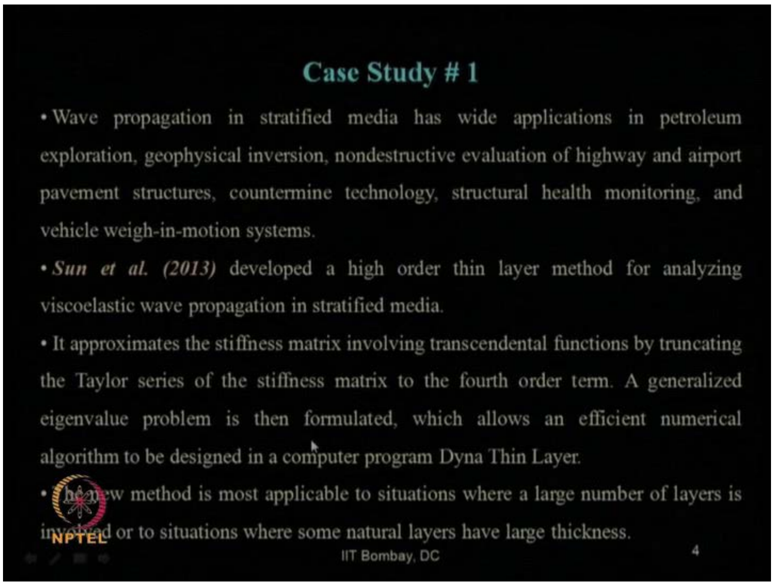
Geotechnical Earthquake Engineering
Prof. Deepankar Choudhury
Department of Civil Engineering
Indian Institute of Technology, Bombay

Module - 6
Lecture - 21
Dynamic Soil Properties

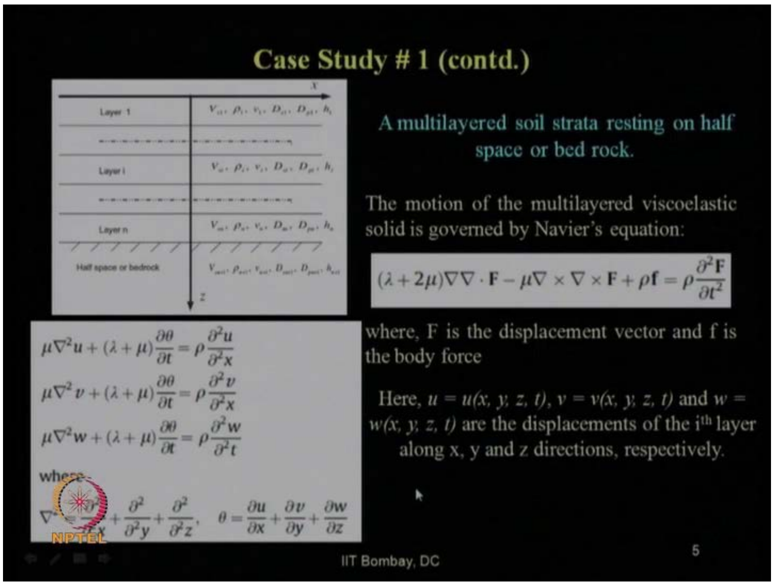
Let us start our today's lecture for NPTEL video course on geotechnical earthquake engineering. Let us look at the slide, we are currently going through our video course on geotechnical earthquake engineering, and we were discussing module number 5, which is wave propagation. So, in the previous lecture a quick recap, what we have learnt in our previous lecture.

(Refer Slide Time: 00:51)



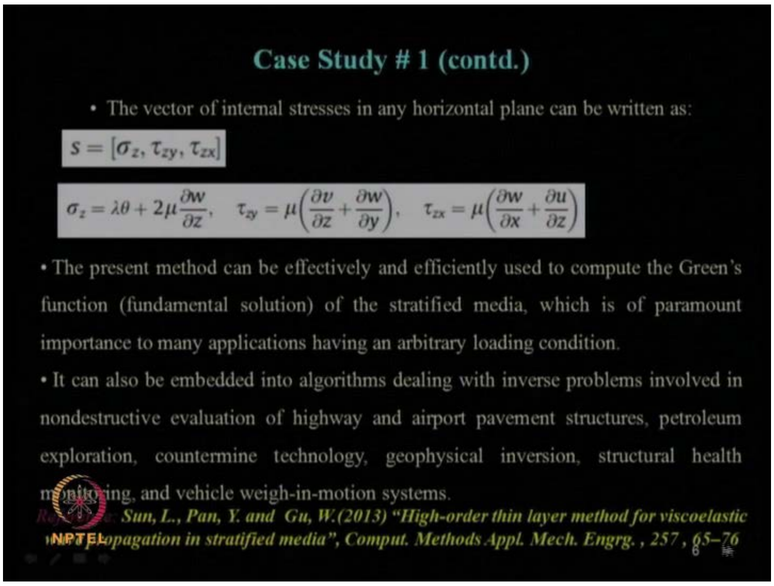
We discussed about various case studies for the wave propagation. The first case study was actually reported by Sun et al in 2013. This is wave propagation in stratified media, has wide applications in petroleum exploration, geophysical inversion, nondestructive evaluation of highway and airway, airport pavement structures, countermine technology, structural health monitoring and vehicle weigh-in-motion system. So, there are several applications of this wave propagation theory, which we have learnt in our previous couple of lectures.

(Refer Slide Time: 01:30)



So, this case study, what it reported, that if there are several layers of soil like this and those layers of soil are on the top of a elastic half space or a bed rock with material property of each layer as shown over here. Then a multilayered soil stator resting on elastic half space or bed rock, then the motion of the multilayered viscoelastic system is governed by the Navier's equation. So, this is the common known form of the Navier's equation.

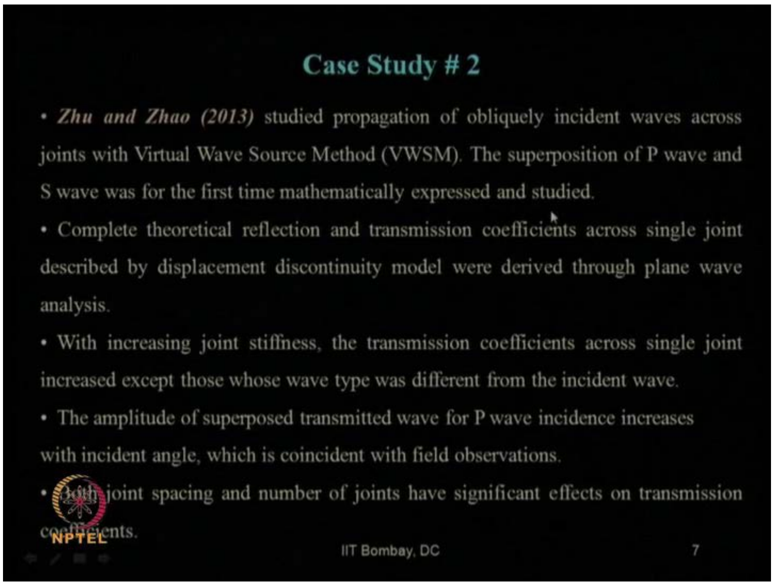
(Refer Slide Time: 02:07)



Now, the vector of internal stresses in any horizontal plane, that can be written in this form, which gives us the normal stress and two shear stresses in Z direction and the present method can be effectively and efficiently used to compute the Green's function. That is the fundamental solution of this stratified media, which is of paramount importance to many applications, as we have mentioned just now, and it can also be embedded into algorithms dealing with inverse problems involved in the nondestructive evaluation of highway and airport pavement structures and other applications as we have detailed.

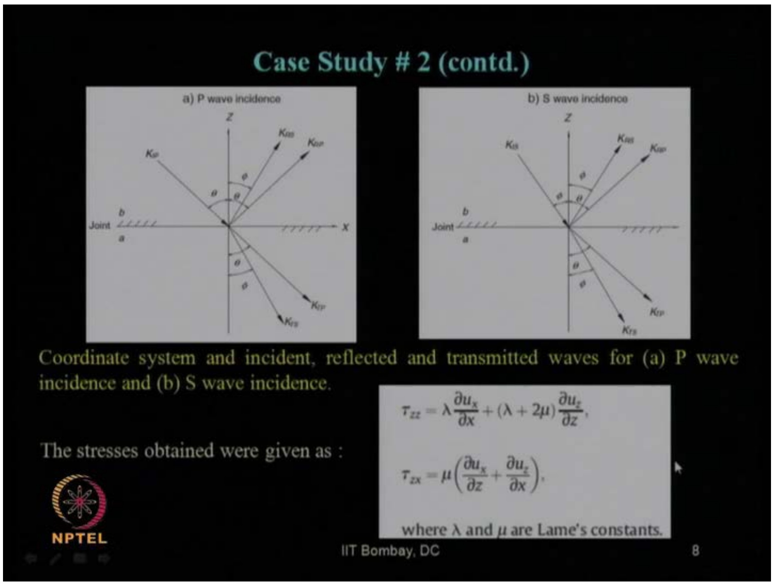
So far, the detailed knowledge about this case study one can refer to this reference, which is shown over here, Sun et al, 2013. This is published in the journal computational methods and applied mechanical engineering; this is the volume number and page numbers.

(Refer Slide Time: 03:12)



Then, in our previous lecture we also discussed about second case study, which was reported by Zhu and Zhao in 2013. They studied propagation of obliquely incident waves across joints with virtual wave source method. So, they have introduced this method of VWSM and the superposition of this P wave and S wave was the, for the first time mathematically expressed and studied in their research.

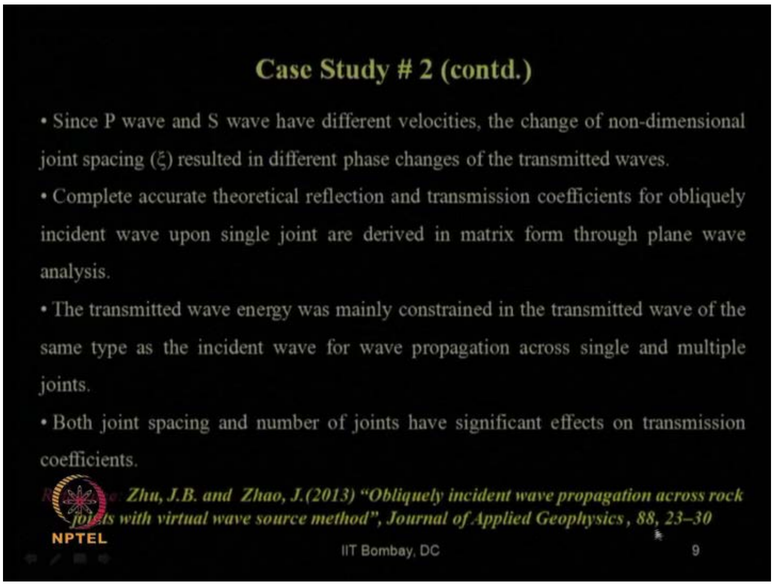
(Refer Slide Time: 03:44)



So, one can see from this slide; that is, in a joint, in a junction of two layers, if P wave incident comes, then how the S wave and P wave get refracted and reflected back in the same and the other media is known and shown by this slide. Similarly, for S wave incidence also this occurs.

So, the coordinate system and incident reflected and transmitted waves for P wave and S wave incident waves are shown in this slide and the stresses obtained can be computed using these equations knowing the Lame's constant. So, this way the combined effect of P wave and S wave can be obtained from the original incident wave of P and S wave.

(Refer Slide Time: 04:34)



So, since the P wave and S wave have different velocities, as we already have discussed, the change of non-dimensional joint spacing resulted in different phase changes of the transmitted waves; that is, it is not that. At the same time, both the waves are going to get transmitted in the other media; there will be a lag between the two.

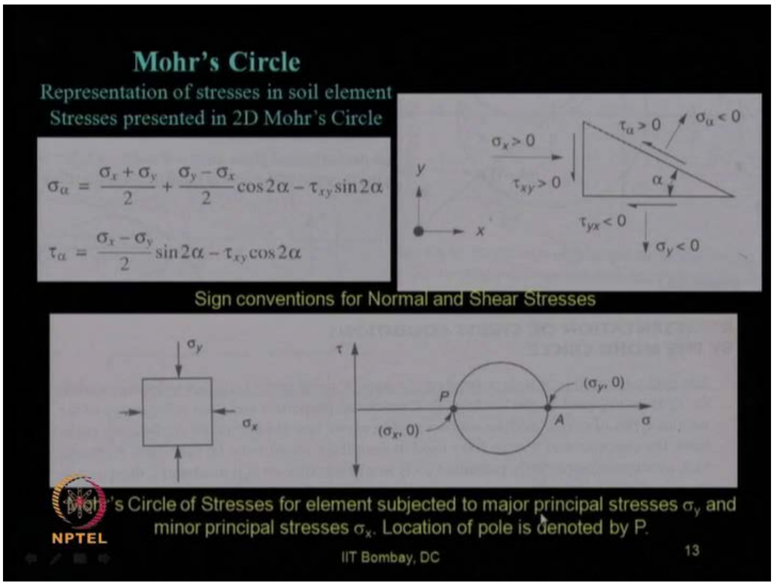
Complete accurate theoretical reflection and transmission coefficients for obliquely incident wave upon joint, single joint are derived in matrix form through plane wave analysis. And the transmitted wave was mainly constrained in the transmitted wave of the same type as incident wave for wave propagation across the single and multiple joints and both joints spacing and number of joints have significant effects on the transmission coefficient.

So, one can get the details in this published paper by Zhu and Zhao 2013. It is published in the journal of Applied Geophysics; this is the volume number and page number. So, with that we have completed in our previous lecture module number 5.

Now, let us start our today's lecture with next module, that is, module number 6. In this next module, module 6, we will discuss about the dynamic soil properties. So, for module 6 on dynamic soil properties I will like to tell this reference, that is, the NPTEL video course on soil dynamics, which also has been developed by me and in that soil dynamics video course of NPTEL one can go through the module number 4. There is a thorough discussion about these dynamic soil properties.

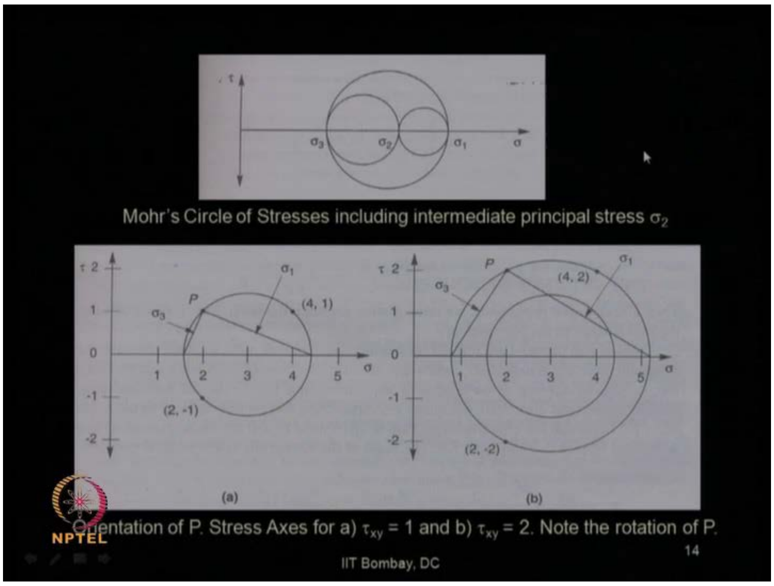
So, for the sake of completeness of the current video course on geotechnical earthquake engineering, I will quickly go through very important part of the dynamic soil properties and further more few developments and which are related to the geotechnical earthquake engineering problem liquefaction hazards study, the shear wave velocity mapping, etcetera in this module. But most of the basic part of this dynamic soil properties has been covered in my another video course on soil dynamics in the module number 4 of that course. So, I will request all the viewers of this course to also go through the course on soil dynamics video course to find out the details on basics about the dynamic soil properties.

(Refer Slide Time: 07:17)



So, we know, that through Mohr’s circle one can represent the stresses in a soil element and representation of the stresses in soil element we generally do using this two-dimensional Mohr’s circle representation. So, when we are considering two dimensional stresses like sigma X and sigma Y like this and we plot it in the standard shear stress versus normal stress plot, we can draw the position of the stresses of any soil element in this fashion, which is nothing but Mohr’s circle, and we can find out the pole of that Mohr’s circle depending on, on which plane, which stresses are acting.

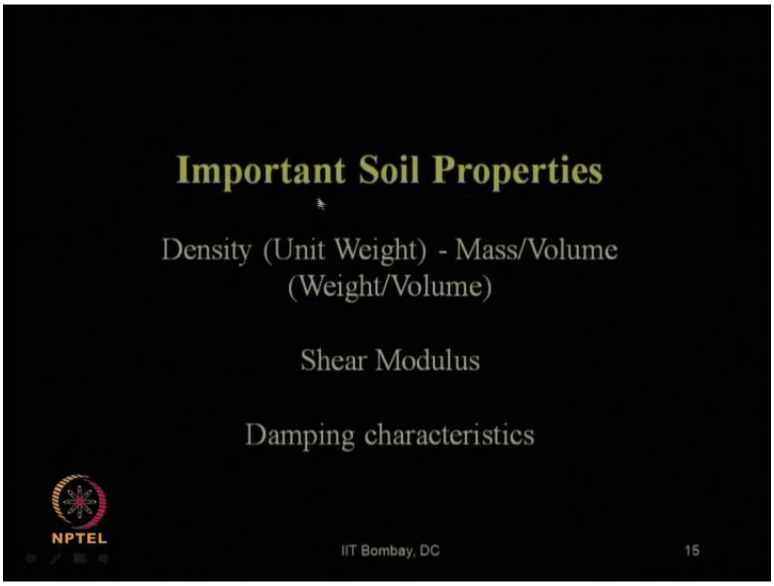
(Refer Slide Time: 08:02)



Now, the same Mohr’s circle, that is, two-dimensional operation of that Mohr’s circle, representation of the Mohr’s circle can be done for three-dimensional stresses also, that is, if we have three-dimensional principal stresses like sigma 1, sigma 2 and sigma 3 in a soil element, which is pretty common and in the case of dynamic problems we will mostly get the three-dimensional stresses, different not like in static case, where we mostly consider sigma 1 and is different than sigma 2 and sigma 3. And we consider sigma 2 and sigma 3 are equal, that is why we deal with mostly two-dimensional stresses or two principal stresses.

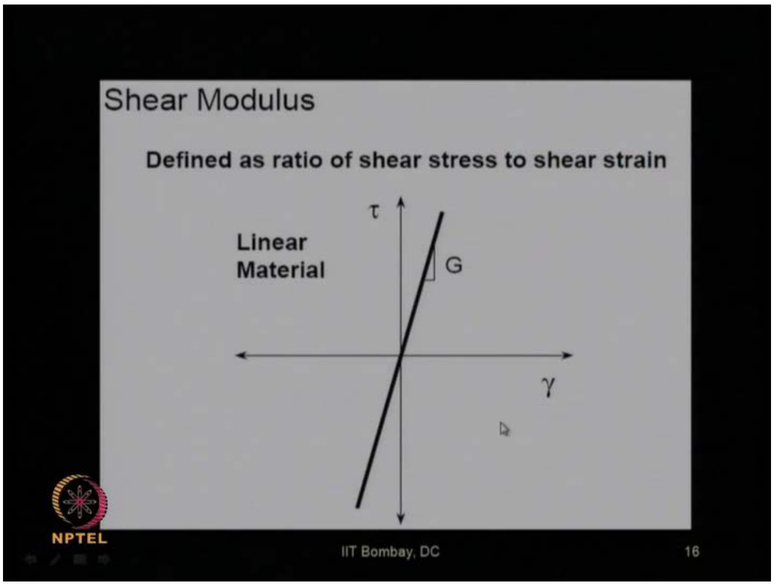
But in this case of dynamics we generally will have three different distinct stresses, principal stresses. One is major principle stress, another minor principle stress and another one is intermediate principle stress. So, this is the way we can represent the three-dimensional stresses also through two-dimensional Mohr's circle representation, which has been discussed in the soil dynamics video course module number 4.

(Refer Slide Time: 09:12)



Now, what are the important soil properties when we are talking about the dynamic soil properties? So, for the dynamic soil property or dynamic soil characterization one must know first, the unit weight or the density of the soil, which is very important and basic parameter to know. As we know, density is nothing but mass per unit volume or unit weight is nothing but weight per unit volume. Other than this, the two major important soil properties under the dynamic loading conditions are shear modulus and the damping characteristics.

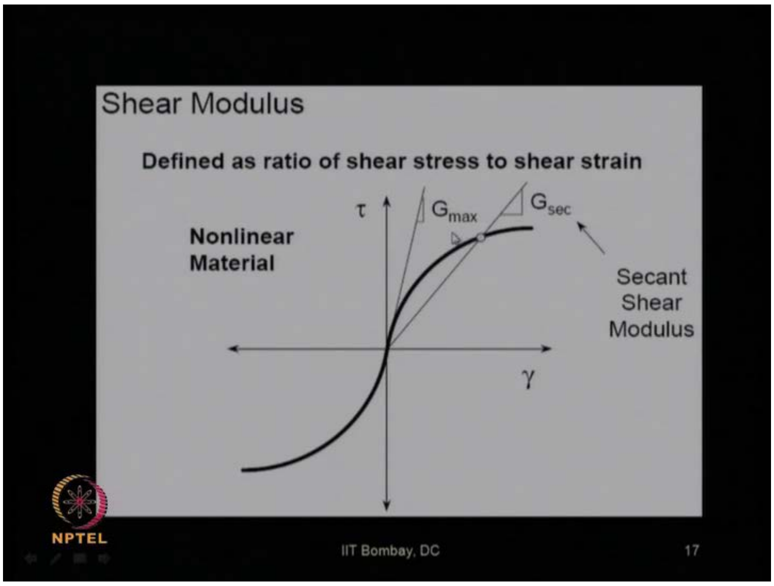
(Refer Slide Time: 09:56)



So, how to estimate these things let us discuss now. So, when we are talking about shear modulus, it is nothing but it is defined as the ratio of the shear stress to the shear strain. As we all know the definition of shear modulus is nothing but ratio of shear stress to shear strain. If we are handling with the linear material, linear material means, the material, which behaves linearly, that is, if we have some increment of the shear strain in this direction, then there will be a linear increment or increase in the shear stress also in this fashion.

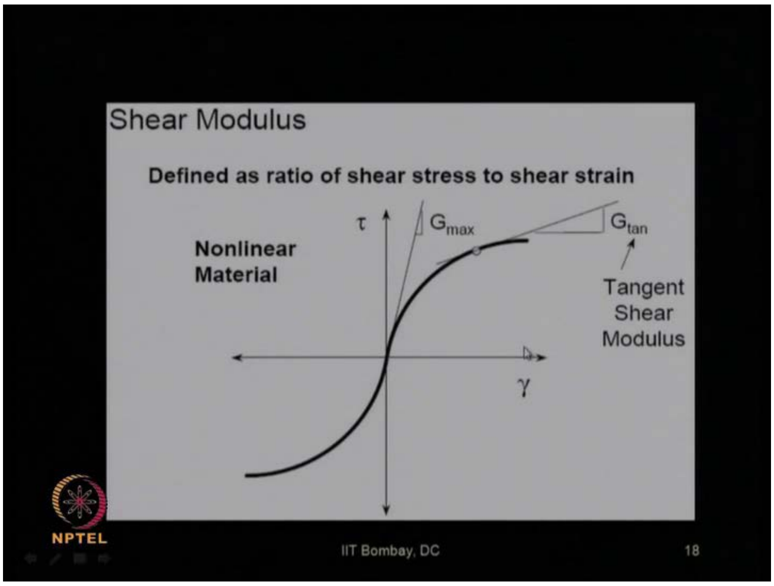
So, if we plot the shear stress versus shear strain for a linear material, it will be some line passing through origin like this and the slope of that line will give us the shear modulus, which is nothing but the ratio of this shear stress versus shear strain, but most of the cases in soil it is not a linear material, it is non-linear material. So, how the behavior actual representation of the shear stress versus shear strain for soil material will look like, that shows in the slide.

(Refer Slide Time: 11:01)



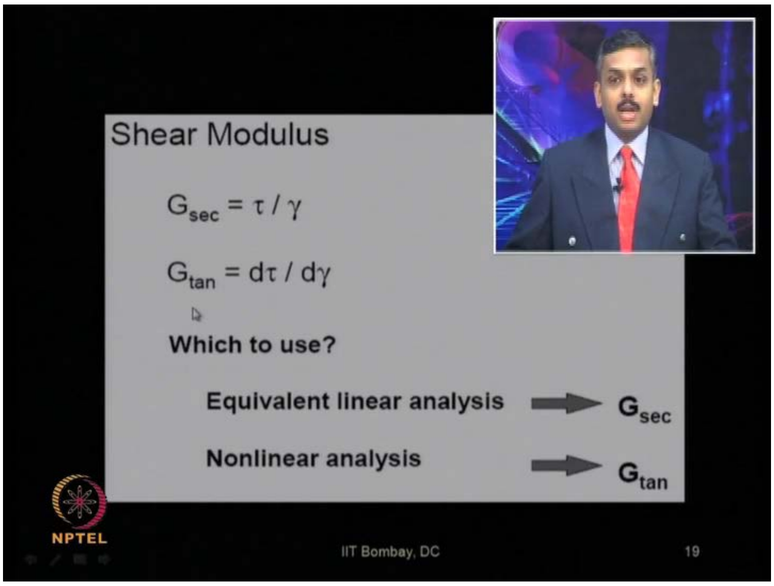
So, for non-linear material this behavior of shear stress versus shear strain will be non-linear, something like this, some curvy linear. In this case, now you can see, there will be two shear modulus which are shown over here: one is the tangent at this initial point of the curve, which is giving us nothing but the maximum value of the shear modulus, G max. And if we want to find out the shear modulus at any high strain values, at any high shear strain value, let us say at this shear strain, then if we join the origin with this point, the slope of that line will give us the G sec, which is known as secant shear modulus. So, this is representing the nonlinearity of the material to some extent, but not in an exact fashion because exact definition of shear modulus is the shear stress to shear strain at that point.

(Refer Slide Time: 12:10)



So, when we are taking a tangent at that point of the curve what slope we will get? That is known as G tan or tangent shear modulus. So, that is the actual shear modulus of any non-linear material at any point of shear strain. So, one can easily understand, that this tangent shear modulus is different at different point of shear strain and G max is nothing but the, it is also called initial tangent shear modulus. Why initial tangent shear modulus? Because it is the slope of this curve at the initial point or tangent at this initial point, so G max is also called initial tangent shear modulus.

(Refer Slide Time: 12:58)

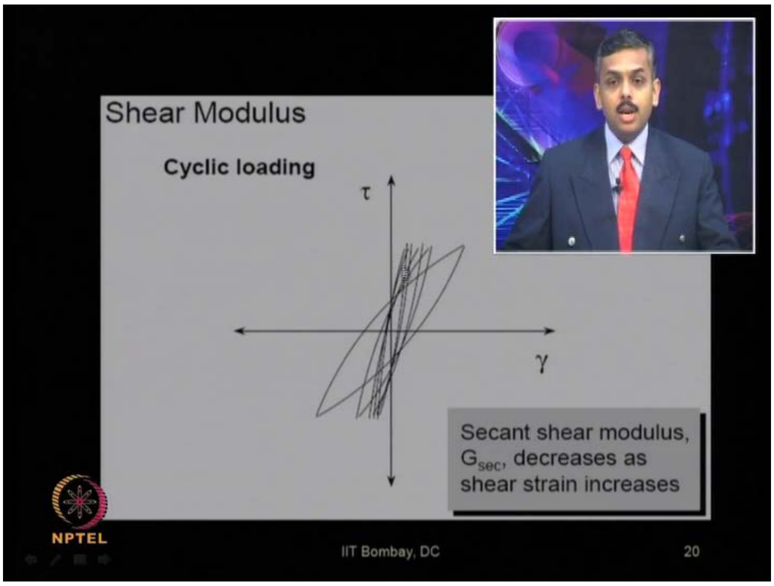


Now, which value of the shear modulus one should use? For the analysis, for all the dynamics studies or dynamic analysis, which shear modulus one should use? As we have seen, G secant modulus is, at any point of shear strain we can find out the ratio of tau by gamma by joining a simple straight line from that point of the shear strain to the origin. So, that gives us kind of an equivalent linear system. So, this is called equivalent linear analysis.

If somebody wants to do the equivalent linear analysis, that means, they are using G secant, that is, the secant shear modulus is in use for the analysis. But if somebody wants to do the actual dynamic analysis, the actual real behavior of the material to capture, then the tangent shear modulus will give us the exact value, because it captures the behavior of the material at each and every strain point. So, this is, at each and every point we can find out the slope of the line, which gives us the tangent shear modulus.

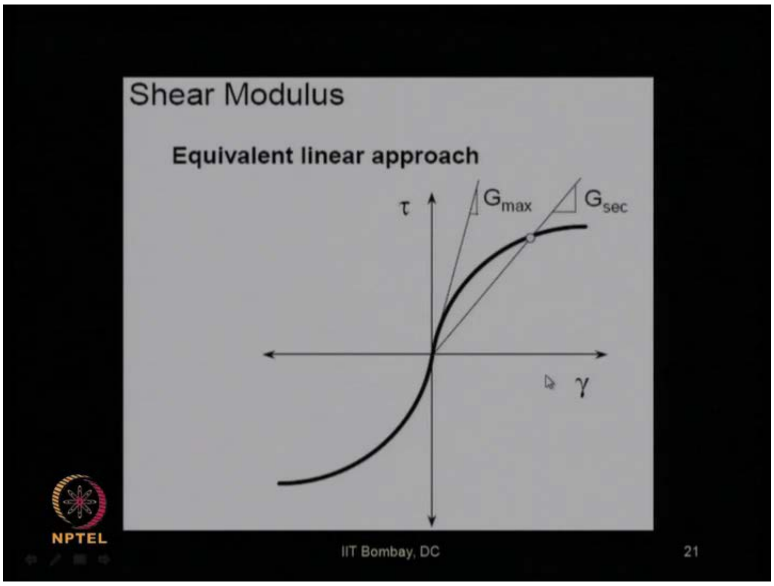
So, to do the non-linear analysis, complete non-linear analysis, means, one must use the value of G tan. If somebody is interested to do the linear analysis, then obviously, G max needs to be used. And one can see from the slope of the curve, as we have seen in the previous slides, G max always gives the maximum value of the shear modulus. As the name suggests, it is the G max, next higher value will be G secant, it will be lower than G max, but that will be higher than G tan. G tan will be the lowest value of the shear modulus among these three types of shear modulus.

(Refer Slide Time: 14:56)



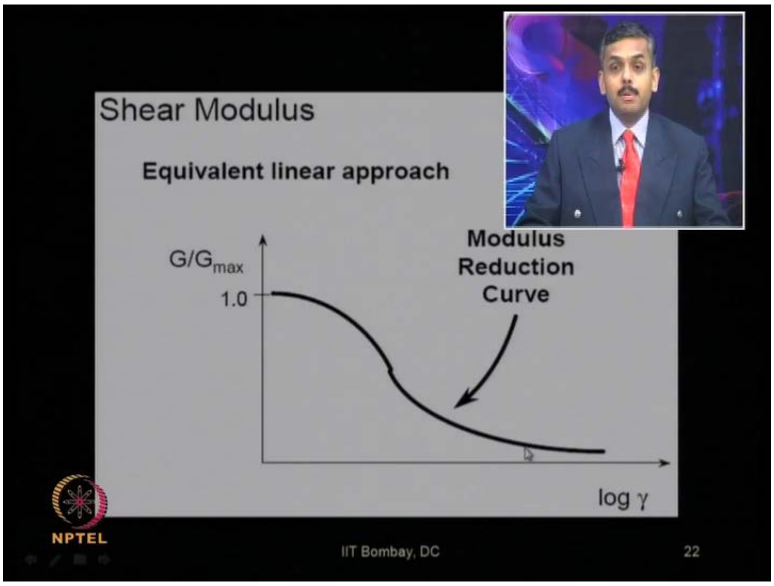
Now, when any material is subjected to cyclic loading, this is a typical behavior of the material or a soil if we are talking about the soil for our course, so this is a typical behavior of shear stress versus shear strain for a cyclically loaded soil material. So, you can see, it will initially start with a steeper slope. As the number of cycles increase, this slope of this cycle will keep on reducing. What does it mean? You can see over here, secant shear modulus, G secant, decreases as the shear strain increases, which is quite obvious from this figure, that as the shear strain increases, there is a decrease in this secant shear modulus and at small shear strain this is higher value.

(Refer Slide Time: 15:52)



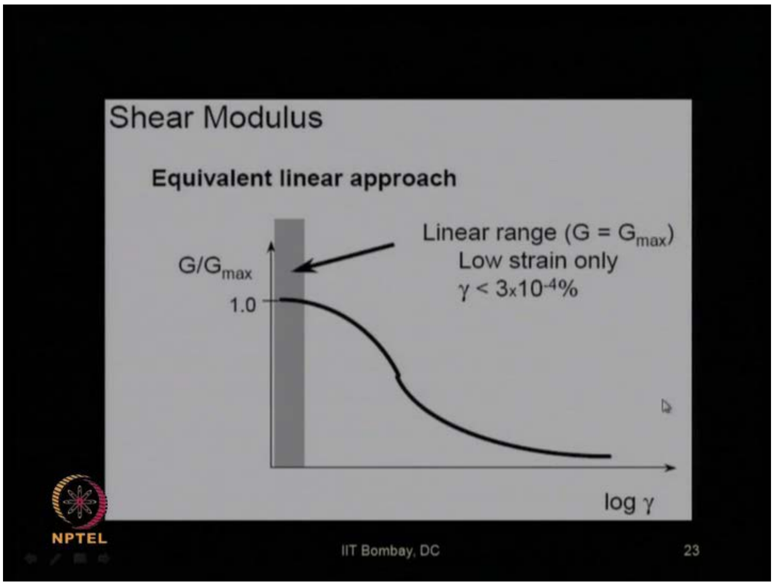
So, in the equivalent linear approach what we are generally using? We are using this secant shear modulus, not this G max value, but you can represent the ratio of these two in the non dimensional form, which is called modulus reduction curve, which is nothing but the ratio of this G secant to this G max value. This G max value is, of course, constant for a particular material, but this G secant will be keep on changing depending on what is the cyclic shear strain value.

(Refer Slide Time: 16:27)



So, this is how the equivalent linear approach is used. As I have mentioned, we generally plot in the y-axis the ratio of G by G max. This G is nothing but G secant and the maximum value of that will be, obviously 1. Then x-axis we plot in log scale, that shear strain values and this will be the typical behavior of the curve, which is known as modulus reduction curve. That means, as the cyclic shear strain increases there will be reduction in the shear modulus, that is why, the name modulus reduction curve for any material.

(Refer Slide Time: 17:09)

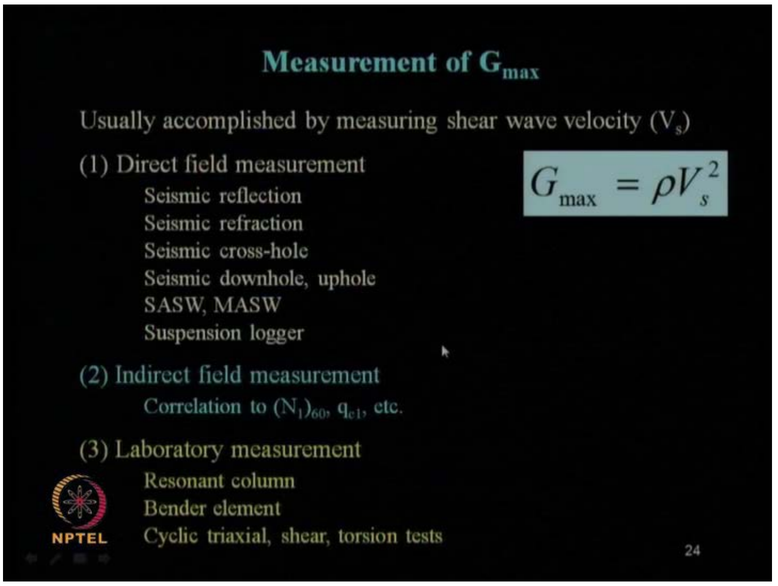


So, for the linear range of analysis, as we have already mentioned, G will be nothing but G max that is nothing but the case when we are handling very low strain problems. Very low strain means, the value of this shear strain will be within the range of there into 10 to the power minus 4 percent, that much of shear strain, within that range will be considered as low strain problem. In that case, we can use this G by G max ratio close to 1 or equals to 1, that is why, G equals to G max is mentioned over here. So, all linear analysis is valid only for this low strain range with the value of G equals to G max.

We need not to consider this degradation of the material as the shear strain increases because it is a low strain problem in the linear range. However, in all practical cases we will find, that the dynamics of the soil properties are not mostly in the low strain range, it is in the intermediate or high strain ranges. For example, if we learn about the earthquake engineering problem, which is a high strain problem because as we know, after the earthquake there will be huge deflection or changes or displacement of the ground. So, it is a high strain problem, it is no way low or medium strain problem.

However, if we are interested to do the machine foundation design where the strain or the displacement of the foundation itself is restricted, that is, is not allowed or the permissible displacement is restricted, in that case it will be obviously, a low strain problem. In that case, only it is possible to use this value of G equals to G max, otherwise in earthquake engineering we never use this linear analysis because it will not at all capture the correct behavior of the material because that material will be at high strain range, not at low strain range. So, instead of using G value at this level one should use G value at this lower level, that is, the degradation of the shear modulus should be considered as per this degradation property of any particular material.

(Refer Slide Time: 19:41)



So, now, how to measure this value of this maximum shear modulus? Typically, this is measured using the shear wave velocity parameter, that is, V s value. Shear wave velocity is measured in several ways and then, from that value the G max is calculated using this equation. So, G max equals to rho times V square where rho is the mass density. Remember, it is not the unique weight, it is density. If somebody is using unit weight, they have to divide it by the acceleration due to gravity G.

So, rho V s square, that gives us the value of G max, and how the value of V s is computed or the G max value is computed? So, there are three major ways to find out this G max value. One is direct field measurement, another is indirect field measurement and another is laboratory measurement.

In direct field measurement, the various techniques are seismic reflection, seismic refraction, seismic cross-hole test, seismic down hole test or seismic up hole test. SASW or MASW test suspension, logger test, all these are direct field measurement through which you will get the value of V s and from V s you can calculate the value of G max.

All this steps we have discussed in our NPTEL video course soil dynamics in module 4. So, I will request all the viewers to go through that course also to get the details about these courses, these methods, which I am not discussing in this course.

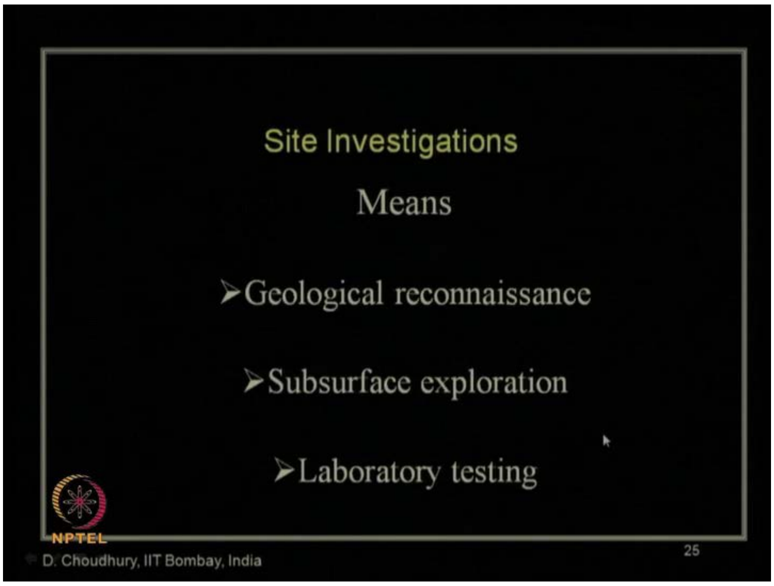
For indirect field measurement correlation to the various static field, tests are done to measure the value of V s or finally, to calculate the value of G max. Those are standard penetration test, SPT, N 1 60 or the cone penetration test q c1. These values are correlated to this V s estimation at site, so that in absence of the procedure to carry out the dynamic soil testing at field. One can also adopt the static test at field, which are usually done for all geotechnical exploration and those values can be correlated finally, to get the value of this V s; finally, which gives us the value of this G max or the maximum shear modulus of the soil.

Through laboratory measurement also by, like using resonant column test or bender element test or cyclic triaxial, cyclic shear or cyclic torsional test, one can find out the value of shear wave velocity or the, in other words, they can find out the G max value of soil material. But remember, it is always advisable to get the value of shear wave velocity directly from the field measurement or through use of indirect field measurement.

Laboratory measurements, though people are finding out, but there are severe limitation of this method to find out V s value because as we know, in laboratory it is very difficult to carry out the test under undisturbed condition and whenever in the static test we can rely mostly on the laboratory test experiments. But in the case of dynamic soil properties when we are bringing out the soil sample from the site to the laboratory and remoulding it and then doing this triaxial test, cyclic triaxial or cyclic shear or cyclic torsional test or the resonant column test. In all this cases the sample structure is totally disturbed and remolded. Hence, whatever value of V s or whatever value of G max we are obtaining from this laboratory test is not the actual one, which is existing at the field. So, that is why one should be very, very careful when somebody is reporting the laboratory value of V s or G max for the design purpose.

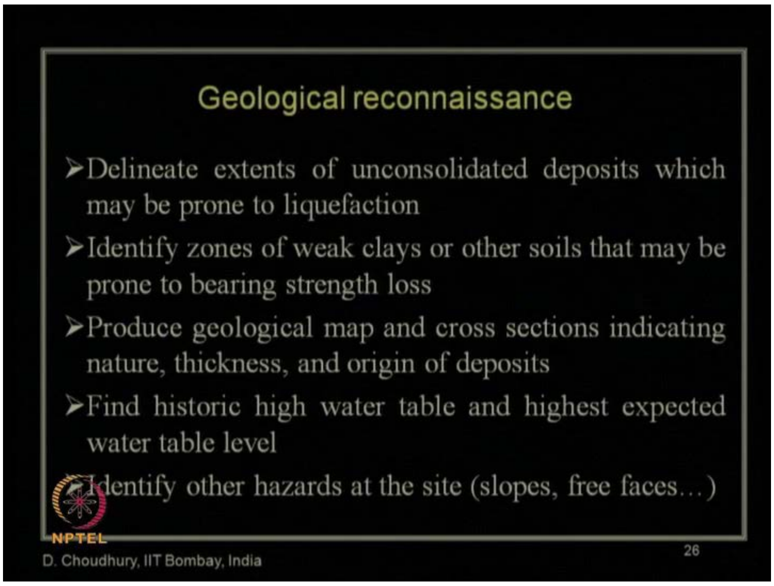
Various researchers has already shown by comparison from the field test and the laboratory test, that there can be as high as two times increase or decrease in the value of the V s or G max value compared to actual field test value and the laboratory measured value. So, this is a word of caution, that one should be very careful about the use of laboratory measured shear wave velocity or laboratory measured G max value for soil material in design.

(Refer Slide Time: 24:36)



So, now let us look at the slide. First step we do the site investigation various means as already we have discussed in our soil dynamics course for module 4 geological reconnaissance, subsurface exploration laboratory testing these are the various steps of site investigation, which are compulsory to also know the dynamic soil properties.

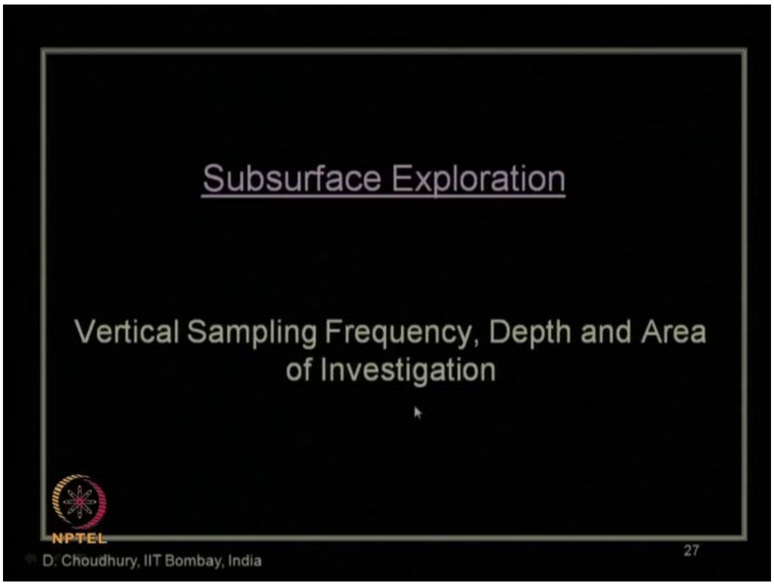
(Refer Slide Time: 24:55)



And in geological reconnaissance we delineate extents of unconsolidated deposits which may be prone to liquefaction, because we should know that is what is the zone of liquefaction we will discuss this also little bit in this course to some extent later on in subsequent lectures

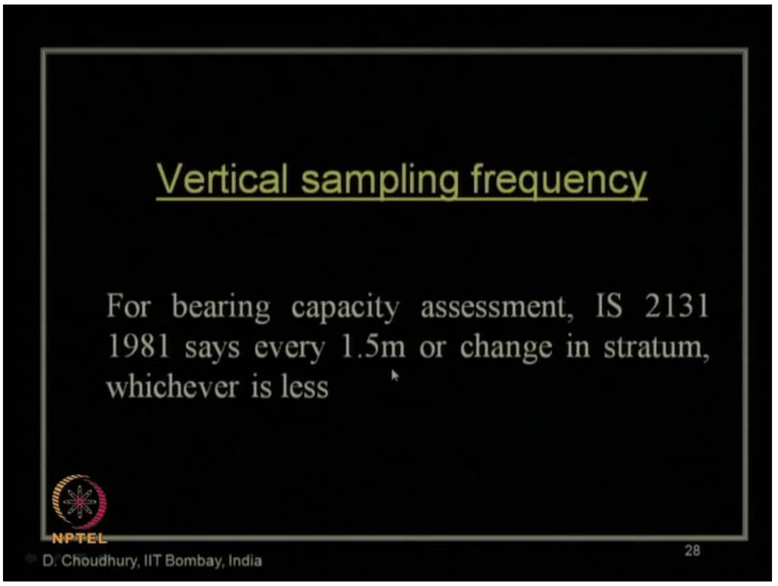
Identify the zones of weak clays and other soils that may be prone to bearing strength loss and prone to liquefaction produce geological map, and cross sections indicating the nature thickness and origin of the deposits find historic high water table and highest expected water table level and identify other hazards at the site. So, these are the part of the geological reconnaissance one must carry out before any design and construction is starting at any particular site.

(Refer Slide Time: 25:56)



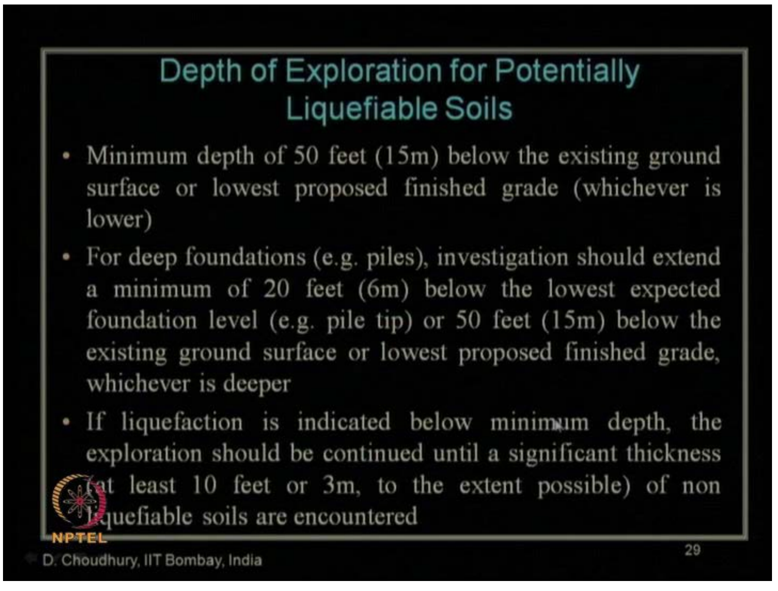
For the subsurface exploration we generally say, the vertical sampling, that is vertical sampling frequency depth and area of investigation should be known.

(Refer Slide Time: 26:08)



For the vertical sampling frequency IS code 2131 suggests, that at every one and half meter distance, that is, when we go vertically from ground surface below the several extent, whatever extent we feel, that it is required to carry out the test, we will carry out the test generally at each one and half meter distance or whenever there is a change of the layer. So, you can see over here, 1.5 meter or there is a change in stratum, whichever is lower.

(Refer Slide Time: 26:50)

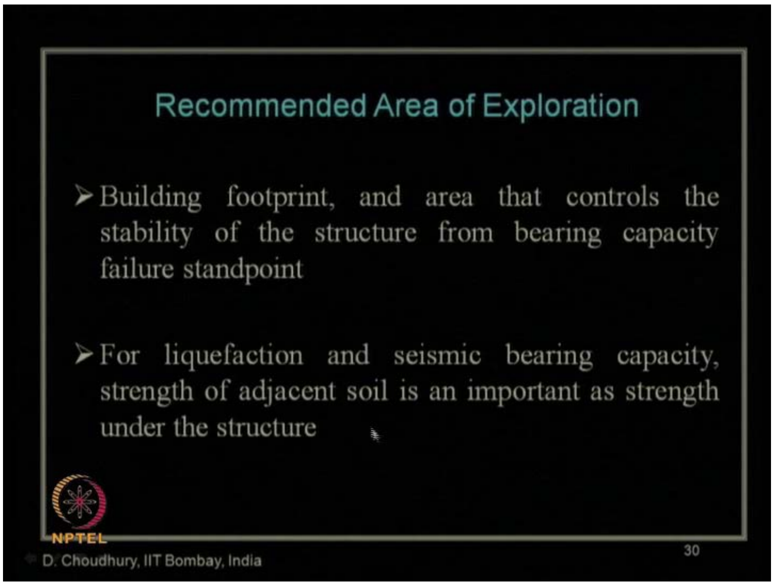


So, in that way we take the sample in the vertical direction and what should be the depth of exploration for potentially liquefiable soil? That is up to what minimum extent one should go through to get the soil data so that the liquefaction studies can be done at a particular site. This is the recommendation, minimum depth of 50 feet, which is equivalent to 15 meter. So, minimum depth of 15 meter below the existing ground surface must be carried out, that is, the soil data up to 15 meter depth minimum should be known to carry out the liquefaction analysis of the soil or it should be lowest proposed finished grade, whichever is the lower between these two values.

For the deep foundations, like when the pile foundations are proposed to be used at a site, then investigation should extend a minimum of 20 feet or 6 meter below the lowest expected foundation level, that is, below the pile tip. Suppose if somebody is planning to go for 20 meter length of pile at a site, the liquefaction study must be done up to a depth of 20 meter plus 6. So, that means, 26 meter below the ground surface, that is what it suggests, below the lowest expected foundation level, that is, pile tip or it should be 50 feet, that is, 15 meter, whichever is deeper, whichever is higher. And if liquefaction is indicated below the minimum depth, that is, suppose we considered this minimum depth criteria for liquefaction analysis and we got the information of about the soil profile within this depth, but even if suppose liquefaction is indicated to occur beyond this minimum depth, then the exploration should be continued until a significant thickness at least of 10 feet or 3 meter to the extent possible of non-liquefiable soils are encountered.

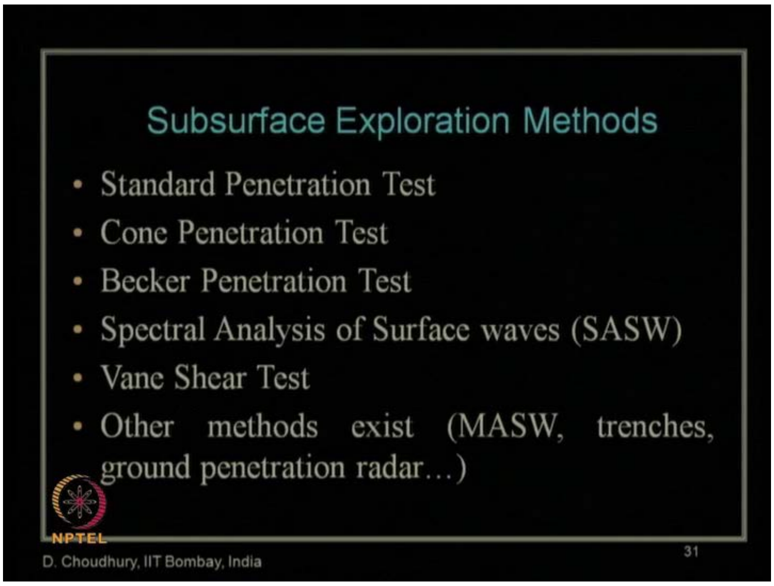
That means, suppose at a site one found out, that after the soil exploration, you can see over here, up to a depth below 15 meters, suppose if somebody has done the soil exploration study and get the soil data, then by doing the liquefaction study, suppose it is obtained, that even up to 15 meter there is a chance of liquefaction and beyond that is expected, then what it should be done. The soil exploration data or the soil bore hole data must be available up to a depth where non liquefiable strata of minimum thickness of 3 meter is available, at least up to that depth the study should be carried out. That means, at least the non-liquefiable portion should be observed or analyzed from the bore hole data, which is collected through this soil exploration or the geotechnical exploration.

(Refer Slide Time: 30:09)



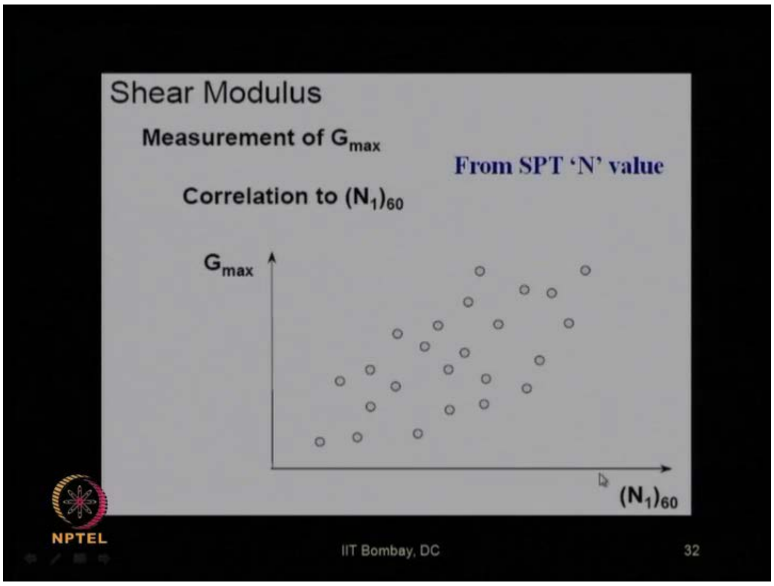
Now, let us look at the slide over here. So, recommended area of the exploration, as we know for the static case also similarly for seismic case; building the, building footprint and area that controls the stability of the structure from bearing capacity failure standpoint must be considered as a area of exploration. For liquefaction and seismic bearing capacity, strength of the adjacent soil is also important as the strength under the structure.

(Refer Slide Time: 30:40)



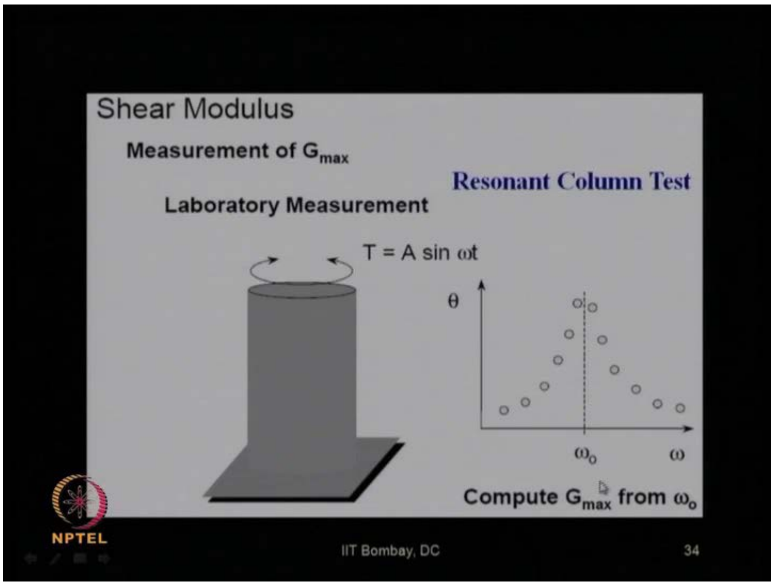
So, subsurface exploration methods, various methods are available like in static case also we carry out this test, standard penetration test or SPT, cone penetration test or CPT, Becker penetration test or BPT, spectral analysis of surface wave SASW, Vane shear test or other methods also exist like MASW, multichannel analysis of surface waves, trenches, ground penetration radar or GPR. So, these are the common subsurface exploration methods. Now, how to use the data of these tests to find out the shear wave velocity or in turn the maximum shear modulus of a soil, we will see.

(Refer Slide Time: 31:26)



Suppose, from SPT test, SPT, we save N value is typically observed at the site and after that the correction is done to find the N 1 60, which we have already discussed in our other video course on soil dynamics in the module number 4. So, one can find out the correlation between the G max value and N 1 60 by putting all the collected data points in this fashion, so that there can be some correlation obtained between these dynamic property and the static property.

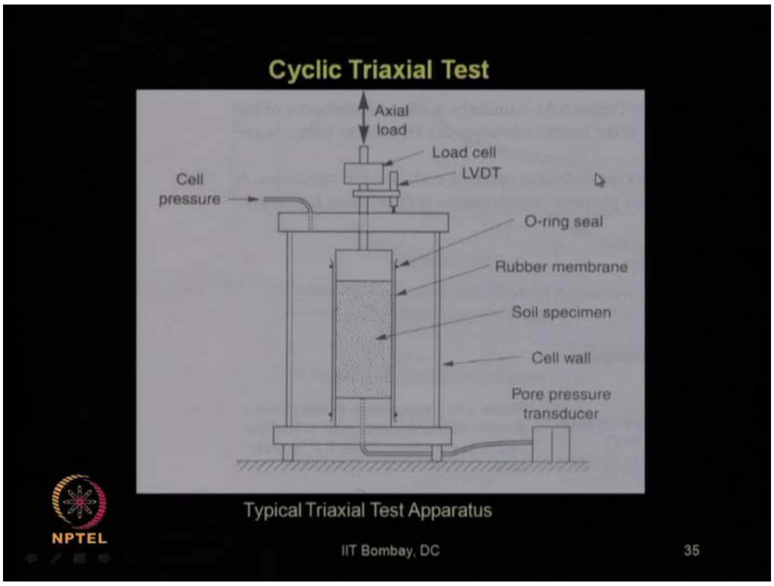
(Refer Slide Time: 32:04)



Also, in the laboratory, as we have mentioned, using the resonant column test one can find out the G max value. This is the typical picture how the soil column is subjected to torsion like this, so apply harmonic torque and measure the angular rotation sweep across various frequencies. So, this will be the data of the angular distortion with respect to different frequency.

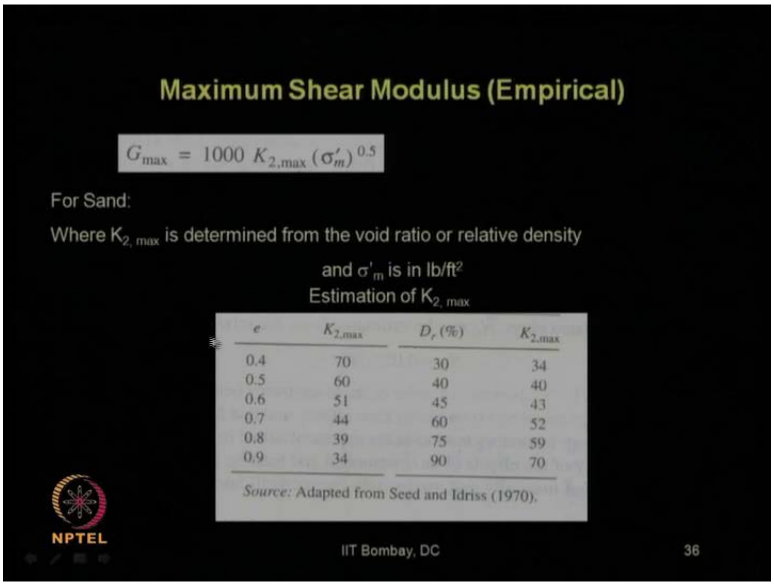
And one can find out the maximum displacement or the resonant condition, that is why the name resonant column test. It has to go through this resonant condition where this theta will be maximum at particular value of omega naught, so that G max is computed from this value of this resonant frequency or omega naught.

(Refer Slide Time: 32:55)



Similarly, in another laboratory test, that is cyclic triaxial test, by providing the axial deviatory load like this one can find out the G max value in the laboratory also.

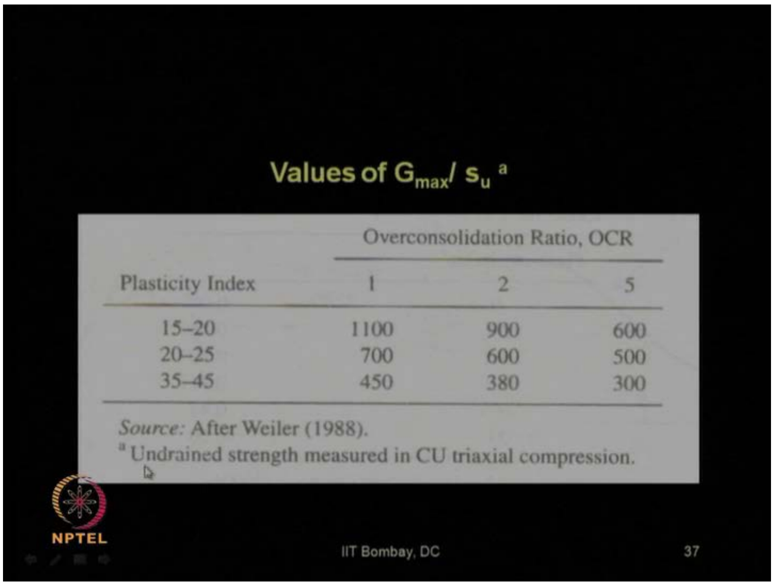
(Refer Slide Time: 33:08)



There are several empirical correlations, which exist in literature, that is, in absence of having the dynamic shear modulus value actually corrected from the field test or the laboratory test, one can also correlate it with respect to the static test results. So, various researchers has proposed it, we can see over here, like Seed and Idriss in 1970, they proposed for Sand, G max may be calculated using this empirical relation. And as we know, empirical relationships are always dependent on the input unit of the various parameters involved, like K 2 max is non-dimensional, which is determined from the void ratio and the relative density of the Sand and sigma dash m, that is, mean effective stress at any depth, that unit should be in pound per feet square as proposed by Seed and Idriss in this equation and similar unit of G max can be obtained.

So, for various values of e void ratio and for various values of relative density of sand D r, in percentage the values of K 2 max is given in the table, as given by Seed and Idriss, which can be used in this empirical relationship to find out the maximum shear modulus for Sand. And remember, these empirical relationships are developed from couple of lab test or couple of field test. So, that is why, there is always the future scope to modify these equations, because you know for developing these empirical relationship as maximum number of data points are available, then we can get a better relationship or more authentic or acceptable relationship rather than using a small number of data set.

(Refer Slide Time: 35:11)


Values of G_{max}/s_u [a]

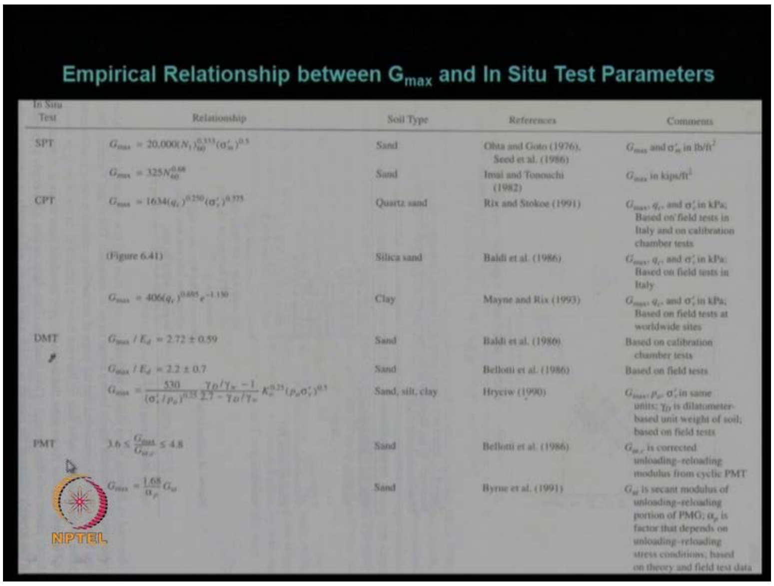
Plasticity Index	Overconsolidation Ratio, OCR 1	2	5
15–20	1100	900	600
20–25	700	600	500
35–45	450	380	300

Source: After Weiler (1988).
[a] Undrained strength measured in CU triaxial compression.

Similarly, another relationship to obtain the G max value for cohesive soil from the S u value is proposed by Weiler in 1988; that is undrained strength, which is measured in CU triaxial compression for different ranges of plasticity index. One can find out these are value of plasticity index range, PI, that is, liquid limit minus plastic limit and for various over consolidation ratio, OCR, values of one, that is, normally consolidated soil and other over consolidated soil with over consolidation ratio of 2 and 5.

These different values of ratio of this G max to S u values are proposed by Weiler and obviously, here it is non-dimensional, so there is no problem to use these values.

(Refer Slide Time: 35:59)



Empirical Relationship between G_{max} and In Situ Test Parameters

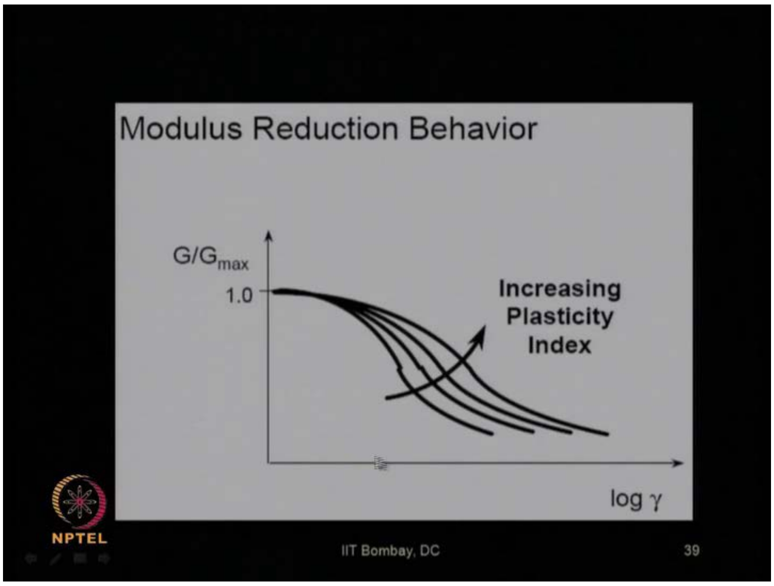
In Situ Test	Relationship	Soil Type	References	Comments
SPT	$G_{max} = 20{,}000(N_1)_{60}^{0.333}(\sigma'_m)^{0.5}$	Sand	Ohta and Goto (1976), Seed et al. (1986)	G_{max} and σ'_m in lb/ft^2
	$G_{max} = 325N_{60}^{0.68}$	Sand	Imai and Tonouchi (1982)	G_{max} in kips/ft^2
CPT	$G_{max} = 1634(q_c)^{0.250}(\sigma'_v)^{0.375}$	Quartz sand	Rix and Stokoe (1991)	G_{max}, q_c, and σ'_v in kPa; Based on field tests in Italy and on calibration chamber tests
	(Figure 6.41)	Silica sand	Baldi et al. (1986)	G_{max}, q_c, and σ'_v in kPa; Based on field tests in Italy
	$G_{max} = 406(q_c)^{0.695}e^{-1.130}$	Clay	Mayne and Rix (1993)	G_{max}, q_c, and σ'_v in kPa; Based on field tests at worldwide sites
DMT	$G_{max}/E_d = 2.72 \pm 0.59$	Sand	Baldi et al. (1986)	Based on calibration chamber tests
	$G_{max}/E_d = 2.2 \pm 0.7$	Sand	Bellotti et al. (1986)	Based on field tests
	$G_{max} = \frac{530}{(\sigma'_v/p_a)^{0.25}}\frac{\gamma_D/\gamma_w - 1}{2.7 - \gamma_D/\gamma_w}K_o^{0.25}(p_a\sigma'_v)^{0.5}$	Sand, silt, clay	Hryciw (1990)	G_{max}, p_a, σ'_v in same units; γ_D is dilatometer-based unit weight of soil; based on field tests
PMT	$3.6 \le \frac{G_{max}}{G_{ur,c}} \le 4.8$	Sand	Bellotti et al. (1986)	$G_{ur,c}$ is corrected unloading–reloading modulus from cyclic PMT
	$G_{max} = \frac{1.68}{\alpha_p}G_{ur}$	Sand	Byrne et al. (1991)	G_{ur} is secant modulus of unloading–reloading portion of PMG; α_p is factor that depends on unloading–reloading stress conditions; based on theory and field test data

Other empirical relationships between G max and various in situ tests parameter are available in literature, like with respect to SPT, standard penetration test, results value, G max is proposed to obtain for by using this relationship, which is given by Ohta and Goto in 1976 Seed et al in 1986 for sandy type of soil. Again, another for sandy type of soil Imai and Tonouchi in 1988 proposed this equation, you can see, what are the different units of this G max in different equations. So, as I have already mentioned just few minutes back, that this empirical relationship is highly dependent on what is the input value of unit is proposed in the equation. Also, it is very important how many data points were used to propose that equation.

So, you will find out, suppose for the same soil, here it is given for both sandy type of soil, but if you want to use both the equations for your obtained SPT value from the site and then correct it to N 1 60 and N 60 and get the G max value, two equations will give us the two different values of G max though both are for sandy soil because it depends on what type of sand. Also, they collected how many data points they collected to finally, propose this empirical relationship. So, that is why one should be very careful when somebody is using this empirical relationship in practice.

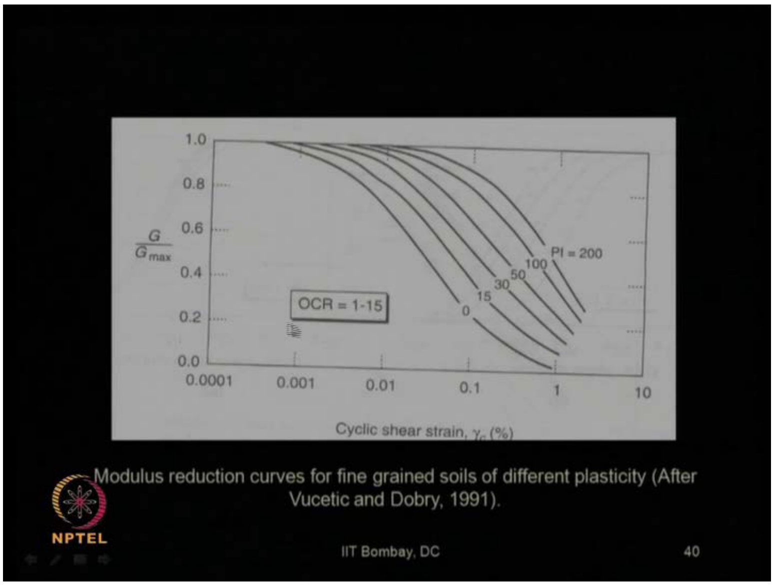
Also, from the CPT; that is for cone penetration test, quartz and silica sand, various types of soil, type are used to propose various G max empirical relationship for the in situ test parameters for as proposed by various researchers. Also, for dilatometer test, DMT, or pressure meter test, PMT, the empirical relationships are available.

(Refer Slide Time: 38:14)



Now, let us look at this modulus reduction behavior curve, that is G max, how it varies with respect to plasticity index? That is, for a cohesive soil where plasticity index is non-zero one can easily find out, that as plasticity increase, index increases, there will be increase in the value of this G max, G by G max ratio with respect to the shear strain.

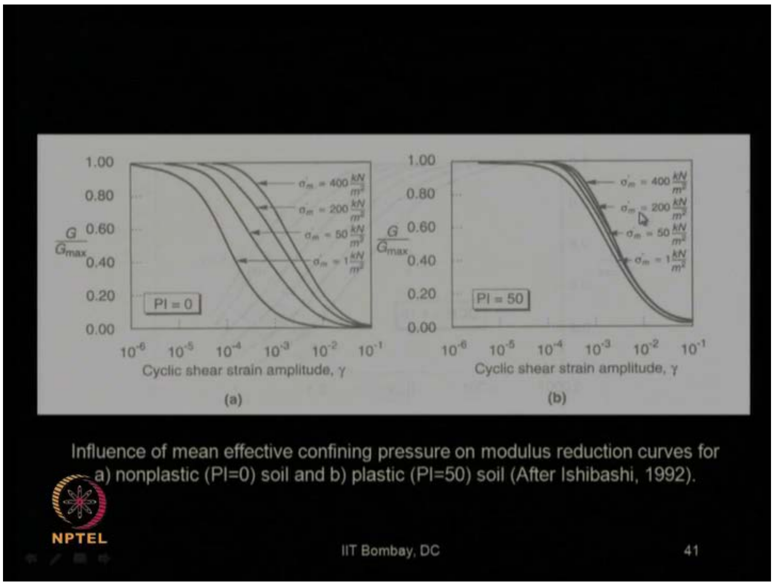
(Refer Slide Time: 38:41)



And this graph shows the typical variation of G by G max with respect to cyclic shear strain. As I have already mentioned, as plasticity index increases, this value increases for various OCR rangers from 1 to 15, as proposed by Vucetic and Dobry in 1991, but later on researchers has mentioned, that this curve for PI equals to 0 is not fully correct because PI equals to 0 refers to all cohesionless soil, purely cohesion less soil, it can be sand, it can be gravel. So, for all sandy soil, for all gravelly soil it is not, that G by G max is a single curve, it also depends on their soil, various parameters.

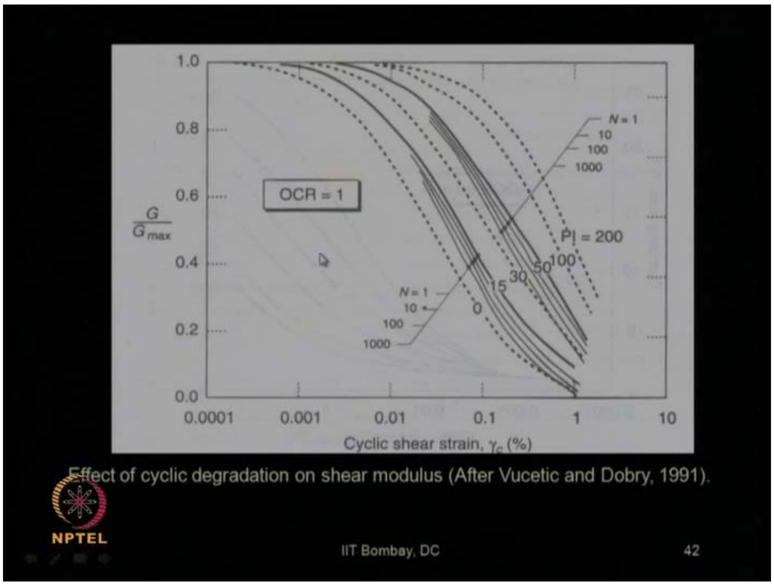
So, it is proposed to use this proposed design curve of Vucetic and Dobry, which they obtained from various laboratory tests. Again, this is from the collected number of soil samples only. This should be valid for various non-zero value of plasticity index ranging from 15 to 200. These curves can be used, not that PI equals to zero line.

(Refer Slide Time: 39:54)



Other researches like Ishibashi in 1992 also had shown, that for plasticity index equals 0, that is, non-plastic soil. There is an effect of this sigma m dash, that is, effective vertical stress mean vertical stress, you can see is, there, if there is an increase in that there will be increase in G by G max ratio with respect to a particular value of this cyclic shear strain modulus. Whereas, for plastic soil with plasticity index of 50 he proposed, that there is hardly any significant increase in the value of G by G max with increase in this mean effective vertical stress.

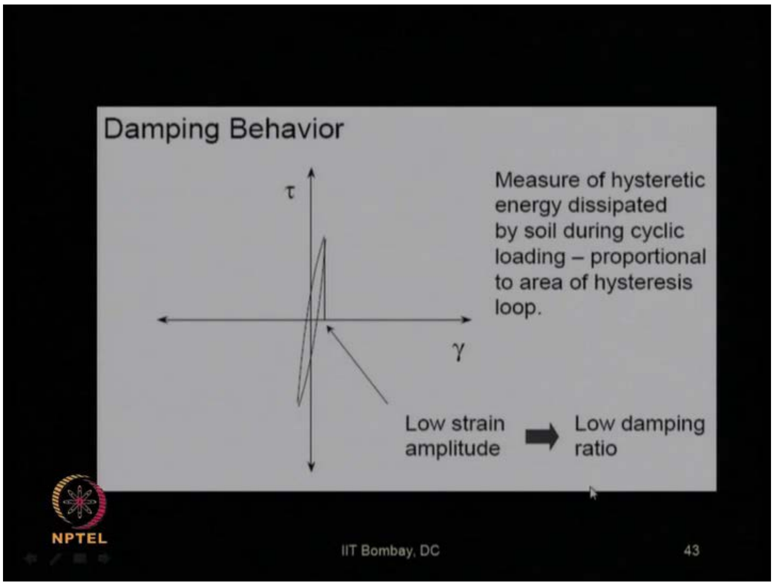
(Refer Slide Time: 40:37)



Now, the effect of cyclic degradation on the shear modulus was proposed by Vucetic and Dobry in 1991 through their laboratory tests experiments, that is, if the number of cycles, that is, number of repetition of this cycle for the same soil, if it increases, obviously, there will be a degradation of this shear modulus, as we have already mentioned.

So, we can see from this slide how much degradation is occurring. So, N is number of cycles of loading, N equals to 1, 10, 100, and 1000. You can see this is the degradation of the G by G max value for various values of plasticity index and OCR value of 1, that is normally consolidated soil.

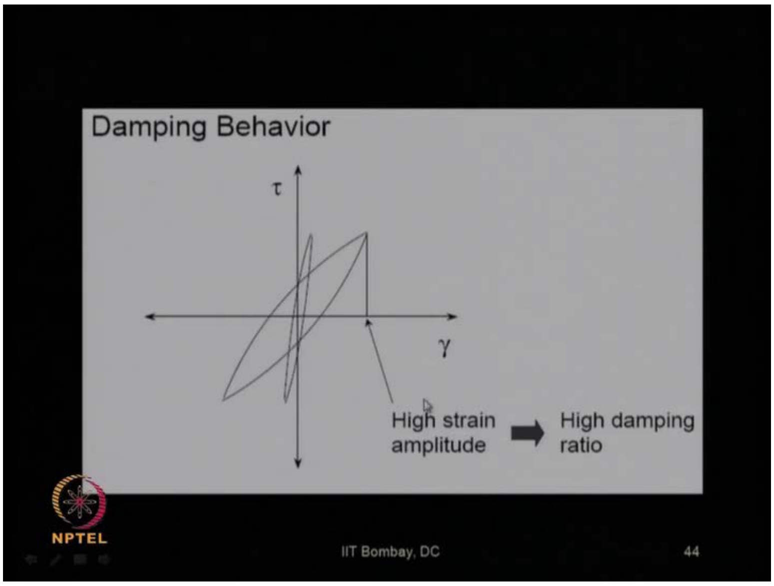
(Refer Slide Time: 41:26)



Coming to another important parameter, as we have mentioned, another important dynamic soil parameter is damping behavior. So, the damping behavior can be obtained also from the area of this hysteresis loop of this tau versus gamma plot of any soil material, that is, shear stress versus shear strain plot for different cycles. And measure hysteretic energy dissipated by soil during cyclic loading proportional to the area of this hysteresis loop, that is this area, it is proportional to this damping behavior.

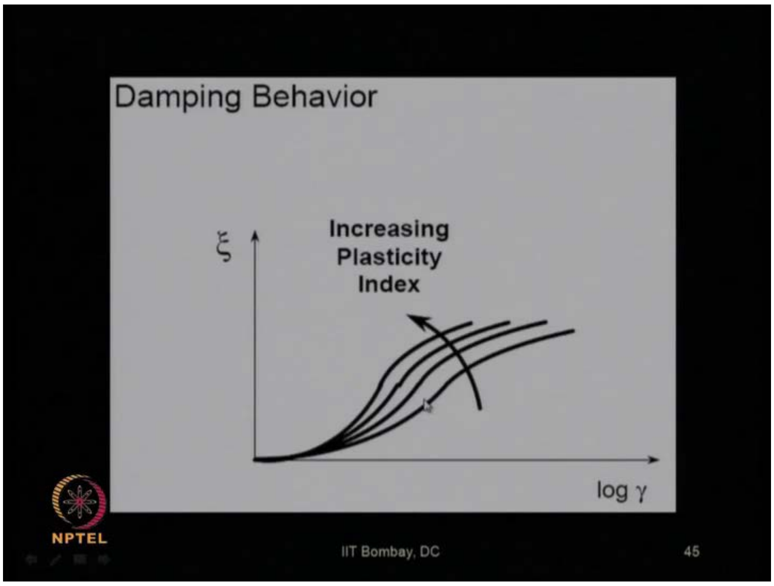
And typically, from the lab test whatever this hysteresis loop we obtained, the third cycle is considered as the representative cycle for any soil material. So far the third cycle we find out what is the area of this hysteresis loop, from that area we can find out the damping behavior or the damping ratio. So, one can easily understand if the strain, the cyclic shear strain is low, then there will be low damping ratio.

(Refer Slide Time: 42:36)



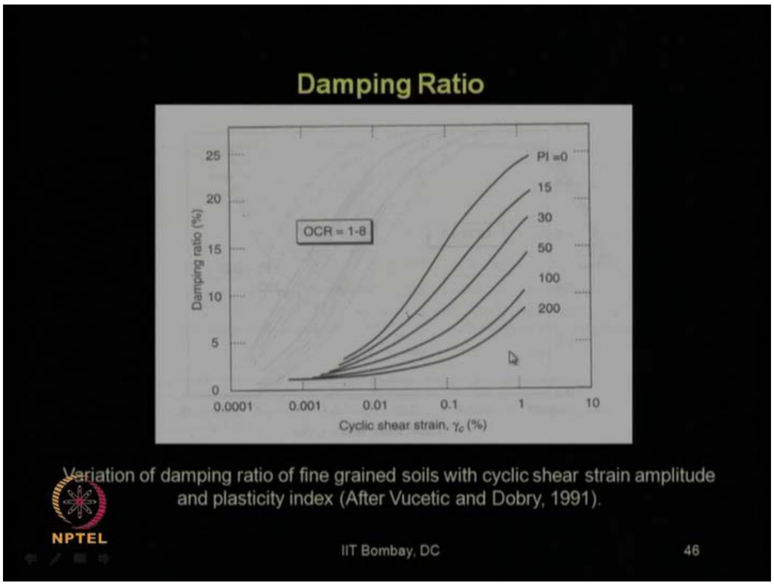
And if it is high, then obviously, it is expected to have high damping ratio, because you can see the area of this hysteresis loop also has increased at high value of cyclic strain.

(Refer Slide Time: 42:50)



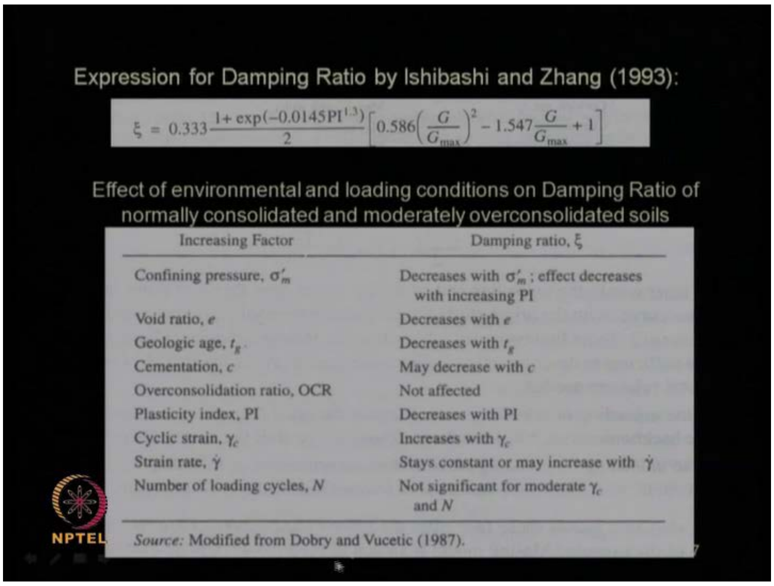
And this is the damping ratio, how it behaves with increase in the cyclic shear strain and plasticity index, like if plasticity index increases, the damping ratio also increases for a particular value of cyclic shear strain.

(Refer Slide Time: 43:09)



So, this laboratory experimented results are also proposed by Vucetic and Dobry in 1991. For various values of plasticity index, for a range of OCR between 1 to 8, one can see the damping ratio expressed in percentage increases as there is an increase in the cyclic shear strain and it decreases as the plasticity index increases over here.

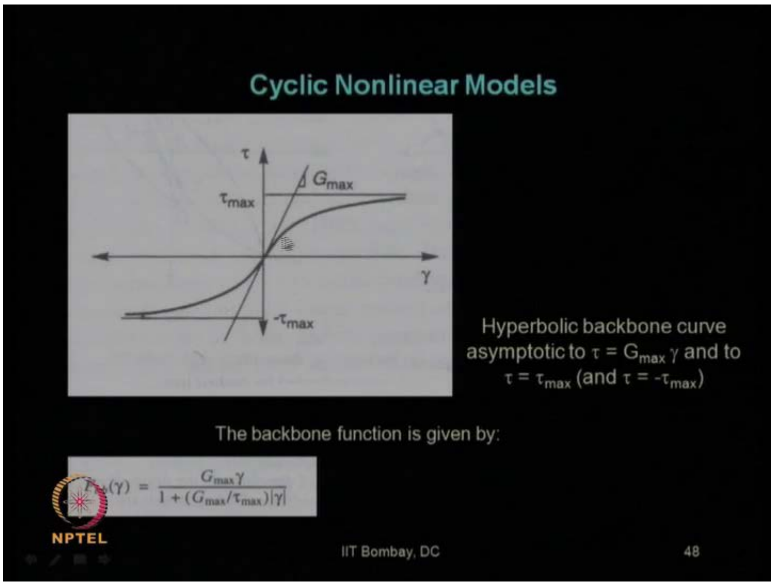
(Refer Slide Time: 43:37)



So, the expression for damping ratio, as proposed by Ishibashi and Zhang in 1993, this is another empirical relationship, which is given by this equation, can be seen from this equation. One can find out the damping ratio from the known value of G by G max ratio and the plasticity index as proposed by this Ishibashi and Zhang empirical relationship.

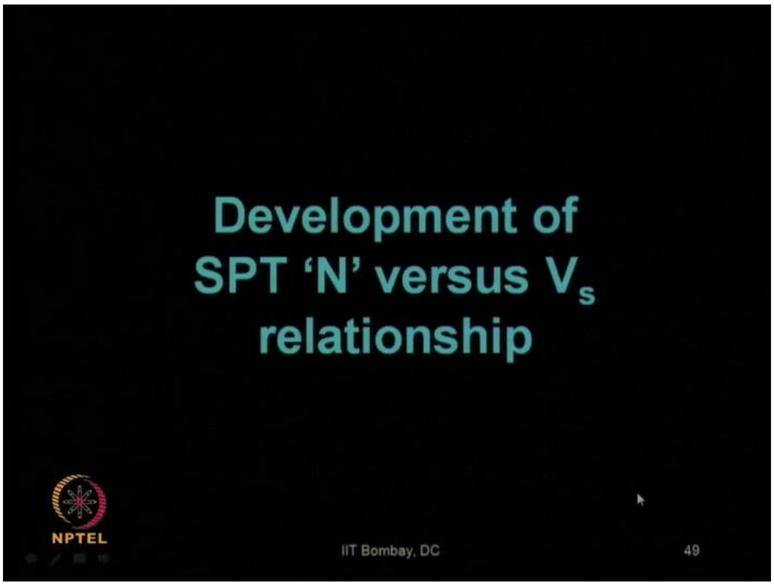
These are various parameters, which affect the damping ratio. They affect how the increasing pattern of each of this parameter changes the values of damping ratio, which is proposed by Dobry and Cucetic in 1987. These things we already discussed in our another video course on soil dynamics in the module 4 of that course, which also discussed the dynamic soil properties.

(Refer Slide Time: 44:29)



Now, the cyclic non-linear model, if somebody wants to use it in the analysis, then they have to capture this exact behavior of shear stress versus shear strain of a soil material and in that the initial tangent modulus will give us the G max value. Say, this is the tau max value and this is minimum tau max, so that hyperbolic backbone curve, this one hyperbolic backbone curve, which is asymptotic to this shear stress, that is, tau equals to G max times gamma and to this tau equals to tau max value, that needs to be obtained and that backbone curve is typically given by this function, that is G max gamma by 1 plus G max by tau max times gamma.

(Refer Slide Time: 45:23)

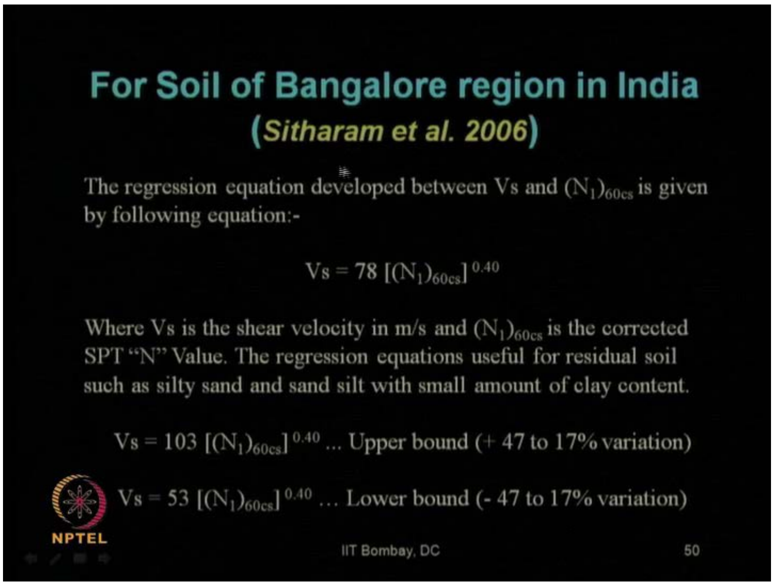


Now, there is a need for development of field static test results with respect to the dynamic characterization of soil property, why? Because in many cases we will find out, that it is difficult to carry out the field dynamic test, because of the cost involved in that project, also because of the availability of the free area, because to obtain the free field soil dynamic property it is required to have an extent of a free zone. Free zone means, there should not be any structure existing, any obstruction existing at a site, then only we can say this only gives the soil dynamic parameter, not the combined parameter of soil and some concrete or some hidden material in the ground.

So, that is why development of SPT N value with respect to the shear wave velocity value relationship is very important and thoroughly researched worldwide by various engineers and researchers. And it also depends on the locality or local regional soil because you know, when there is a change of type of soil at a particular region, their profile with respect to depth, there will be different ranges or different changes in this shear wave velocity or dynamic property of the soil also.

So, it is not, that universally worldwide equations can always be used blindly. It has to be checked and tested for local soil condition also, that is why for each and every region there is a need to develop this SPT N versus the V s value. Why SPT N, because standard penetration test is a very common test, which is usually done at all sites wherever geotechnical exploration is conducted.

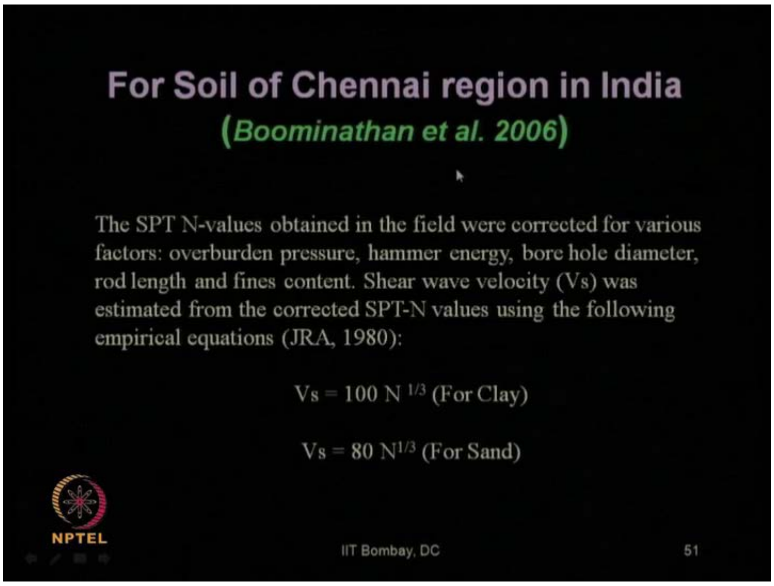
(Refer Slide Time: 47:26)



So, through that SPT N value various researchers in India, they have reported the empirical relationships developed for obtaining the shear wave velocity, V s value, form the SPT N value. For soil of Bangalore region in India, Sitharam et al 2006, they proposed the regression equation to compute the shear wave velocity V s from this equation, 78 N 1 60 cs to the power 0.4. N 1 60 cs is nothing but corrected SPT N value with respect to energy correction and all other static corrections including the clean sand condition.

Clean sand correction we have already discussed in our other course on soil dynamics in module 4 of that course. So, one can go through that course to understand what are the various corrections for SPT N value, which I am not discussing in this course. So, using this empirical relationship one can obtain the ranges of values, of V s values from a known corrected value of SPT N value for various soils in the Bangalore region at different depths. Also, the regression equation useful for residual soils, such as silty sand and sandy silt with small amount of clay content, these are the two different equations, which have been proposed by these researchers.

(Refer Slide Time: 48:55)

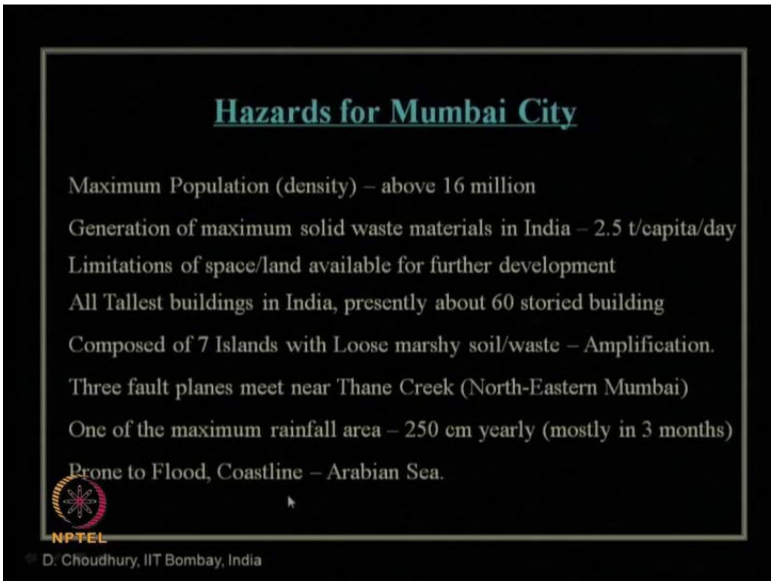


Another researcher's group, they did the similar study for the soil of Chennai region in India. Boominathan et al in 2006, they also proposed similar set of equations, that is, to obtain the shear wave velocity from the SPT N value. So far clay and for sand they proposed these two equations for the soils of Chennai region.

(Refer Slide Time: 49:24)

Now, application of research for dynamic soil characterization of Mumbai city will be discussed now in this course thoroughly, which is carried out by Doctor Sumedh Y Mhaske. He completed his PhD in 2011 at IIT Bombay, Mumbai, India under my supervision. So, I am going to discuss a portion of the PhD thesis topic of doctor Mhaske who carried out the dynamic soil characterization and proposed this shear wave velocity versus SPT N value for Mumbai soil.

(Refer Slide Time: 50:01)



Why it is required? Let us first understand need of the study. Need of the study is, there are several hazards for the Mumbai city, like of course, the maximum population density all over the world is a one big hazard because whenever there is a moderate earthquake also coming in Mumbai and if there is some damages, it is going to affect huge number of people. That is why to minimize the damages we have to be very careful in design and construction of these geotechnical earthquake engineering problems where this aspects are taken care of.

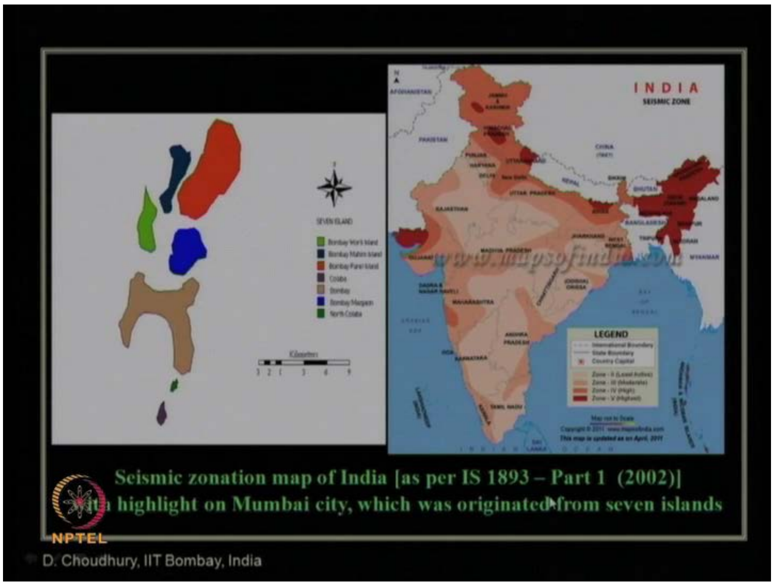
Also, various other hazards, like generation of maximum solid waste material in India, limitations of space and land, that is why, only further development in terms of the vertical development, there is hardly any scope to develop laterally. That is why? All the tall buildings are located in Mumbai, that is in India all the tallest buildings are located in Mumbai.

Originally, Mumbai is composed of seven islands and with time they got combined with loose and marshy soil and waste dumped material and today's Mumbai; that is how it has been formed through ages. That means, there is a chance of soil amplification, which amplifies any earthquake motion, which comes in bedrock and passes through the soft soil.

So, even if the bedrock is having a moderate or low magnitude of earthquake, it may become a large magnitude of earthquake or large damages can occur if it go-passes through this loose marshy landfill material or the dumped material or reclaimed land in Mumbai region.

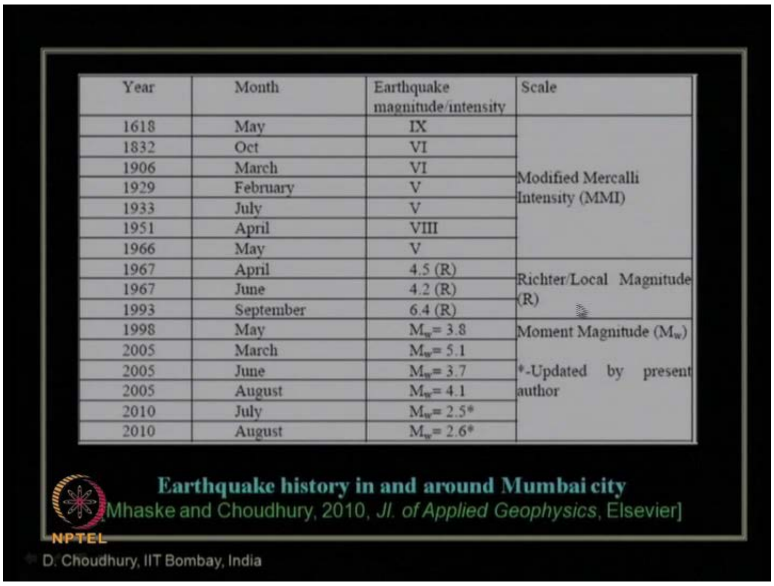
There are three fault planes near Thane creek region. We can see in this slide over here, there are three fault planes, which meet near Thane creek region. Thane creek is nothing but north-eastern part of Mumbai, one of the maximum rainfall areas in India about 250 centimeter yearly. But remember this entire rain occurs within the three months duration, it is not distributed uniformly all over the year, it is only concentrated in three months. That is why, this is another big hazard, which causes several landslide and slope failure problem and prone to flood or because of the coastline in the Arabian Sea. Because of this hazard it is also necessary to study the earthquake hazards for the Mumbai region.

(Refer Slide Time: 52:45)



As I have already mentioned, one can see these are the seven major islands, which have been now connected at present days through the field of marshy land with time. And you can see from Indian seismic code, IS 1893 part one of latest 2002 version, there are four seismic zones, zone 2 to zone 5 and Mumbai comes under zone 3, which is having a possibility of moderate earthquake intensity of 6 to 6.5 to occur.

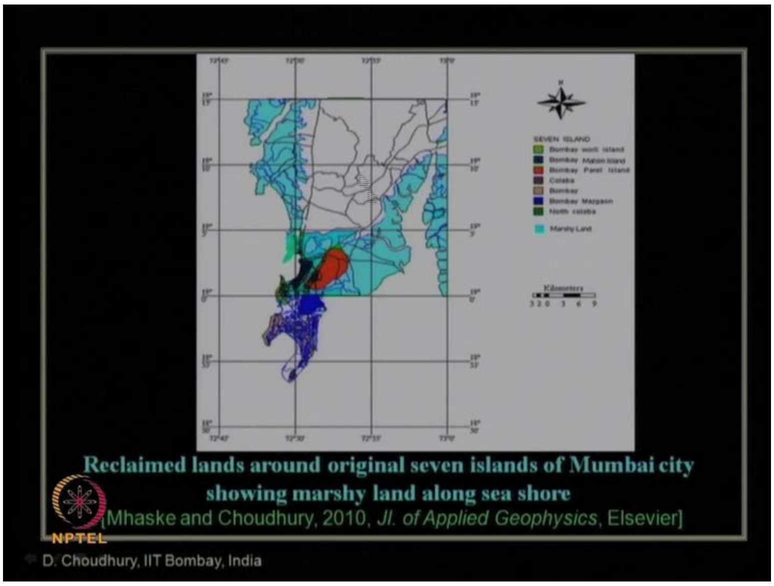
(Refer Slide Time: 53:16)



Year	Month	Earthquake magnitude/intensity	Scale
1618	May	IX	Modified Mercalli Intensity (MMI)
1832	Oct	VI	
1906	March	VI	
1929	February	V	
1933	July	V	
1951	April	VIII	
1966	May	V	
1967	April	4.5 (R)	Richter/Local Magnitude (R)
1967	June	4.2 (R)	
1993	September	6.4 (R)	
1998	May	M_w = 3.8	Moment Magnitude (M_w)
2005	March	M_w = 5.1	*-Updated by present author
2005	June	M_w = 3.7	
2005	August	M_w = 4.1	
2010	July	M_w = 2.5*	
2010	August	M_w = 2.6*	

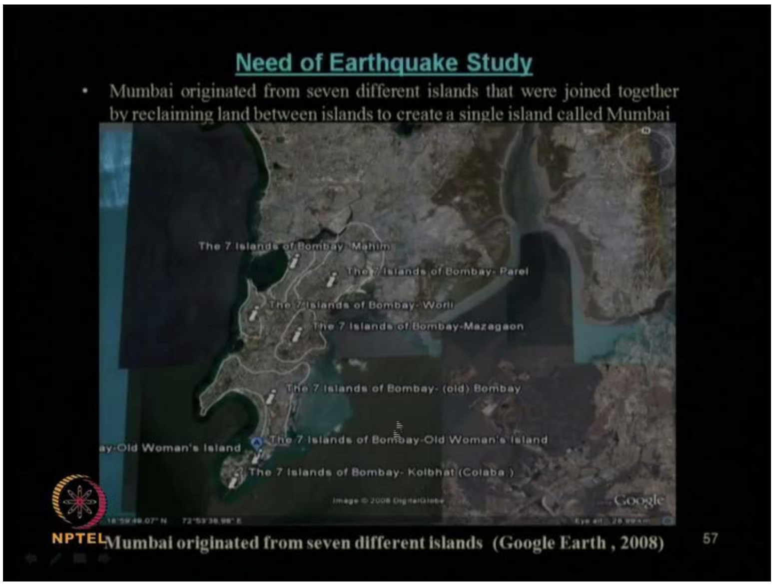
There are several historical earthquakes, which occurred near or in the vicinity of Mumbai city, which are reported by several researchers. So, this is earthquake history in and around Mumbai city, which is reported by Mhaske and Choudhury in 2010 in the journal of Applied Geophysics, Elsevier journal. These are the various intensity or magnitude of earthquake occurred in different years and month as mentioned over here.

(Refer Slide Time: 53:46)



This slide shows the GIS map, that is reclaimed land in and around that original seven island of Mumbai city, which shows the marshy land along the seashore. This sky blue color shows the all marshy land along seashore, which is now actually used as a land and there are several constructions. So, these are loose material, which with time get deposited and combined with the original seven islands and today's Mumbai has been formed.

(Refer Slide Time: 54:23)



You can see again, the Mumbai originated from seven original islands, these are the seven original island and these are the marshy land region. This is from the Google earth.

(Refer Slide Time: 54:36)

And this is the Mantralaya, which is the Vidhan Bhavan of Maharashtra state, that is, the state assembly. This is also not within the mainland of the seven islands, but it is also in the reclaimed land. You can see the border line over here, so it is in the reclaimed land region.

(Refer Slide Time: 54:59)

Then, BARC, Bhaba Atomic Research Center of Mankhurdh, that is also developed on the reclaimed land like this. So, it is very important to study the earthquake hazards of this Mumbai and surrounding region, because of these important structures lying over there.

(Refer Slide Time: 55:21)

So, GIS based soil liquefaction susceptibility map is very important to develop and for that the Mumbai region has been marked, between the which is ranging between latitude of 18 degree 53 minute North to 19 degree 15 minute North and longitude of 72 degree 48 minute East to 73 degree East. The city of Mumbai covers of total area of 437 square kilometer and Mumbai is the financial capital or economic capital of India megacity with maximum population density. So, that is why, it is important to study this earthquake hazard for Mumbai city. So, we will discuss further in out next lecture on this topic.