REMOTE SENSING FOR NATURAL HAZARD STUDIES

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Lec 32b: Remote Sensing for Liquefaction Studies - I Part B

Hello everyone, welcome back to Lecture 32. So, this is a continuation of the first part. So, this is Part 2 of Lecture 32. So, in the previous part, we started discussing identifying a new parameter that can be correlated with the liquefaction potential. So, here to overcome the challenges that are associated with the laboratory-based methods, Seed and Idris (1971). They came up with the stress-based approach, and in this approach, they correlated the liquefaction potential to the standard penetration-based end result SPTN value. SPTN is one of the parameters that we generally acquire in geotechnical engineering studies. So, it is available to many of us. So, here is one of the examples of how we do it in the field.

EVALUATION OF LIQUEFACTION POTENTIAL

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Stress Based Approach

CSR (Cyclic Stress Ratio)

Golesorkhi (1989) did detailed analysis for this purpose. According to him,

$$r_d = \exp[\propto (z) + \beta(z) \times M]$$

Where, $\propto (z) = -1.012 - 1.126 \times \sin(\frac{z}{11.73} + 5.133)$

$$\beta(z) = -0.108 - 0.118 \times \sin(\frac{z}{11.28} + 5.142)$$

Where z is the depth of layer.

So, when we talk about this stress-based approach, CSR (cyclic stress ratio) and CRR (cyclic resistance ratio) are used. When we talk about this CSR, it deals with the characterization of the loading. So, it depends on how much load will be sustained on a particular column of soil.

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Stress Based Approach

CRR (Cyclic Resistance Ratio)

Youd et al (2001) presented all the correction factors involving liquefaction resistance. Cetin et al. (2004) and Idriss and Boulanger (2004, 2008, 2014) put forward the curve separating the liquefaction and non-liquefaction incidences.
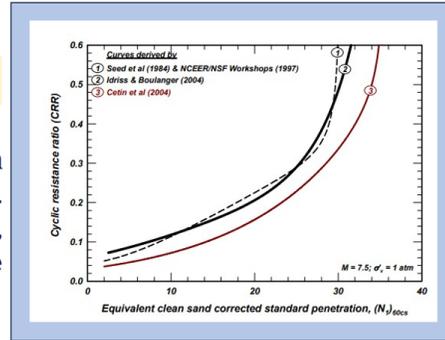
Comparison between relation given by youd et al(2001), Cetin et al (2004), Idriss & Boulanger(2004) (Idriss and Boulanger, 2014)

When we say this CRR, these parts tell us about the CSR that would cause liquefaction. So, basically, CSR is the cyclic stress ratio, and CRR tells what CSR this particular soil will fail. So, suppose this is the column of soil, and we have a CSR value. So, this is simply the characterization of the loading, but when we talk about CRR, it is basically at what value of CSR this soil will show the behavior of liquefaction.

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Stress Based Approach

CRR (Cyclic Resistance Ratio)

$$CRR_{M=7.5, \sigma'=1\,atm} = \exp\left(\left(\frac{(N_1)_{60cs}}{14.1}\right) + \left(\frac{(N_1)_{60cs}}{126}\right)^2 + \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8\right)$$

$(N_1)_{60cs}$ is corrected for clean sand.

$(N_1)_{60}$ is N_M corrected for different factors.

So, we utilize the CRR and CSR to evaluate the liquefaction potential of a specific soil or location.

Stress Based Approach

CRR (Cyclic Resistance Ratio)

$$CRR_{M=7.5,\sigma'=1\,atm} = \exp((\frac{(N_1)_{60cs}}{14.1}) + \left(\frac{(N_1)_{60cs}}{126}\right)^2 + \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8)$$

$$(N_1)_{60} = C_N \times C_E \times C_R \times C_B \times C_S \times N_M$$

C_N is correction due to overburden pressure
C_E is correction for Hammer Energy Ratio
C_R is rod length correction
C_B is Borehole diameter correction
C_S is liner correction

So, let us understand this CSR; this concept was put forward by Seed et al. (1971). The shear stress developed on a block of soil is simply the unit weight of soil times the acceleration due to ground motion, normalized by gravity. So, this is called the cyclic stress ratio. 65 percent of the maximum shear stress is taken to be the magnitude of uniform stress, and the number of cycles depends on the magnitude of the earthquake. So, here, the moment magnitude will be used. But this works if the soil is rigid, whereas that is not the case. So, the reduction factor in r_d is considered. So, r_d is very important because this works only if the soil is rigid. But we are investigating liquefaction susceptibility. So, we expect that our soil column is not rigid. So, that is why is this the road we have to know?

The CSR can be calculated using this equation. So, here you can see this road is there. So, here we are using peak ground acceleration. So, this is the max. g is the acceleration due to gravity, which is in the denominator; then sigma v, which is the total stress, is here; then sigma dash v, which is the effective stress, is again in the denominator; and $r_{d,}$ which is the depth reduction factor, is here. So, we have to find this out. So, the development of R started with Seed and Idriss (1971). They were the first ones to investigate this road. And then many researchers have worked on this problem, and they came up with several expressions to evaluate this r_d. So, this r_d can be calculated using this equation. This is from Golesorkhi 1989. He did the detailed analysis, and then he proposed this particular equation; here, you can see that alpha z, beta z, and m are all used.

Stress Based Approach

CSR (Cyclic Stress Ratio)

Golesorkhi (1989) did detailed analysis for this purpose. According to him,

$$r_d = \exp[\propto (z) + \beta(z) \times M]$$

$$\text{Where,} \propto (z) = -1.012 - 1.126 \times \sin(\frac{z}{11.73} + 5.133)$$

$$\beta(z) = -0.108 - 0.118 \times \sin(\frac{z}{11.28} + 5.142)$$

Where z is the depth of layer.

So, z is the depth. So, z is the depth of the soil column or layer. So, this alpha z is equal to minus 1.012 minus 1.126 multiplied by the sine of this, and beta z is calculated using this. So, this can be used to calculate the r_d. Idriss and Golesorkhi have proposed this graph, where you can see the x-axis is the r_d, and this is the depth M. In the previous equation, it was Idris and Golesorkhi in 1997 who proposed this particular graph, where they used the x-axis as r_d and the y-axis as depth in meters, and in the previous equation, where we were calculating the rd, this was z alpha z and beta z, if you remember.

So, this depth here has been used in meters, and here you have r_d. So, for any moment magnitude, let us say this is 5.5. If you know the magnitude and the depth, you will be able to estimate what the r_d is. If you know the depth of the soil and the moment magnitude of the earthquake, you will be able to estimate the radius. Similarly, for 6.5 moment magnitude, for 7.5 moment magnitude, and for 8, you will be able to derive this r_d value from this graph. Now, we will talk about the CRR, which is the cyclic resistance ratio. Seed et al. (1971) have been working in this area since 1971. Later, the method given by Seed et al. (1971) has been used by different researchers to update the proposed chart.

We will see them one by one. So, laboratory tests correlated the relative density of soil to its liquefaction susceptibility for fine sands. Now, here the D_{50} is equal to 0.2 millimeters and very fine, while the D_{50} is 0.7 millimeters. for water table depths of 5 meters, 10 meters, and 20 meters. So, using this fine sand and very fine sand, and for different water tables, they have analyzed the liquefaction susceptibility. Evaluating the relative density of soil in regular projects is not a practice. Henceforth, the SPT data were chosen to be

the standard field test data used for CRR estimation because of the limitations of laboratory availability or possibly the availability of instruments. So, this field information has been investigated in the SPT data. The relation between SPT and relative density from Gibbs et al. (1957) was used to check for the liquefaction susceptibility of sand with a water table at several depths because we know that SPT and relative density can both be related. So, here the data set, which was generated by Gibbs et al.1957, was used to further investigate different water tables. The standard chart was presented in Seed et al. (1971), from 35 case histories to separate liquefaction-susceptible sand from sand with no chance of liquefaction. So, they have 35 locations, which are liquefiable and non-liquefiable, and these were used further to derive a relationship. Seed and Idriss (1971) further incorporated the liquefaction and non-liquefaction incidences from various earthquakes in 1983. And that was from China and Japan, with their previous record from Seed et al. (1971). A large database was created because previously, they had only 35 points. Now, various points have been included, and then the database was generated. So, Youd et al. (2001) presented all the correlation factors involving liquefaction resistance set in et al. (2004), and Idris and Bolanger (2004, 2008, and 2014) put forward the curve separating the liquefaction and non-liquefaction incidents.

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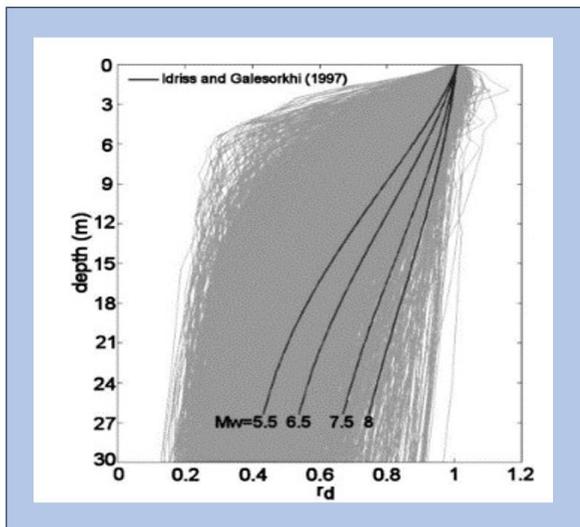
Improved r_d recommendations of Idriss and Golesorkhi (personal communication, 1997) and comparison with calculated values from cetin et al (2004)

Now, please observe this particular graph. Here, you can see that there are three lines. So, this is the first, this is the second, this is the third. So, you can carefully see this graph here; you have 1.2, and 3 lines, and that is the moment magnitude of 7.5, and the pressure is 1 atmosphere. This is the comparison between the relations given by Youd et al. (2001), Satin et al. (2004), and Idriss and Boulanger (2014). This is Idriss and Boulanger; they published it in 2014. So, here you can see the CRR value and SPTN value that were

used, and carefully observe that this is $(N1)_{60CS}$. This is the SPTN value, and this is 60 CS; CS is the clean sand. So, for each line, they are separating the liquefiable and non-liquefiable materials, and here you can see the CRR value, which is plotted for both. So, it is very important to evaluate or to calculate the $(N1)_{60CS}$ value for our sample. So, CRR, this is a moment magnitude of 7.5, and here this is 1 atmospheric pressure.

So, this is calculated using this equation. Now, here you can see what values are used. Here you can see that $(N1)_{60CS}$ is being used. So, $(N1)_{60}$ is corrected for clean sand, and $(N1)_{60}$ is the Nm that we generally observe in the field.

So, this is corrected for different factors. So, now we will see the basic information about the correction of different factors, and then we will also learn how to calculate this $(N1)_{60CS}$, which is for the clean sand. So, here is the equation that we were referring to in the previous slide. So, here we are talking about the $(N1)_{60CS}$. So, $(N1)_{60}$, first let us calculate the $(N1)_{60}$, and that is basically the correction. So, here we are using the correction due to overburden pressure. Then, the correction for the hammer energy ratio: Cr is the rod length correction, Cb is the borehole diameter correction, and cs is the liner correction. All corrections are done; then we call it $(N1)_{60}$.

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Stress Based Approach

CRR (Cyclic Resistance Ratio)

➢ C_N is can be calculated as per Kayen et al (1992) upto 300 KN/m² effective stress

$$C_N = \frac{2.2}{(1.2 + \frac{\sigma'}{100})}$$

So, this liquefaction resistance increases with increasing confining stress; this is taken into account by C_N, which is the overburden pressure correction that we have discussed in the previous slide. So, these researchers provided the expression for this C_N.

Stress Based Approach

CRR (Cyclic Resistance Ratio)

❖ Liquefaction resistance increases with increasing confining stress.
❖ This is taken into account by C_N (Overburden Pressure Correction).
❖ Youd et al (2001), Boulanger (2003), Idriss and Boulanger (2008), Idriss and Boulanger (2014) gave expressions for this.
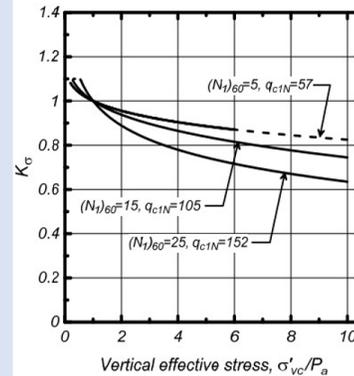
Overburden correction factor (K_σ) relationship (Idriss and Boulanger (2014))

Now, you see this graph here; they have given these lines, and this is, let us say, for this line (N1)$_{60}$ is equal to. This is for (N1)$_{60}$, which is equal to 15, and this one is for (N1)$_{60}$, which is equal to 25. So, this is the overburden correction factor. So, this is the relationship with the vertical effective stress, sigma dash Vc.

Stress Based Approach

CRR (Cyclic Resistance Ratio)

$$(N_1)_{60cs} = (N_1)_{60} + \Delta(N_1)_{60}$$

Where,

$(N_1)_{60cs}$ is $(N_1)_{60}$ corrected for clean sand.

$\Delta(N_1)_{60}$ is a function of Fines Content.

Stress Based Approach

CRR (Cyclic Resistance Ratio)

➢ C_N is can be calculated as per Kayen et al (1992) upto 300 KN/m² effective stress

$$C_N = \frac{2.2}{(1.2 + \frac{\sigma'}{100})}$$

For the CRR calculation and for the correction, C_N is calculated using the equation given by Kayen et al., which is applicable up to 300 effective stresses. See the unit. So, here you can see that C_N is equal to 2.2 divided by 1.2 plus sigma dash divided by 100. So, this sigma dash, now we have to see if C_N can be calculated as per Youd et al. (2001).

They have also given the formula for C_N calculation, and it is beyond the 300 effective stress. So, C_N up to 1.7 is considered here; beyond that, the value of 1.7 is only taken, and CE is ER by 60 percent. So, where ER is the rod energy ratio. So, 60 percent of the rod energy is being utilized. Cr is the rod length correction factor that accounts for the energy ratio being smaller with shorter rod lengths. Cb is the borehole diameter correction.

And CS is the linear correction. These corrections were used in the previous equation, and then subsequently, $(N1)_{60CS}$ will be calculated. Now, here we have calculated $(N1)_{60}$. Now, we have to look for this delta $(N1)_{60}$. So, $(N1)_{60CS}$ is the $(N1)_{60}$ corrected for clean sand, which is this one, and delta $(N1)_{60}$ is a function of fines content. So, what is the content of the fines in your sample? So, this delta N1 can be calculated using this expression.

Stress Based Approach

CRR (Cyclic Resistance Ratio)

$$\Delta(N_1)_{60} = \exp\left(1.63 + \frac{9.7}{FC + 0.001} - \left(\frac{15.7}{FC + 0.001}\right)^2\right)$$

Where FC is Fines Content.

❖ **Fines content** refers to the percentage of fine-grained particles (silt and clay) present in a soil. These particles are typically smaller than 0.075 mm (75 microns) in diameter, as defined by the Unified Soil Classification System (USCS).

And, where the FC is used, FC is basically your fines content, which refers to the percentage of fine-grain particles, namely silt and clay, present in your soil sample. These particles are typically smaller than 0.075 millimeters or 75 microns in diameter, as defined by the USCS. So once CRR is computed, it is corrected with respect to the static stress and magnitude factor. Now we are going to correct this CRR with respect to static stress and the magnitude factor.

Stress Based Approach

Once CRR is computed, it is corrected with respect to static stress and magnitude factor.

$$CRR_{M,\sigma'} = CRR_{M=7.5,\sigma'=1\,atm} \times K_\alpha \times MSF$$

MSF is Magnitude Scaling Factor

K_α is the correction for static stress

So, here you can see that this expression is used. So, here, MSF is the magnitude scaling factor. This one and k-alpha are the corrections for static stress. So, the magnitude scaling

factor that we calculate using this graph. So, Seed and Idriss (1971) introduced the magnitude scaling factor in 1983, and then the scaling factor for magnitude was subsequently modified according to Youd et al. (2001). The complete set has to be used together. So, the earthquake moment magnitude is on the x-axis, and the magnitude scaling factor, which is MSF, is you remember the previous equation.

So, here the MSF is being used. Now, here you can see that MSF is equal to 6.9, which is the exponential of m by 4. So, subtract m by 4; this m is your moment magnitude. So, this is the relationship that is used further to investigate the liquefaction potential. Now, let us talk about the initial static shear stress. This is k-alpha, so we have to use it in the previous equation. It was initially proposed by Seed and Harded (1990); Youd et al. (2001) gave the variation of k-alpha with respect to relative density. Now, here you have four different relative densities, and you have a relation with the k-alpha.

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Stress Based Approach

Initial Static Shear Stress (K_α)

❖ It was initially Proposed by Seed and Harded (1990)

❖ Yould et al (2001) gave the variation of K_α with respect to relative density
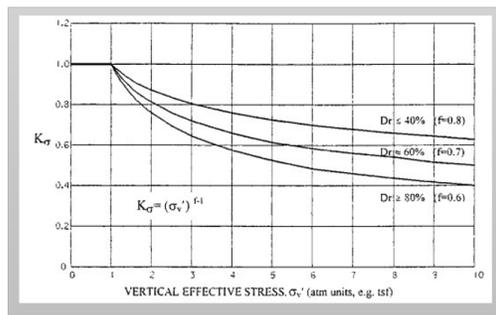
Recommended Curves for Estimating Ks for Engineering Practice (Youd et al, 2001)

So, if you refer to this graph, the vertically effective stress is given, and the k-alpha is given. So, using this relation, you can calculate the k-alpha. So, finally, we are having the CRR meeting and sigma dash, and the CSR. I told you that CRR indicates at what CSR the soil has liquefaction susceptibility.

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FACTOR OF SAFETY:

$$FOS = \frac{CRR_{M,\sigma'}}{CSR}$$

Where, M is the moment magnitude and σ' is the effective overburden pressure.

Once FOS is computed, we can compute the liquefaction potential index which accounts for all the depths till 20m and gives the liquefaction vulnerability for a particular location.

So, this factor of safety can be calculated using this equation, where m is the moment magnitude and sigma dash is the effective overburden pressure. So, once the factor of safety is computed, we can compute the liquefaction potential index, which accounts for all the depths up to 20 meters and gives the liquefaction vulnerability for a particular location. Now, we have the factor of safety for a specific location for a particular soil.

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$$\text{Liquefaction Potential Index (LPI)} = \int_0^{20} F(z) \times w(z)$$

Where ,
$F(z) = 1 - FOS$ when FOS <0.95
$F(z) = 2 \times 10^6 \times e^{-18.427 \times FOS}$ when 0.95 < FOS <1.2
$F(z) = 0$ when FOS >1.2
$W(z) = 10 - 0.5 \times Z$ when Z (depth below ground level is equal to or less than 20 m.)
Or else $W(z) = 0$.

Now, we will talk about the Liquefaction Potential Index. So, this is the function of z. To calculate the liquefaction potential index, we are using this formula, and here we are integrating the depth up to 20 meters. So, let us see the details. So, F(z) is equal to 1

minus fos when fos is less than 0.95. Then comes the second criterion. So, F(z) is equal to 2 times 10 to the power of 6 multiplied by e to the power of this multiplied by the factor of safety.

When the factor of safety is less than 0.95, we use this to calculate F(z). So, this is 1 minus the factor of safety. When the factor of safety has this condition. Then, we use this to calculate F(z). When the factor of safety is greater than 1.2, we use F(z) equal to 0. Now comes the W(z). So, we calculate W(z) when z. Then comes the W(z). So, we calculate W(z) using this formula. So, 10 minus 0.5 multiplied by z, when z is the depth below ground level, which is equal to or less than 20 meters.

$$\text{Liquefaction Potential Index (LPI)} = \int_0^{20} F(z) \times w(z)$$

Analysis of LPI Values:
- If LPI is 0, liquefaction risk is very low
- If LPI is between 0-5, liquefaction risk is low
- If LPI is between 5-15, liquefaction risk is high
- If LPI is >15, liquefaction risk is very high

So, as I said, it is the integration of the depth up to 20 meters. But what if we have more than that? So, if W(z) is equal to 0, it is being used in this liquefaction potential index. Now, how do we analyze these results and the value we are getting from this LPI? To analyze the values obtained from the LPI calculation, if the LPI is 0, we will say that the liquefaction risk is very low. If LPI is between 0 and 5, liquefaction risk is low; if LPI is between 5 and 15, liquefaction risk is high; and if LPI is greater than 15, then liquefaction risk is very high. Therefore, we analyze the susceptibility of a particular soil to liquefaction.

These are the references that I have used in this presentation. So, if you are interested in having more details on each of the parameters or the method, then you can refer to these papers.

Thank you. Thank you very much.