Failure Envelopes For Jointed Rocks In Lesser Himalayas

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"Nothing satisfies the man who is not satisfied with little"
- *Epicurus (341-270 B.C.)*

ABSTRACT

Insitu shear strength is difficult to measure. Accurate representation of the real field conditions is difficult because the strength parameters, cohesion (c) and angle of internal friction (ϕ) are not constant throughout the rock mass but vary from place to place, from project to project. In fact, correct measurement of rock mass shear strength has always remained a big field problem. Usually failure of a rock mass occurs partially along the joints and partially in solid rock, but in boundary cases, failure may occur entirely along a joint or entirely in solid rock. Thus, the failure of a rock mass lies within the area bounded by the failure envelope for a single joint and the failure envelope for solid rock. This paper discusses the shear strength envelopes developed for various rock mass ratings, degree of saturation and rock types tested in the Lesser Himalayas. The recommended failure criteria are based on the results of extensive field tests, judgment and own experience of the author. It has been realised that for highly jointed rock masses shear strength will not be governed by the strength of the rock material. The effect of saturation on the shear strength of poor rocks has been found to be significant. The results of the study have been presented in the form of failure envelopes which may be used for estimating the angle of internal friction (ϕ) and shear strength developed at a given normal stress.

1. INTRODUCTION

The failure envelopes for the jointed rock masses show generally a non-linear trend. The strength characteristics in such cases are primarily controlled by the rock type, the block shape and the size and surface condition of the intersecting discontinuities. Extensive large scale in-situ block shear tests were carried out in different types and quality of rocks so that they represent an average condition of the rock mass. The locations of the tests were decided such that the effects of specific features such as faults, folds, dykes or shear zones are also included. The failure envelopes which have been developed for both dry and saturated rock masses show stress dependency and in many cases envelopes show similar trend as given by Hoek and Brown (1980). The envelopes may be used for shear strength determination at the desired level of normal stress and will prove helpful in carrying out stability analyses of rock masses to be encountered in the Lesser Himalayas.

2. FAILURE ENVELOPES FOR 'POOR' ROCK MASSES

Four different category of "poor" rock masses were investigated in the Lesser Himalayas. The properties and characteristics of these rocks have been listed in Table I.

Table I Properties and Characteristics of "Poor" Rock Masses *[Mehrotra (1992)]*

Jointed Rock Mass	[1]nmc (%)	[2]RMR	[3]Q-index	[4]q_c (nmc) (kg/cm^2)	q_c (sat) (kg/cm^2)
Limestone	0.30-2.80	29-37	0.4-1.5	300-500	200-400
Slate, Xenolith and Phyllite	0.75-1.85	23-37	0.3-1.0	350-850	200-600
Sandstone and Quartzite	0.40-1.50	22-36	0.1-2.5	400-1000	350-700
Trap and Metabasic	0.28-0.60	24-40	0.3-2.5	750-1500	600-1200

1 natural moisture content [nmc]

2 Bieniawski's rock mass rating [RMR]

3 Barton's rock mass quality index [Q]

4 uniaxial compressive strength of rock material at natural moisture content [$q_{c(nmc)}$]

5 uniaxial compressive strength of rock material at saturation [$q_{c(sat)}$]

2.1 Limestone

The failure envelopes for jointed limestone at natural moisture content and saturated conditions have been predicted by the following expressions [Mehrotra (1992)]:

$$\tau_{nmc} = 2.5(\sigma + 0.80)^{0.646} \quad [1]$$

$$\tau_{sat} = 1.5(\sigma + 0.75)^{0.646} \quad [2]$$

Figure 1 shows the failure envelopes for naturally -moist and- saturated limestones. The rock has been categorised as "poor" rock mass (RMR = 29 - 37). Figure 1 also shows friction factor ($\tan\phi$) plotted as a function of normal stress (σ), ϕ being the angle of internal friction of the rock mass at the failure plane. The cohesion parameter (value of τ at $\sigma = 0$) of the limestone for naturally moist, and under saturation have been found to be 2.20 kg/cm^2 and 1.25 kg/cm^2 respectively. It is further observed that there is no significant change in the values of $\tan\phi$ beyond a normal stress (σ) value of 20 kg/cm^2 at which $\tan\phi$ equals 0.55 ($\phi=29^0$) for the naturally moist and 0.33 ($\phi=18^0$) for the saturated rock mass.

2.2 Slates, Xenoliths and Phyllites

The failure envelopes for naturally moist and saturated slates, xenoliths, phyllites have been predicted by the following equations [Mehrotra (1992)]:

$$\tau_{nmc} = 2.65(\sigma + 0.75)^{0.655} \quad [3]$$

$$\tau_{sat} = 1.75(\sigma + 0.70)^{0.655} \quad [4]$$

The plots of the failure envelopes are shown in Fig. 2.

Figure 2 also shows $\tan\phi$ plotted as a function of normal stress (σ). The rocks have been categorised as 'poor' rock mass (RMR=23-37). It is observed that the rock mass has cohesion values of 2.2 kg/cm^2 and 1.4 kg/cm^2 for naturally moist and saturated rock masses respectively. It is also observed that there is no significant change in the values of tanf beyond a normal stress (σ) value of 20 kg/cm^2 at which $\tan\phi$ equals 0.61 ($\phi=31^0$) and 0.40 ($\phi=22^0$) for the naturally moist and saturated rock masses respectively. If we compare these results with those of limestone we find that cohesion is comparatively higher in case of saturated slates, xenoliths and phyllites as against 1.3 kg/cm^2 in case of limestone. The value of $\tan\phi$ are also comparatively higher in case of slates, xenoliths and phyllites. Low strength of the poor quality limestone at saturation may be due to possible disintegration of material at the joints of the rock mass. Such disintegration effect may be on account of the presence of some minerals which might be chemically active with moisture. This strongly calls for a long-term study of the limestone under saturation [Mehrotra et al. (1991)]:

2.3 Sandstone and Quartzite

The failure envelopes for jointed sandstone and quartzite at natural moisture content and saturated conditions are expressed by the following equations [Mehrotra (1992)]:

$$\tau_{nmc} = 2.8 \ (\sigma + 0.70)^{0.672} \quad [5]$$

$$\tau_{sat} = 2.0 \ (\sigma + 0.65)^{0.672} \quad [6]$$

Figure 3 shows the failure envelopes for naturally moist and saturated sandstone and quartzite which have been categorised as "poor" rock mass (RMR=22-36). As in case of limestone and slate, xenoliths and phyllite, the failure envelopes are stress dependent and show the cohesion intercepts of 2.2 kg/cm^2 and 1.5 kg/cm^2 for naturally moist and saturated rock masses respectively. As in previous cases, it is observed that there is no significant change in the values of tanf beyond a normal stress value of 20 kg/cm^2 at which $\tan\phi$ equals 0.70 ($\phi=35^0$) for the saturated rock masses. Figure 3 also shows that the shear strengths of the jointed sandstone and quartzite are comparatively higher than those of the limestone, slates, xenoliths and phyllites.

2.4 Metabasics and Trap Rocks

Failure envelopes for naturally moist and saturated metabasics and trap rocks have been fitted to the following expressions [Mehrotra (1992)]:

$$\tau_{nmc} = 3.00 \ (\sigma + 0.65)^{0.676} \quad [7]$$

$$\tau_{sat} = 2.25 \ (\sigma + 0.60)^{0.676} \quad [8]$$

The rocks have been classified as "poor" rock mass (RMR = 24 - 40). The failure envelopes for Eq.(7) and Eq.(8) are shown in Fig. 4. It is seen that cohesion for the naturally moist and saturated rock masses are 2.2 kg/cm^2 and1.6 kg/cm^2 respectively. Figure 4 also shows that beyond a normal stress (σ) value of 20 kg/cm^2 there is no significant change in the values of $\tan\phi$. At normal stress (σ) of 20 kg/cm^2, $\tan\phi$ equals 0.76($\phi=37^0$) for the rock mass at natural moisture and 0.57 ($\phi=30^0$) for the rock mass under saturation.

As noted from Figs.1 to 4 the effect of saturation on the shear strength has been found to be significant. When saturated, the reduction in the shear strength is about 30 per cent at the normal stress (σ) level of 20 kg/cm^2.

3. FAILURE ENVELOPES FOR "FAIR" ROCK MASSES

Three different categories of "fair" rock masses have been investigated in the study. The properties and characteristics of these rocks are listed in Table II.

Table II Properties and Characteristics of "Fair" Rock Masses *[Mehrotra(1992)]*

Jointed Rock Mass	nmc (%)	RMR	Q-index	q_c (nmc) (kg/cm^2)	q_c (sat) (kg/cm^2)
Slate, Xenolith and Phyllite	0.25-0.94	43-56	2.0-3.5	350-850	200-600
Sandstone and Quartzite	0.40-1.50	41-58	1.9-5.1	400-1000	350-700
Trap and Metabasics	0.28-0.60	42-59	1.5-4.0	750-1500	600-1200

3.1 Slates, Xenoliths and Phyllites

The failure envelopes for jointed slates, xenoliths and phyllites at natural moisture content and saturated conditions have been predicted by the following expressions [Mehrotra (1992)]:

$$\tau_{nmc} = 2.75(\sigma + 1.15)^{0.675} \quad [9]$$

$$\tau_{sat} = 2.15(\sigma + 1.10)^{0.675} \quad [10]$$

Figure 5 shows the failure envelopes for the naturally moist and saturated slates, xenoliths and phyllites. These rocks have been categorised as "fair" rock mass (RMR = 43-56). Figure 5 also shows $\tan\phi$ plotted as a function of normal stress (σ).

It is observed that the failure envelopes are non-linear with cohesion intercepts of 3 kg/cm^2 for the rock mass at natural moisture and 2.3 kg/cm^2 for the rock mass under saturation. As in case of "poor" rock masses, it is observed in "fair" category jointed slates, xenoliths and phyllites also that there is no significant change in the values of tanϕ beyond a normal stress (σ) value of 20 kg/cm^2 at which tanϕ equals 0.64 (ϕ=35°) for the naturally moist, and 0.54 (ϕ=28°) for the saturated rock masses. It is thus seen that shear strength scenario of "fair" category slates, xenoliths and phyllites is comparatively better than those of "poor" category rock masses which is expected also.

3.2 Sandstone and Quartzites

Failure envelopes for naturally moist and saturated sandstones and quartzites, categorised as 'fair" rock mass (RMR = 41 - 58) have been predicted by the following expressions [Mehrotra (1992)]:

$$\tau_{nmc} = 2.85(\sigma + 1.10)^{0.688} \quad [11]$$

$$\tau_{sat} = 2.25(\sigma + 1.05)^{0.688} \quad [12]$$

Figure 6 shows the failure envelopes for naturally moist and saturated sandstones and quartzites. These rocks have been classified as "fair" rock mass (RMR = 41 - 58). It is seen that the failure envelopes are stress dependent and show the cohesion values of 3 kg/cm^2 for the rock mass at natural moisture and 2.3 kg/cm^2 for the rock mass under saturation. It is also observed that there is no significant change in the values of tanϕ beyond a normal stress value of 20 kg/cm^2 at which tanϕ equals 0.76 (ϕ=37°) for naturally moist, and 0.60 (ϕ=31°) for saturated rock mass.

3.3 Trap and Metabasic Rocks

The failure envelopes for naturally moist and saturated trap and metabasic rocks have been predicted by the following expressions [Mehrotra (1992)]:

$$\tau_{nmc} = 3.05\ (\sigma + 1.00)^{0.691} \quad [13]$$

$$\tau_{sat} = 2.45\ (\sigma + 0.95)^{0.691} \quad [14]$$

Figure 7 shows the failure envelopes for trap and metabasic rocks which have been classed as "fair" rock mass (RMR=42-59). Fig. 7 shows that the envelopes are stress dependent. The cohesion value is 3 kg/cm^2 at natural moisture content and 2.4 kg/cm^2 for the rock mass under saturation. As in rock masses discussed previously it is seen that there is no significant change in the values of tanϕ beyond a normal stress (σ) value of 20 kg/cm^2 at which tanϕ equals 0.82 (ϕ=39°) for naturally moist, and 0.66(ϕ=33°) for the saturated rock masses.

4. FAILURE ENVELOPES FOR "GOOD" ROCK MASSES

Trap and metabasic rocks were also investigated under the category which was classified as "good" rock mass. The properties and characteristics of these rocks have been listed in Table III.

Table III Properties and characteristics of "Good" Rock Masses *[Mehrotra (1992)]*

Rock Mass	nmc (%)	RMR	Q-index	$q_{c(nmc)}$ [kg/cm²]	$q_{c(nmc)}$ [kg/cm²]
Jointed Trap and Metabasic Rocks	0.4 -0.8	61-72	8.0-14.5	750-1500	600-1200

4.1 Trap and Metabasic Rocks

The failure envelopes for "good" quality jointed trap and metabasic rocks at natural moisture content and saturated conditions have been predicted by the following expressions [Mehrotra (1992)]:

$$\tau^{*}_{n(nmc)} = 0.50\ (\sigma_n + 0.003)^{0.698} \qquad [15]$$

$$\tau^{**}_{n(sat)} = 0.49\ (\sigma_n + 0\ 002)^{0.698} \qquad [16]$$

$\tau^{*}_{n(nmc)}$ is shear strength (normalised) at natural moisture content
σ_n is normal stres. (normalised)
$\tau^{**}_{n(sat)}$ is shear strength (normalised) at saturation.

Figure 8 shows the failure envelopes for naturally moist and saturated trap and metabasic rocks. The RMR value of these rocks lies between 61 and 72. Cohesion values for naturally moist and saturated rock masses have been estimated as 7.6 kg/cm^2 and 3.9 kg/cm^2 respectively. It is observed that there is no significant change in the values of tanϕ beyond a normal stress (σ) value of 22 kg/cm^2 at which tanϕ equals 1.00 (ϕ=45°) for naturally moist and 0.88 (ϕ=42°) for the saturated rock masses.

5. DISCUSSIONS

Failure envelopes which have been deduced from the data of large scale block shear tests on different rock types show stress dependent behaviour. It is seen that the envelopes show the similar trend as given by Hoek and Brown (1980). The effect of saturation on the shear strength of "poor" and "fair" rock masses has been found to be quite significant. When saturated, the reduction in the shear strength is about 30 per cent in case of "poor" quality rock masses and 25 per cent in case of "fair" quality rock masses. It is thus necessary to give due consideration for the effect of saturation while carrying out stability analyses of rock masses in the Lesser Himalayan region. The equations for failure envelopes for the "poor" and "fair" quality jointed rock masses should only be used for preliminary stability analyses of rock slopes and dam abutments. For detailed design, the actual non-linear strength envelope should be obtained from block shear tests.

6. CONCLUSIONS

The results of the present study of failure envelopes found for poor, fair, and good quality rock masses lead to the following conclusions :

1. For "poor" and "fair" category rock masses, shear strength will not be goverened by the strength of the rock material. On the other hand, for "good" quality rock masses shear strength will be goverened by the strength of rock material.

2. The cohesion intercept is not negligible but significant at least for "good" category rock masses.

3. Beyond a normal stress (σ) value of 20 kg/cm^2, there is no significant change in the values of tanϕ.

4. The effect of saturation on the shear strength of "poor" and "fair" quality rocks has been found to be significant. It is necessary to investigate into the effects of prolonged saturation on the long-term properties of poor rock masses so that the ultimate behaviour of pressure tunnels and dam foundations could be analysed in advance.

7. REFERENCES

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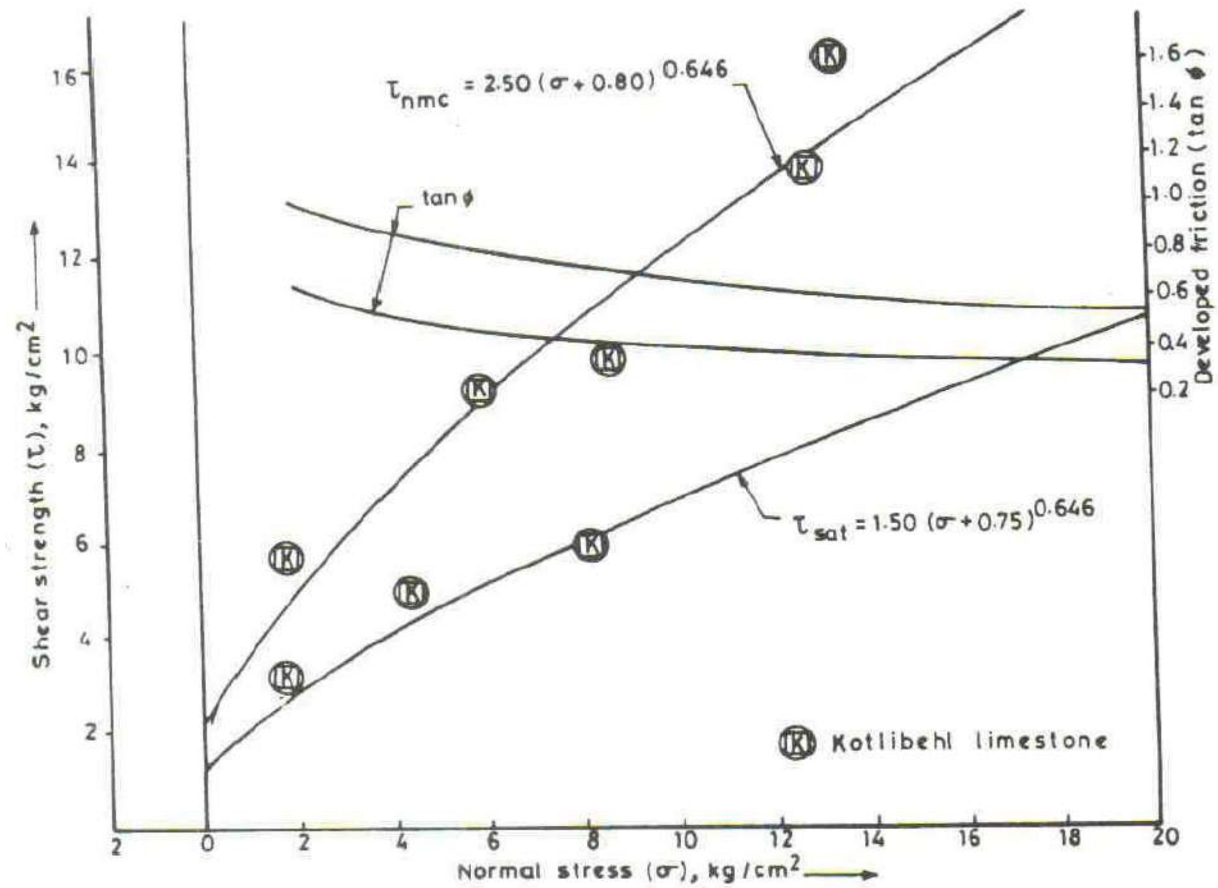

FIG. 1- FAILURE ENVELOPES FOR JOINTED LIMESTONE AT NATURAL MOISTURE CONTENT (0.3% - 2.8%) AND SATURATED CONDITIONS [RMR = 29-37, Q = 0.4-1.5, $q_{c(nmc)}$ = 300-500 kg/cm², $q_{c(sat)}$ = 200-400 kg/cm²]

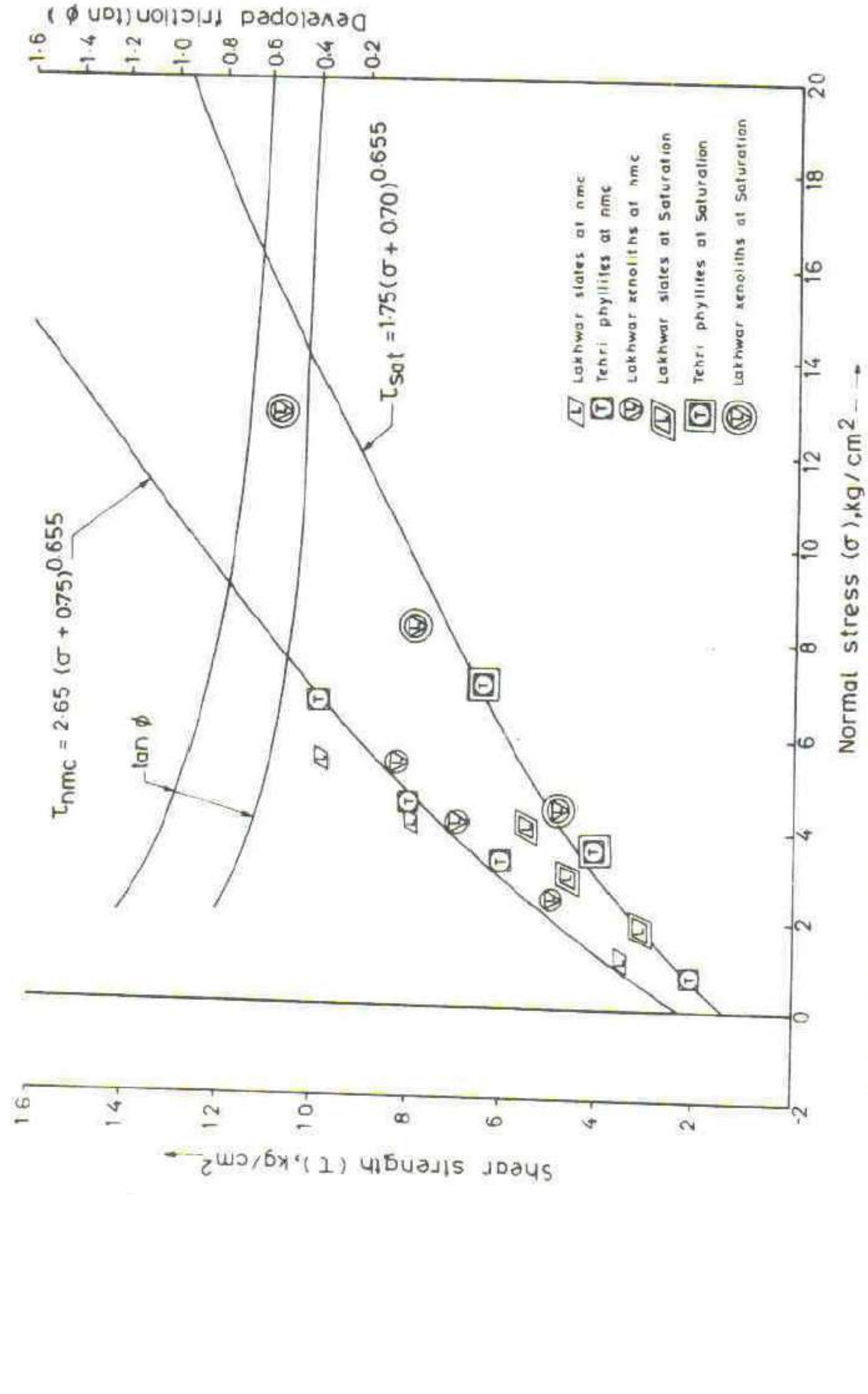

FIG. 2–FAILURE ENVELOPES FOR JOINTED SLATE, XENOLITH AND PHYLLITE AT NATURAL MOISTURE CONTENT (0·75%–1·85%) AND SATURATED CONDITIONS [RMR = 23–37, Q = 0·3–1·0, $q_{c(nmc)}$ = 350–850 kg/cm², $q_{c(sat)}$ = 200–600 kg/cm²]

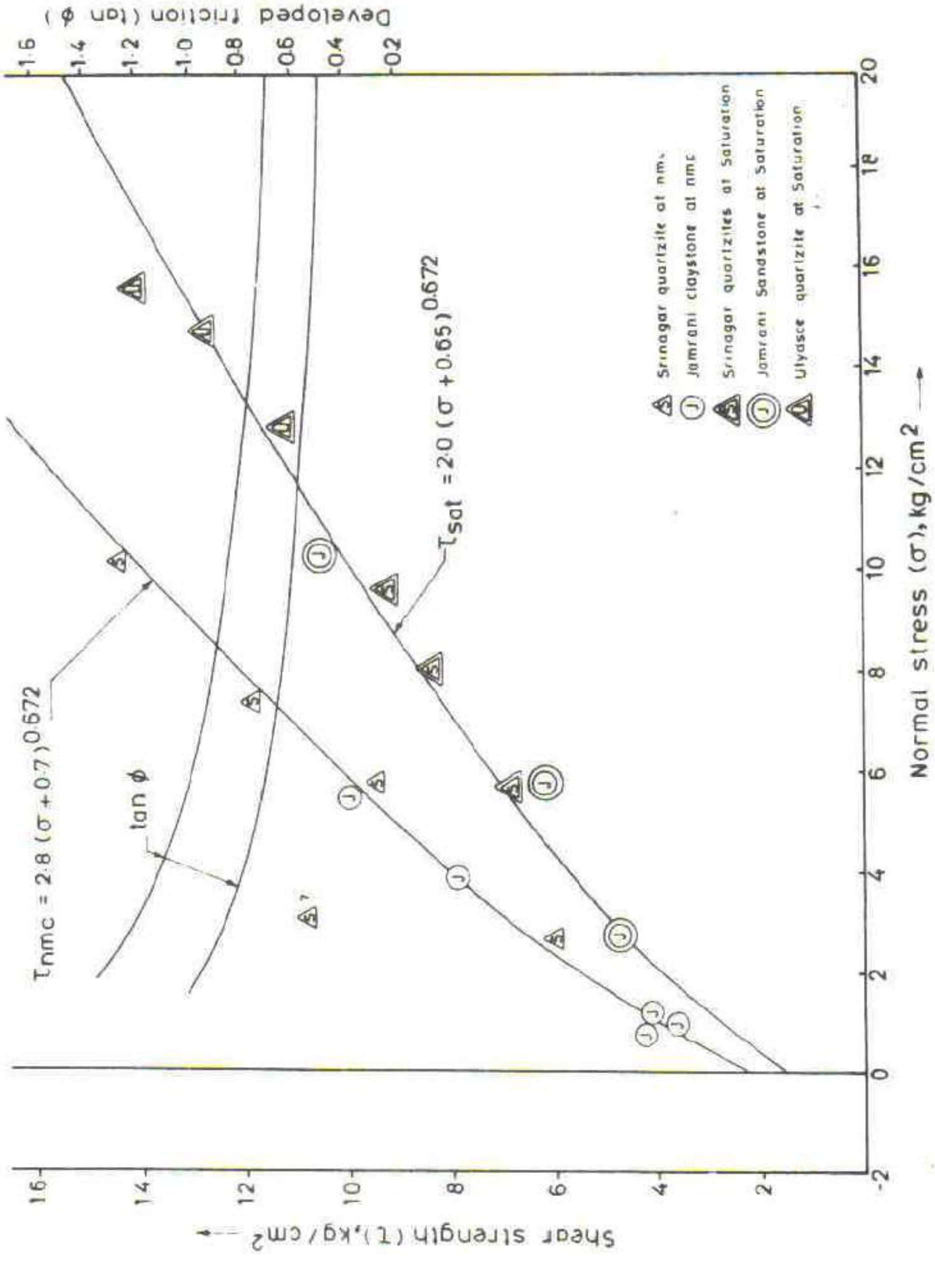

FIG.3- FAILURE ENVELOPES FOR JOINTED SANDSTONE AND QUARTZITE AT NATURAL MOISTURE CONTENT (0.40%–1.5%) AND SATURATED CONDITIONS [RMR = 22-36, Q = 0.1-2.5, $q_{c(nmc)}$ = 400-1000 kg/cm², $q_{c(sat)}$ = 350-700 kg/cm²]

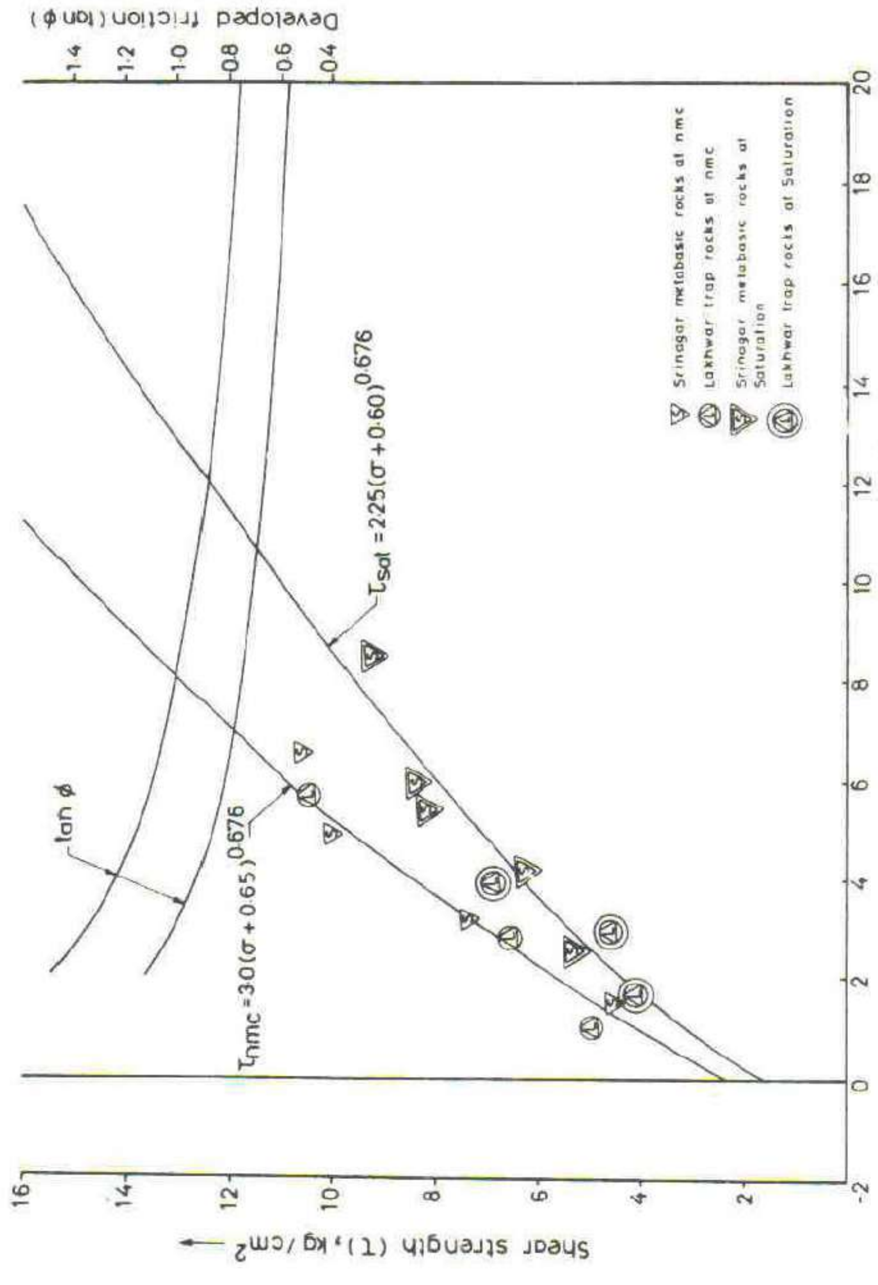

FIG. 4 - FAILURE ENVELOPES FOR JOINTED TRAP AND METABASIC ROCK AT NATURAL MOISTURE CONTENT (0.28%–0.6%) AND SATURATED CONDITIONS [RMR = 24–40, Q = 0.3–2.5, $q_{c(nmc)}$ = 750–1500 kg/cm², $q_{c(sat)}$ = 600–1200 kg/cm²]

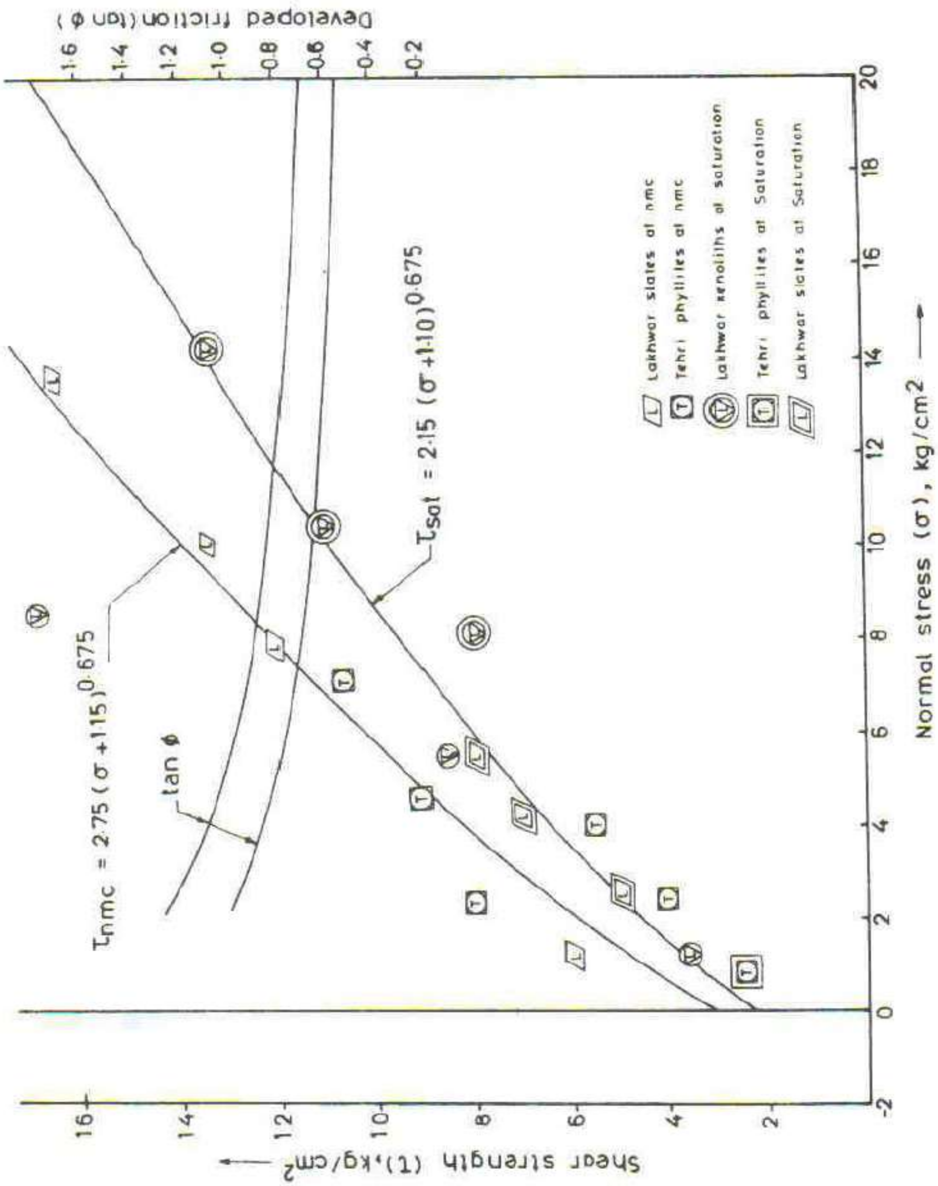

FIG. 5 - FAILURE ENVELOPES FOR JOINTED SLATE, XENOLITH AND PHYLLITE AT NATURAL MOISTURE CONTENT (0·25%-0·94%) AND SATURATED CONDITIONS [RMR=43-56, Q=2·0-3·5, $q_{c(nmc)}$ = 350-850 kg/cm^2, $q_{c(sat)}$ = 200-600 kg/cm^2]

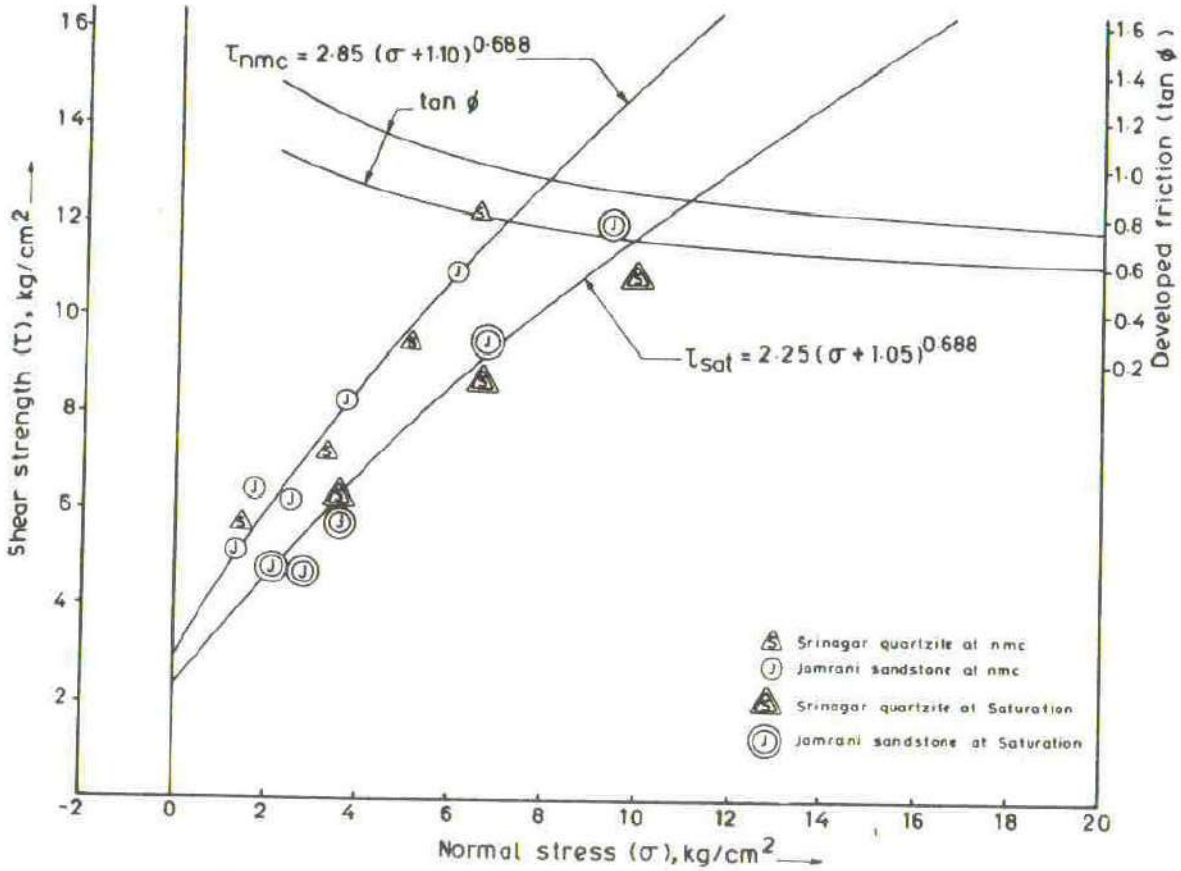

FIG.6- FAILURE ENVELOPES FOR JOINTED SANDSTONE AND QUARTZITE AT NATURAL MOISTURE CONTENT (0·4%-1·5%) AND SATURATED CONDITIONS [RMR = 41-58, Q = 1·9-5·1, q_c (nmc = 400-1000 kg/cm^2, $q_{c(sat)}$ = 350-700 kg/cm^2]

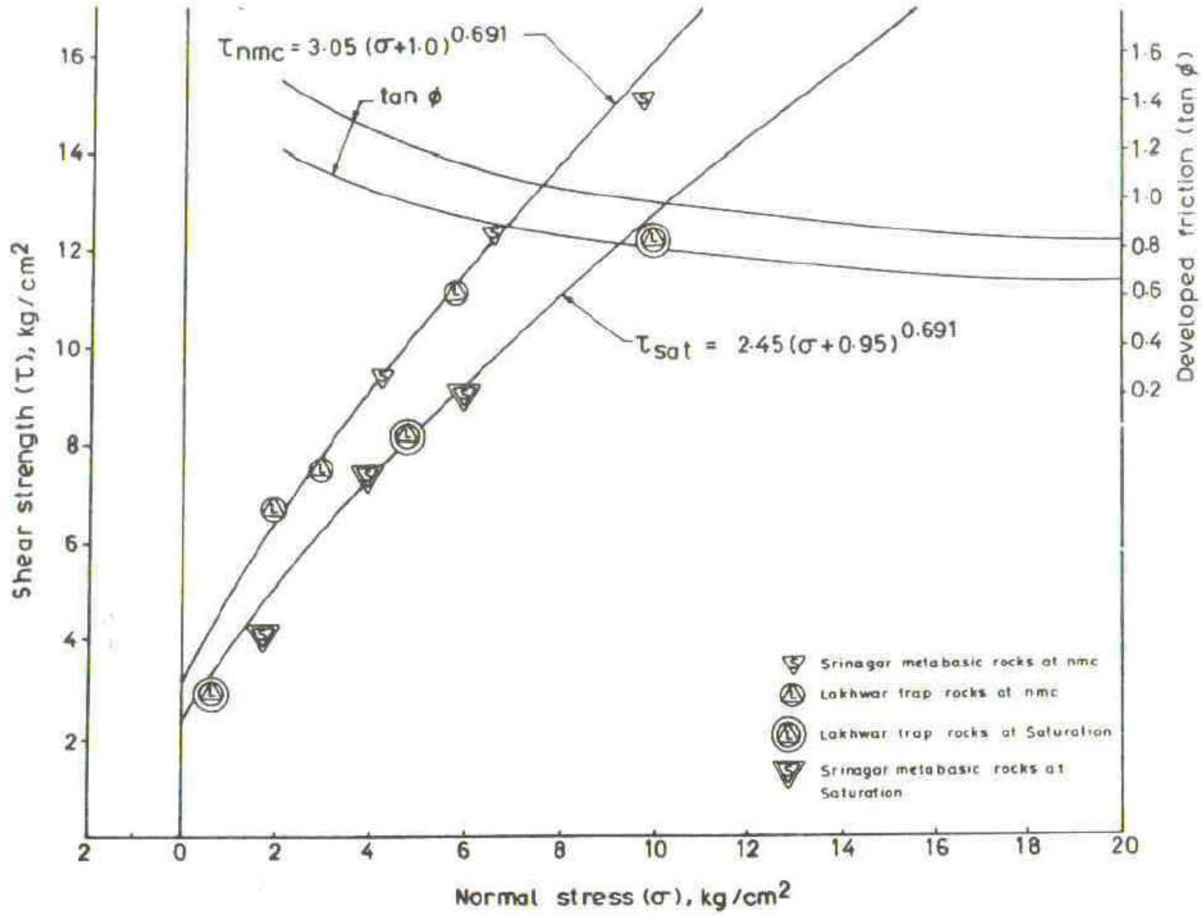

FIG.7 - FAILURE ENVELOPES FOR JOINTED TRAP AND METABASIC ROCKS AT NATURAL MOISTURE CONTENT (0.28%-0.60%) AND SATURATED CONDITIONS [RMR = 42-59, Q = 1.5-4.0, $q_{c(nmc)}$ = 750-1500 kg/cm², $q_{c(sat)}$ = 600-1200 kg/cm²]

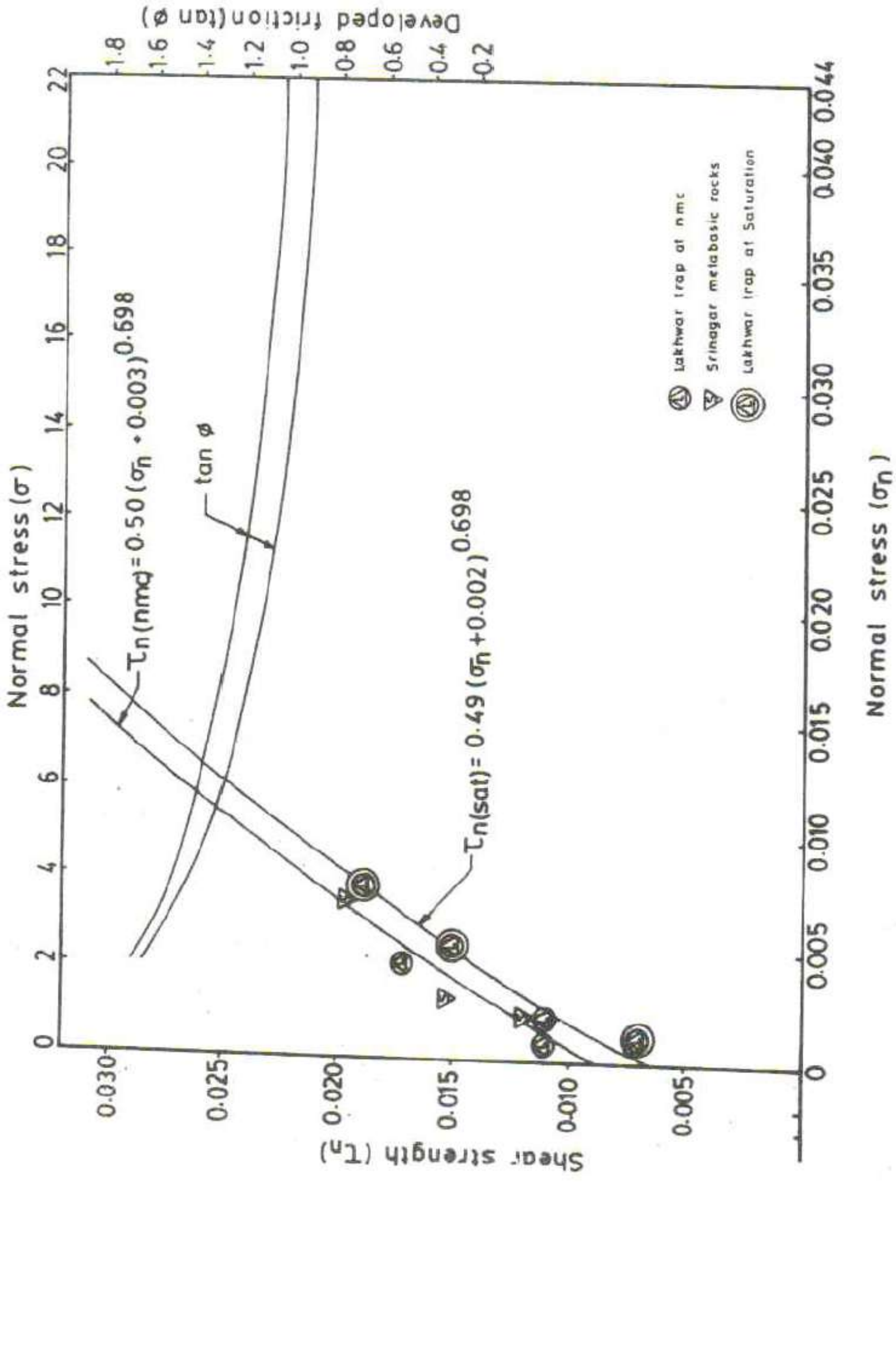

FIG. 8– FAILURE ENVELOPES FOR JOINTED TRAP AND METABASIC ROCK AT NATURAL MOISTURE CONTENT (0.40%–0.80%) AND SATURATED CONDITIONS [RMR=61–72, Q = 8.0–14.5, q_c(nmc) = 750–1500 kg/cm^2, q_c(sat) = 600–1200 kg/cm^2]