Rock Mechanics and Tunneling
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Lecture No. 34
Empirical Failure Criteria for Rock (Continued)

Hello everyone, I welcome all of you to the third lecture of module 7. So, in module 7 we are discussing about the rock and rock mass failure criteria. In our previous lecture we have started discussing about different empirical failure criteria for rock and we will continue that discussion today also.

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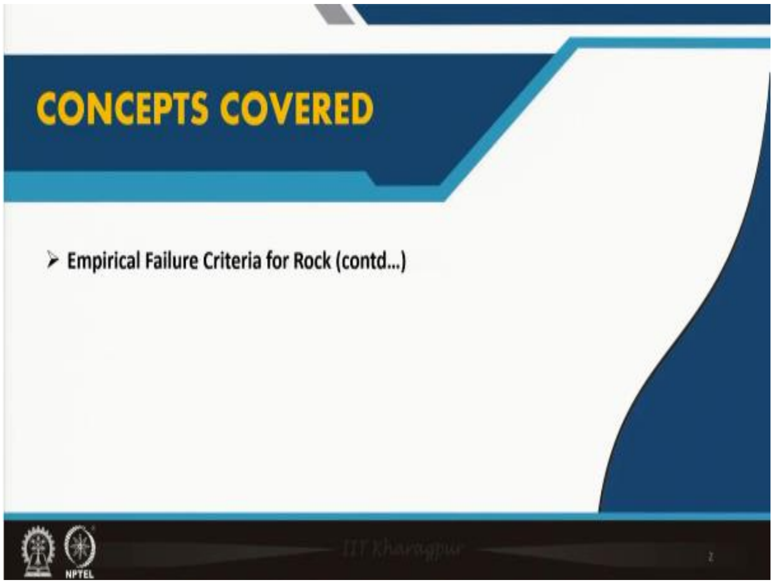

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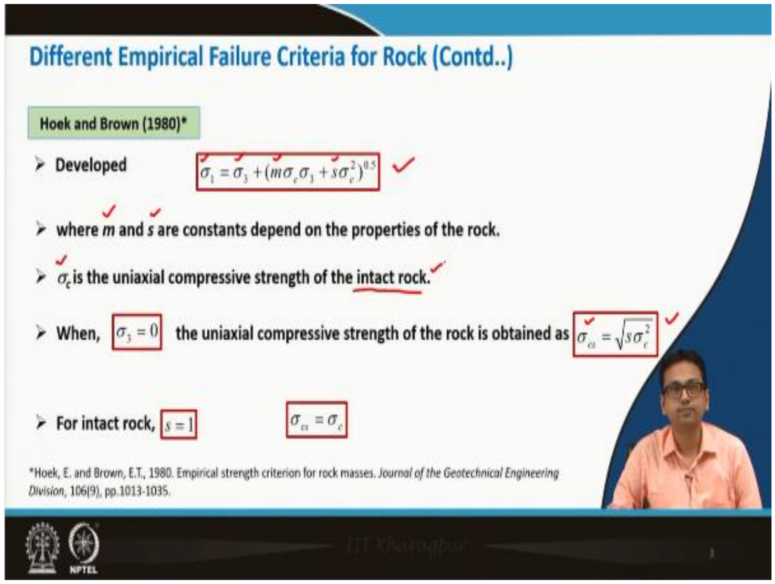

Hoek and Brown (1980)

developed $\sigma_1 = \sigma_3 + (m\sigma_c\sigma_3 + s\sigma_c{}^2)^{0.5}$

where σ_1 is major principle stress, σ_3 is minor principle stress, m and s are the constants that depend on the properties of rock. σ_C is the uniaxial compressive strength of intact rock. Now when $\sigma_3 = 0$, the uniaxial compressive strength of the rock mark is obtained as $\sigma_{cs} = \sqrt{s\sigma_c{}^2}$. Now for intact rock $s = 1$, so $\sigma_{cs} = \sigma_c$.

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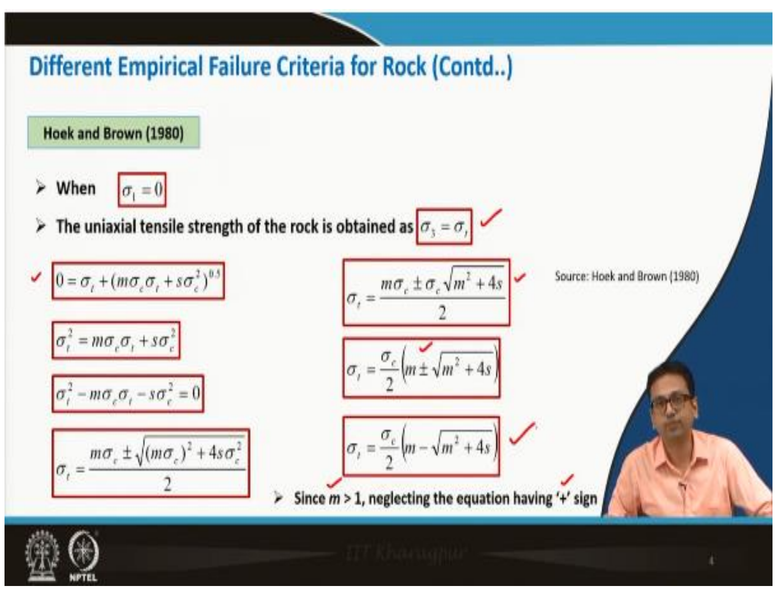

Now for further discussion when $\sigma_1 = 0$, the uniaxial tensile strength of the rock is obtained as $\sigma_3 = \sigma_t$ or by further simplifying the previous equation

$$\sigma_1 = \sigma_3 + (m\sigma_c\sigma_3 + s\sigma_c{}^2)^{0.5}$$

$$0 = \sigma_t + (m\sigma_c\sigma_t + s\sigma_c{}^2)^{0.5}$$

$$\sigma_t{}^2 = m\sigma_c\sigma_t + s\sigma_c{}^2$$

$$\sigma_t{}^2 - m\sigma_c\sigma_t - s\sigma_c{}^2 = 0$$

$$\sigma_t = \frac{m\sigma_c \pm \sigma_c\sqrt{m^2 + 4s}}{2}$$

$$\sigma_t = \frac{\sigma_C}{2}\left(m \pm \sqrt{m^2 + 4s}\right)$$

Now since m is greater than 1, (as suggested by Hoek and Brown)

$$\sigma_t = \frac{\sigma_C}{2}\left(m - \sqrt{m^2 + 4s}\right)$$

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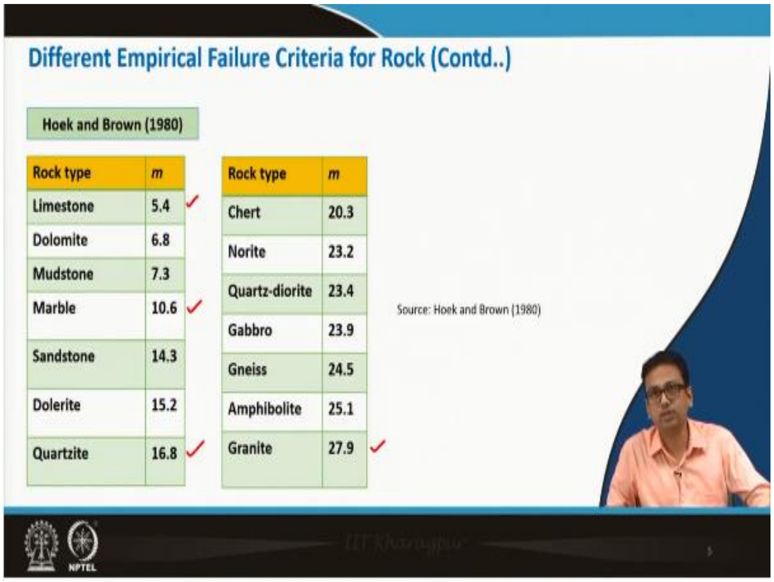

Refer to the tables given in slide 6 of this lecture for *m* values of different types ofrock so by giving these as the input you can utilize the equation of Hoek and Brown for any numerical calculation.

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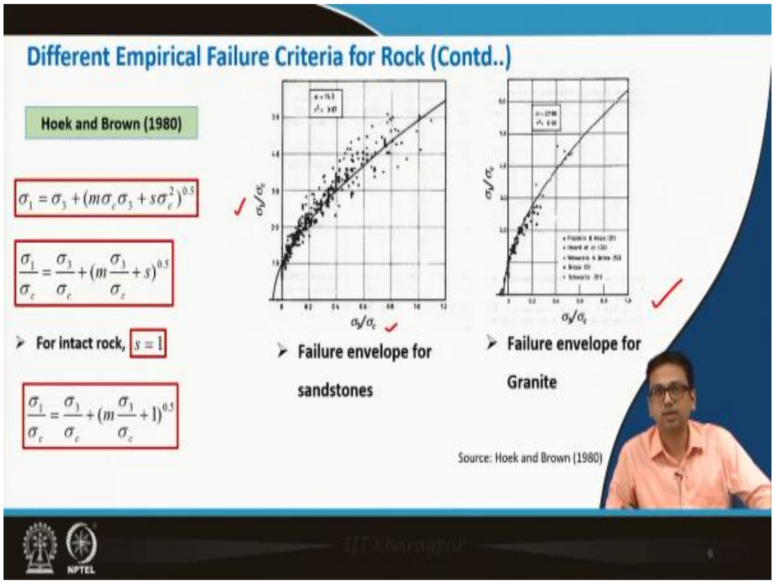

Now by further playing with the following equation

$$\sigma_1 = \sigma_3 + (m\sigma_c\sigma_3 + s\sigma_c{}^2)^{0.5}$$

$$\frac{\sigma_1}{\sigma_C} = \frac{\sigma_3}{\sigma_C} + \left(m\frac{\sigma_3}{\sigma_C} + s\right)^{0.5}$$

For intact rock $s = 1$

$$\frac{\sigma_1}{\sigma_C} = \frac{\sigma_3}{\sigma_C} + \left(m\frac{\sigma_3}{\sigma_C} + 1\right)^{0.5}$$

The above equation can be used to fit the failure envelope plot for different rocks. Refer to the plots in slide 6 and you can see that the fit is quite good.

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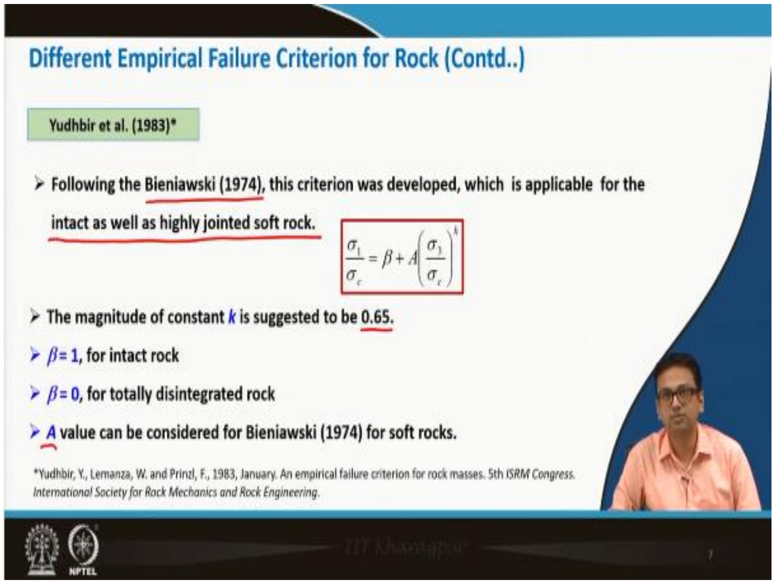

Yudhbir et al. (1983)

Following Bieniawski (1974), this criterion was developed, which is applicable for the intact as well as highly jointed soft rock.

$$\frac{\sigma_1}{\sigma_C} = \beta + A\left(\frac{\sigma_3}{\sigma_C}\right)^k$$

the magnitude of the constant k is suggested to be 0.65.

So, $\beta = 1$ for intact rock and $\beta = 0$ for totally disintegrated rock. A value can be considered, from Bieniawski 1974 for soft rock.

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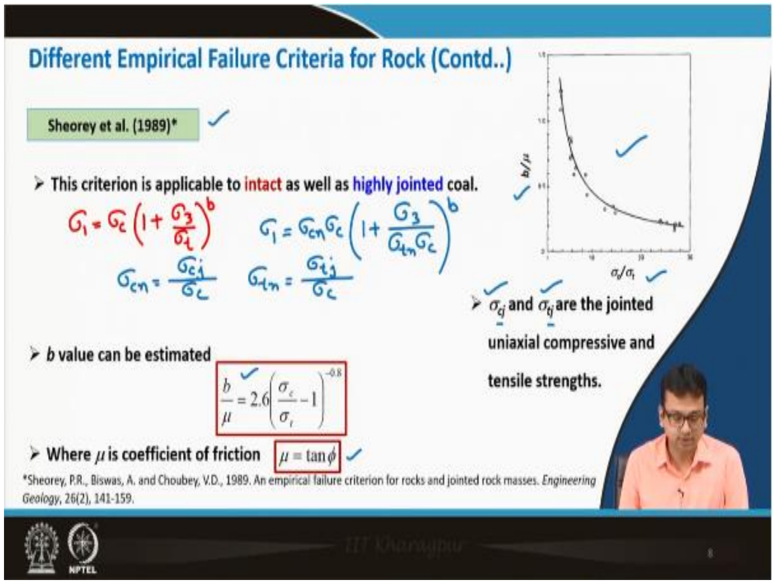

Sheorey et al (1989)

This criterion is applicable to intact as well as highly jointed coal.

For intact coal

$$\sigma_1 = \sigma_C \left(1 + \frac{\sigma_3}{\sigma_t}\right)^b$$

For highly jointed coal

$$\sigma_1 = \sigma_{Cn}\sigma_C \left(1 + \frac{\sigma_3}{\sigma_{tn}\sigma_C}\right)^b$$

$$\sigma_{Cn} = \frac{\sigma_{Cj}}{\sigma_C} \text{ and } \sigma_{tn} = \frac{\sigma_{tj}}{\sigma_C}$$

where σ_{Cj} and σ_{tj} are the jointed uniaxial compressive and tensile strength of intact rock.

b value can be estimated from the equation provided by Sheorey et al. 1989,

$$\frac{b}{\mu} = 2.6\left(\frac{\sigma_c}{\sigma_t} - 1\right)^{-0.8}$$

Refer to the plot in slide 8.

where μ is the coefficient of friction, $\mu = \tan\phi$.

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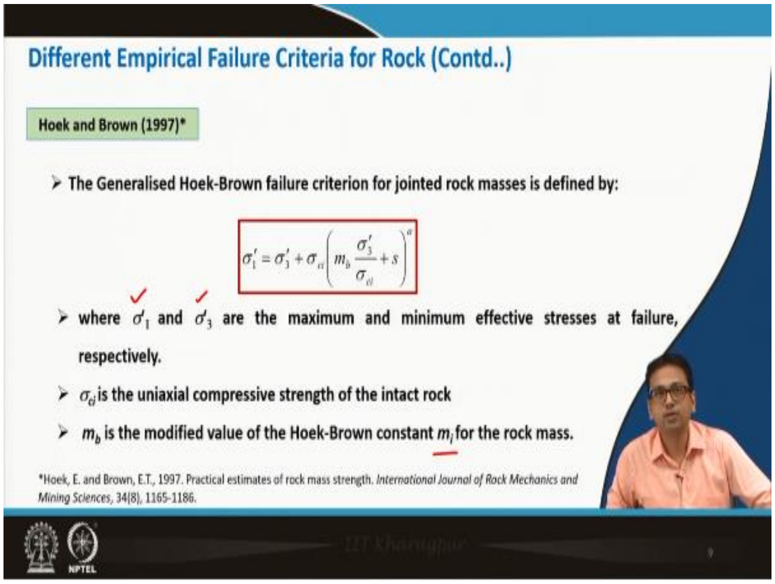

Hoek and Brown (1997)

The generalized Hoek Brown failure criterion for jointed rock masses is defined by the following equation

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_b \frac{\sigma_3'}{\sigma_{ci}} + s\right)$$

where σ_1' and σ_3' are the maximum and minimum effective stresses at failure, σ_{ci} is the uniaxial compressive strength of the intact rock, m_b is the modified value of Hoek Brown constant m_i for the rock mass.

$$m_b = m_i \exp\left(\frac{GSI - 100}{28}\right)$$

value of the constant m_i can be obtained from the table (refer to slide number 10).

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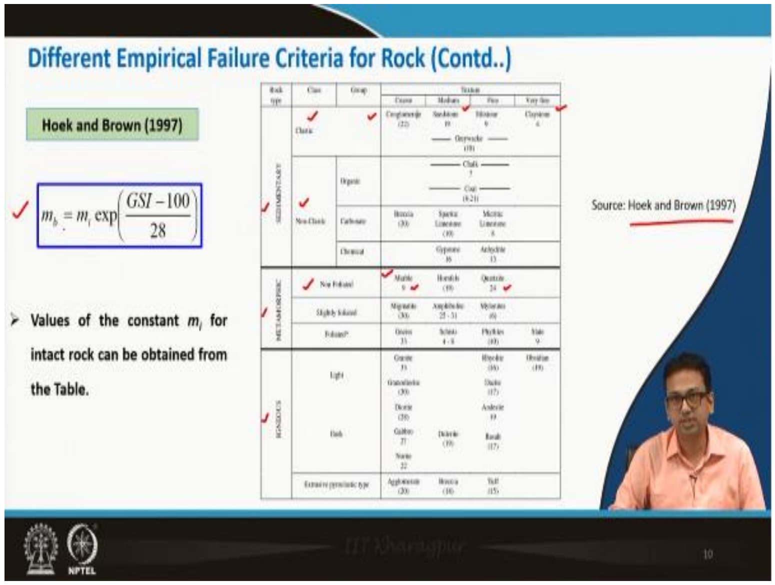

GSI value can be found from the table given by Hoek Brown 1997 based on structure and surface condition.

Later Hoek and Brown suggested that if GSI>25, $GSI = RMR_{89} - 5$.

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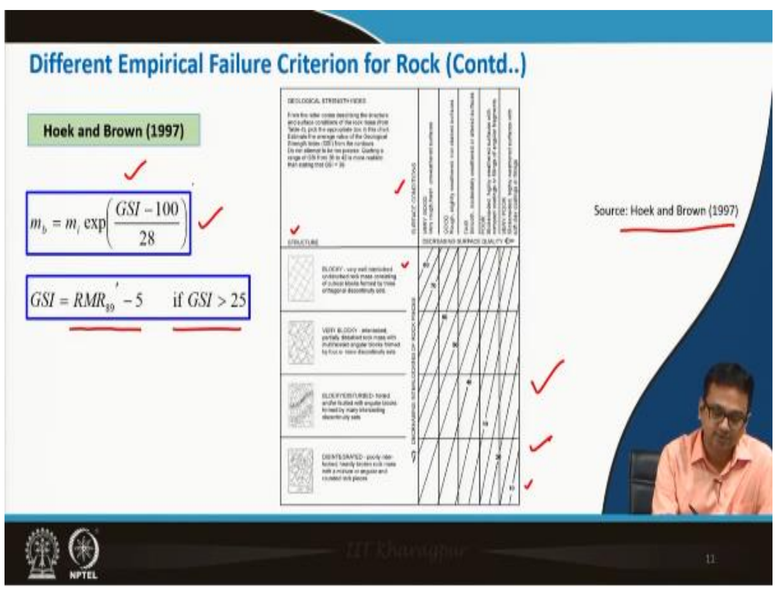

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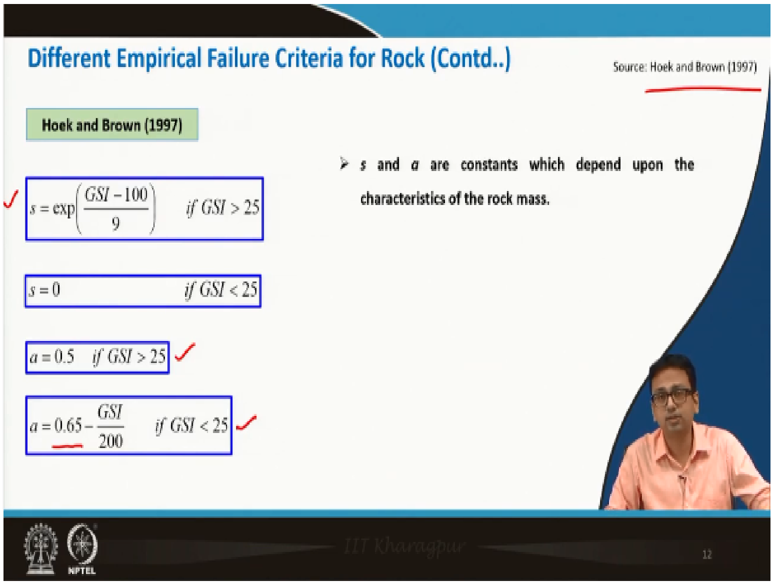

Now as per this Hoek and Brown there are other two parameters *s* and *a*.

$$s = \exp\left(\frac{GSI-100}{9}\right) \qquad if\ GSI > 25$$

$$s = 0 \qquad if\ GSI < 25$$

$$s = \exp\left(\frac{GSI-100}{9}\right) \qquad if\ GSI > 25$$

$$a = 0.65 - \frac{GSI}{200} \qquad if\ GSI < 25$$

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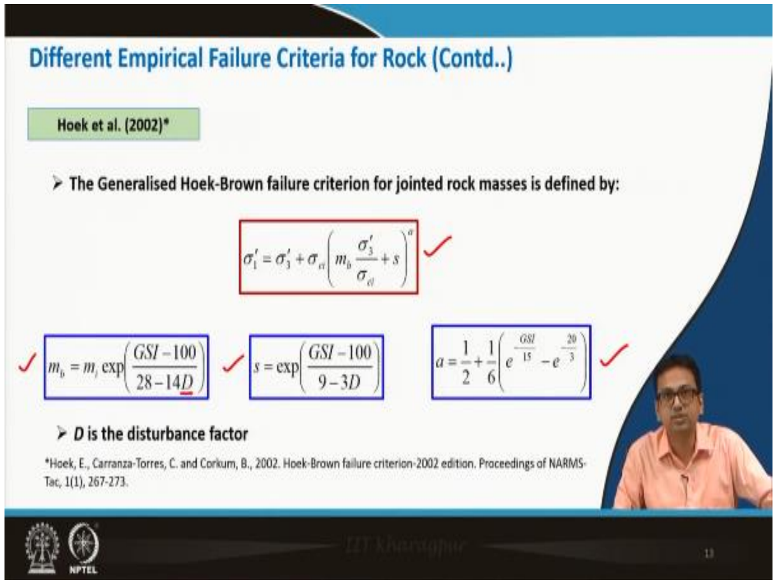

Hoek et al 2002, is the most widely used criterion as it takes into account almost all the flaws that were there in the previous version. So, the generalized Hoek Brown failure criteria for jointed rock masses is defined by

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_b \frac{\sigma_3'}{\sigma_{ci}} + s\right)^a$$

$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D}\right) \qquad s = \exp\left(\frac{GSI - 100}{9 - 3D}\right) \qquad a = \frac{1}{2} + \frac{1}{6}\left(e^{-\frac{GSI}{15}} - e^{-\frac{20}{3}}\right)$$

The above equations are quite similar to Hoek and Brown 1997 but with some modifications. Authors have introduced a new factor, D. D is the disturbance factor.

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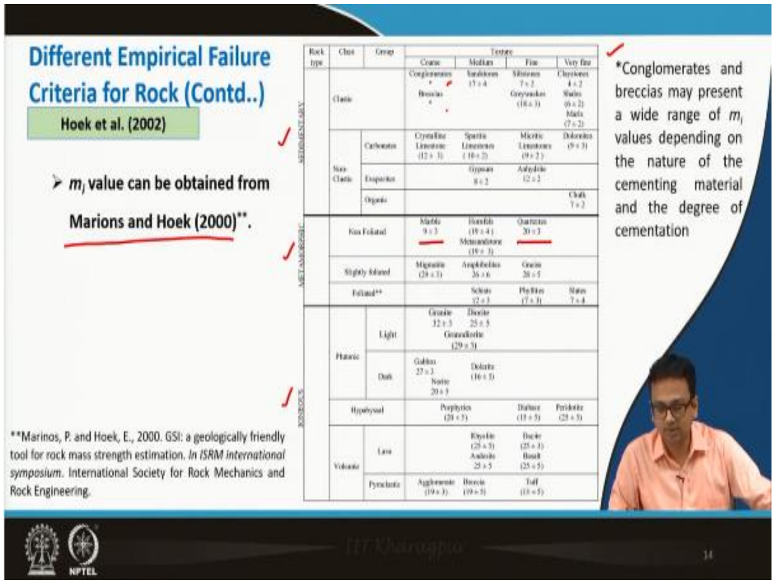

Now for finding out m_i, in 1997, a table was given different types of rock like sedimentary, metamorphic, igneous but again Marions and Hoek in 2000 modified it and they have given a new table which is a little different from the previous one. In this table for different rocks m_i can fall in a range.

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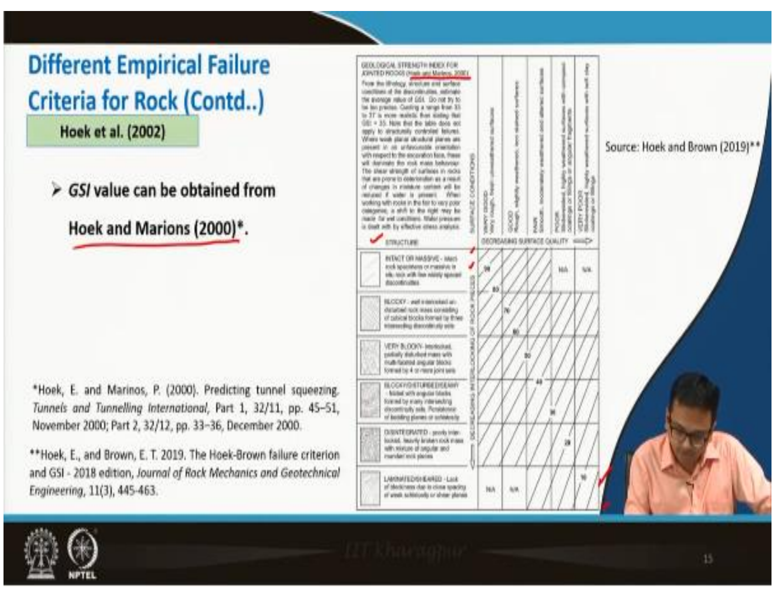

Now for the GSI value again Hoek and Marions 2000 gave another table (refer to the slides)

Hoek et al 2002 says that now you do not have to use RMR table, you can directly find out your GSI using this table and utilize that for obtaining your required parameters like m_b, s and a.

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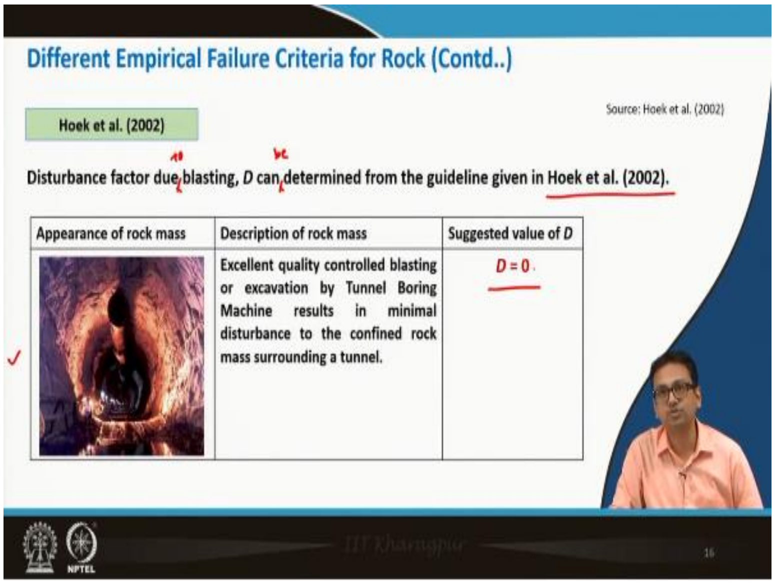

So, now regarding D, the disturbance factor due to blasting can be determined from the guideline given in Hoek et al 2002. In their paper you will find pictures and description of rocks and D value corresponding to that.

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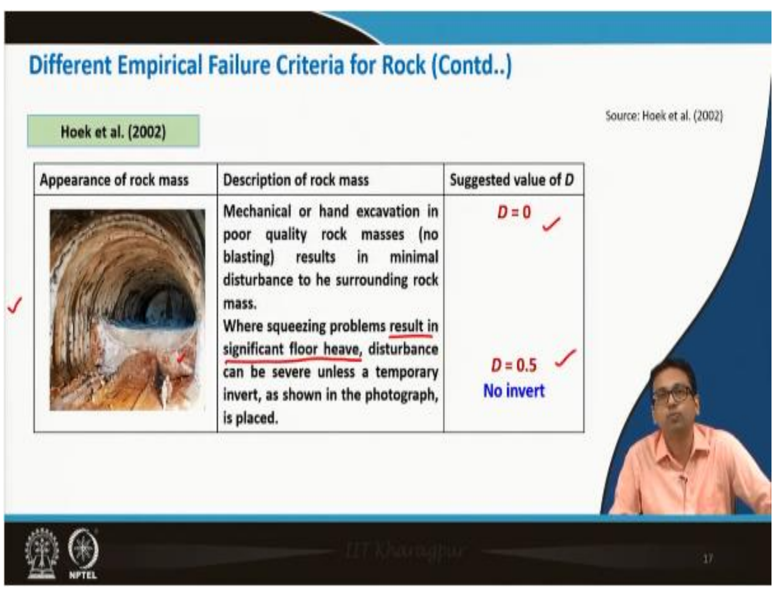

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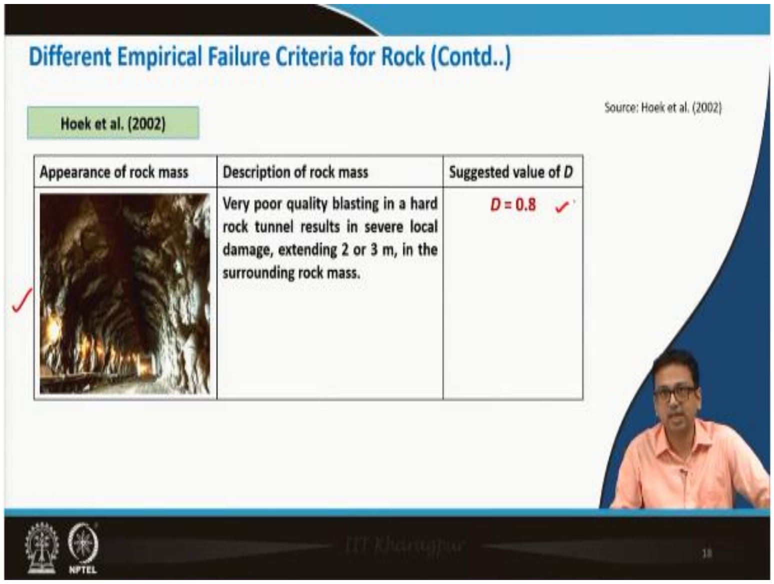

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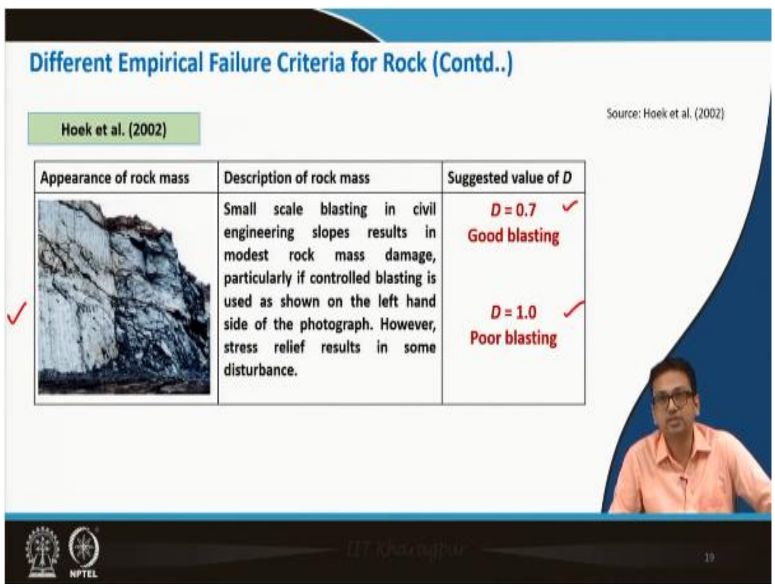

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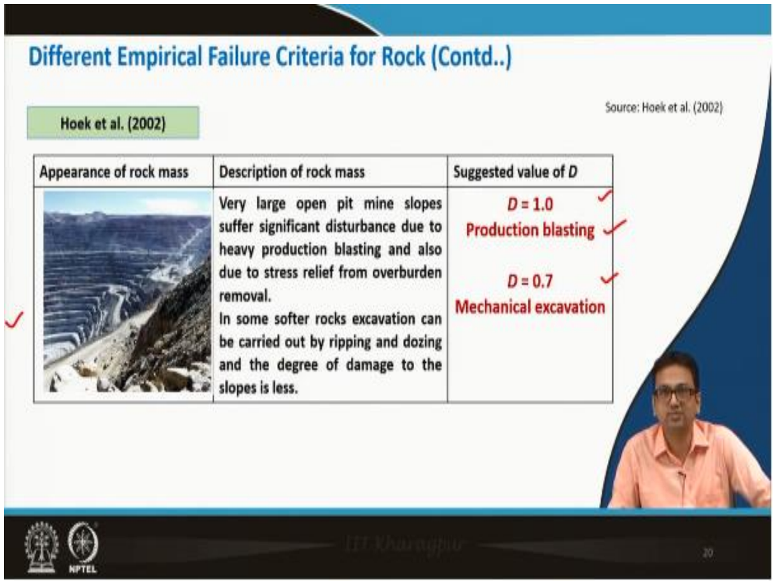

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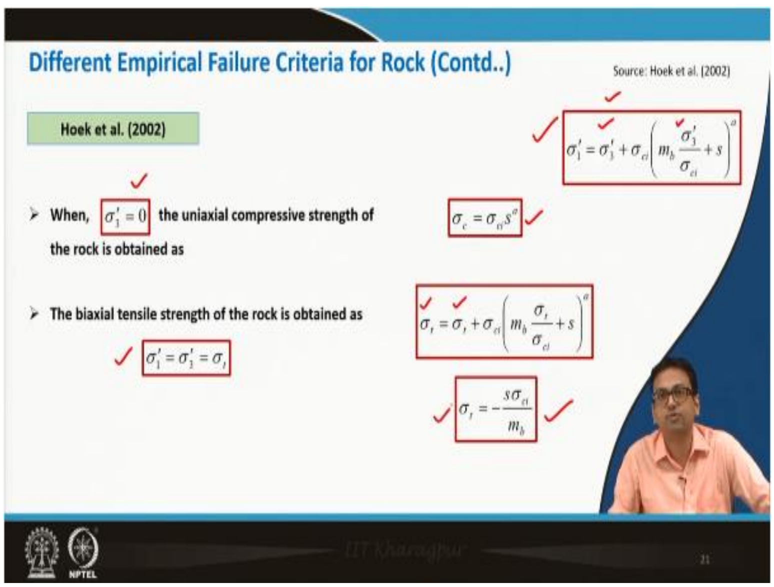

So, finally from Hoek et al 2002 equations,

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_b \frac{\sigma_3'}{\sigma_{ci}} + s\right)^a$$

When, $\sigma_3' = 0$ the uniaxial compressive strength of the rock is obtained as

$$\sigma_c = \sigma_{ci} s^a$$

The biaxial tensile strength of the rock is obtained as

$$\sigma'_1 = \sigma'_3 = \sigma_t$$

$$\sigma_t = \sigma_t + \sigma_{ci} \left(m_b \frac{\sigma_t}{\sigma_{ci}} + s \right)^a$$

$$\sigma_t = -\frac{s\sigma_{ci}}{m_b}$$

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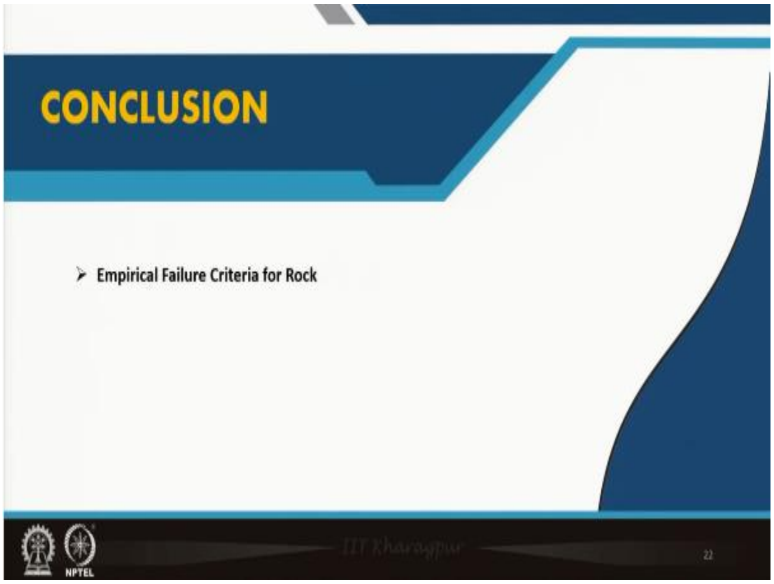

So, in conclusion what we can say basically we have today also discussed about the empirical failure criteria for rock and in our previous tasks also we have discussed the few other empirical failure criteria and then we have discussed about the most important failure criteria that is Hoek et al 2002 and we have discussed that in detail which need to be used for rock mass modeling. For a better modeling of the rock mask this criterion is quite acceptable and is used with good confidence. So, thank you, so let us conclude our today's lecture here only.