Influence of Saturation on Modulus of Deformation of Himalayan Rock Masses

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We should learn to live with danger.

- Prof. E. Hoek, 1998

ABSTRACT

The geological nature and deformation characteristics of rocks always play significant and vital role in the selection of site, design, durability, economy and desired performance of dam structures. Results of insitu tests obtained from seventy uniaxial jacking tests carried out at natural moisture content and another fifty tests carried out on saturated rock masses show that modulus of deformation is affected significantly by a change in the moisture regime of rocks, particularly for the "poor" and the "fair" category of rock masses. The test involved application of load on rock surface by means of hydraulic jack and measurment of the resulting deformation in dry as well as saturated rock mass. The experimental technique and other conditions during the test performance were maintained the same throughout. This paper identifies the influence of moisture on the deformability of rock mass. When saturated, the reduction in the modulus values can be of the order of 90 per cent for "poor" and 75 per cent for "fair" quality rocks with water sensitive minerals.

1.0 INTRODUCTION

The deformation characteristics are influenced greatly by the presence of fissures, micro-cracks, foliation, layering, bedding planes, microfolds, secondary alterations, weathering status, grain-texture, mineralogy, petrology, lithology and heterogeneity within the rock masses, and above all the moisture regime. For the stability of structures built in or founded on rock mass, it is generally the defomability, rather than the strength of the rock mass, which is the governing design criterion. Modulus of deformation (Ed) and modulus of elasticity (Ee) are the essential parameters for the design of tunnels, underground cavities and dam foundations. The mechanical properties of rocks, particularly the soft rocks are greatly affected by a change in the moisture content. This is mainly because the texture and/or bond of the particles is broken down by swelling (or slaking and/or disintegration) and the modulus of deformation distinctly declines. As such, the relation between stress and strain varies appreciably with different moisture content at least for "poor" and "fair" quality rocks. In fact, influence of water changes fundamentally the mode of rock failure. Based on an experimental study, Mehrotra et al. (1991) observed that deformation characteristics of some rocks in the Lesser Himalayan region may be affected significantly once the rock mass is finally saturated during reservoir filling behind dams. The design parameters need, therefore, to be evaluated taking into account the effects of prolonged saturation. It is thus important to investigate the effect of saturation on the deformability of rocks encountered in the Lesser Himalayan region. In order to study the effect of saturation on different rocks, extensive uniaxial jacking (UJ) tests on 60 cm diameter plates were carried out both on saturated and the naturally moist rock masses. On the basis of test results, the effect of saturation has been estimated and Ed values were recommended for adoption at projects having similar conditions.

2.0 TESTS PERFORMED

Insitu tests form an extremely important part in design considerations of all major hydro-projects. These tests play unique role because the resulfs of these tests provide representative information on the values of different parameters to be used in the design process. In fact, the mechanical behaviour of a rock mass cannot be determined purely from laboratory tests, since they are limited to data on rock material which is free of the discontinuities found in rock masses. For example, to analyse a concrete gravity dam, it is necessary to know the deformability of the rock mass on which it rests. In case of poor and soft rock masses, the deformability depends greatly on the extent of plastic movement of joints and weak planes under saturation. Jacking tests are usually employed to determine the modulus of deformation and the modulus of elasticity of foundation rock. The great advantage of this method is the ability to test large and undisturbed volumes of rock masses under the desired test conditions. An assumption of this test is that the rock mass is linearly elastic and isotropic. It is also assumed that rock mass is not damaged significantly around drift by blasting.

Great precaution was taken in enlarging the drift manually by chiselling at the test location just before test. The load was kept constant until deformation was stabilised. The rock mass quality (Q-value) and rock mass rating (RMR) were also found at each location.

Six major hydroelectric schemes were therefore selected for the purpose of carrying out uniaxial jacking tests. For the purpose of estimation of modulus of deformation, the area of the six hydro-project sites was divided into eleven geostructural zones involving ten different kinds of rocks. Table 1 shows the dam sites, rock types and number of uniaxial jacking tests performed in the exploratory drifts by U.P. Irrigation Research Institute, Roorkee.

Table 1. Dam sites, rock types and number of uniaxial jacking tests

Name of Test	Dam sites (Lesser Himalayan region)											Total number of tests
	Jamrani		Kotlibehl		Lakhwar			Srinagar		Tehri	Utyasu	
	Rock type											
	Sand-stone	Clay-stone	Lime stone	Shale	Slate	Xeno-lith	Trap	Meta-basic	Quart-zite	Phyl-lite	Quartzite	
	Number of Tests											
Uniaxial Jacking	9	4	10	3	10	8	29	7	5	22	13	120

Experimental insitu evaluation of modulus of deformation of Lesser Himalayan rocks, encountered at the six hydro-project sites involving ten different rock type, were determined by uniaxial jacking tests. Utilising the experimental load-displacement data and identifying the importance and significance of first and subsequent loading cycles, recovery cycles, stress level and non-recoverable deformation, the modulus of deformation

(Ed) and modulus of elasticity (Ee) have been evaluated. For the evaluation purpose, Boussinesq's rigid punch equation has been used. Method of estimation of Ed and Ee has been illustrated in Fig.1. The results are based on the assumption that the plate settlement is half of the total deflection between the top and the bottom plates.

In order to check the appropriateness of the method, fourteen sets of UJ tests were carried out separately on the same rock mass both at the natural moisture content (nmc) and saturation. Each set consisted of repeating the test on the same horizon, under similar test conditions but separated by a distance of about 4 to 5 m. The results are shown in Figs. 2 and 3.

It is seen in Figs. 2 and 3 that there is not much scatter in the test results obtained on the rock masses at natural moisture and at saturation. This goes to indicate and ensure that consistency of data in the test method is appropriate and the data have not been influenced by the test procedure.

The summary of the test results of insitu and laboratory investigations is given in Table-2 and 3.

Table -2. Summary of results of insitu and laboratory investigations

Rock type		Modulus of			Q-value	RMR	Poisson's ratio (v)	Permeability (Lugeon)
		deformation [Ed] (GPa)	elasticity [Ee] (GPa)	rock [Er] (GPa)				
Sandstone	D	0.44-2.10	1.75-2.90	6.76	0.7-2.0	20-45	0.30-0.36	7-19
	S	0.35	1.20	17.50	0.2	27	-	-
Claystone	D	0.74-1.55	1.43-3.67	8.41	0.7-1.8	24-38	-	-
	S	-	-	-	-	-	-	-
Slates	D	0.49-4.04	0.98-7.80	20.00	0.3-3.9	18-45	0.39	2.5-5.0
	S	0.50-1.30	1.09-3.60	14.74	0.1-2.1	23-42	-	-
Xenolith	D	1.58	2.95	14.74	1.5-1.6	28-33	0.32	-
	S	0.41-4.60	0.98-5.07	12.35	0.4-2.7	30-60	-	-
Trap	D	1.60-9.12	1.98-13.00	12.35-36.43	1.7-11.7	30-61	0.24-0.27	7-21
	S	0.86-8.47	1.60-9.70	21.50-42.80	1.2-13.2	43-64	-	-
Shale	D	0.90-1.57	2.22-2.95	10.80	0.9-1.5	25-30	0.36	-
	S	0.30-0.50	1.09-1.15	-	0.1-0.2	23-25	-	9
Limestone	D	0.26-3.08	0.55-4.80	11.90	0.1-4.0	11-53	0.32	14-21
	S	-	-	-	-	-	-	-
Metabasic	D	1.45-3.08	4.38-7.11	21-22.4	3.3-4.7	37-60	0.29	2-11
	S	1.20-1.25	3.39-5.73	22.4	2.5-3.0	49	-	-
Quartzite	D	0.84-13.70	0.98-14.37	28.25-49.8	0.3-19.0	27-71	0.33	8
	S	0.78-5.55	1.78-6.52	20.0-40.16	1.2-4.9	37-58	-	-
Phyllite	D	0.54-3.48	0.73-4.13	6.68-7.07	0.3-4.1	18-50	0.24-0.32	1-28
	S	0.38-4.08	1.25-5.14	16.27	0.3-6.5	31-61	-	-

D - Indicates the value at natural moisture content
S - Indicates the value at saturated condition.

Table 3 - Classification of test sites

Rock	Classification System	
	RMR	Q value
Sandstone	Class-IV : Poor rock mass	Poor rock mass
Claystone	Class-IV : Poor rock mass	Poor rock mass
Limestone	Class-IV : Poor rock mass	Poor rock mass
shale	Class-IV : Poor rock mass	Poor rock mass
Slate	Class-IV : Poor rock mass	Poor rock mass
Xenolith	Class-IV : Poor rock mass	Poor rock mass
Traprock	Class-III : Fair to good rockmass	Fair rock mass
Quartzite	Class-III : Fair rock mass	Fair rock mass
Metabasic	Class-III : Fair rock mass	Poor rock mass
Phyllite	Class-IV : Poor rock mass	Poor rock mass

3.0 DISCUSSION AND INTERPRETATION OF TEST DATA

The geology in the Lesser Himalaya where the six hydro-projects are located varies from place to place, from project to project. The rock mass in the region varies considerably in quality, having RMR ranging between 11 - 71 and the moduli values varying from 0.26 GPa to 13.7 GPa. Thus the following correlation was established (Mehrotra, 1993).

$$Ed_{nmc} = 10^{(RMR - 25) / 40} \quad [GPa] \qquad (1)$$

The plot of the moduli values obtained on the saturated rock mass has been shown in curve-2 of Fig. 4. For the rock mass having natural moisture content of the order of 5-6 per cent, the RMR has been estimated by taking into account the condition of groundwater having the rating 10 (for damp rock mass). For rock mass having moisture content at saturation, the rating has been taken as 7 (for wet rock mass). Thus for the same type of rock mass, the RMR values of dry (at nmc) and the saturated states differ by rating of 3.

It is seen in Fig. 4 that the effect of saturation is more predominant in poor rocks than in fair quality rocks. With increase in the RMR values, the effect of saturation is diminished. The trend of the curve is not well defined for RMR values less than 30 in case of saturated rock mass.

Verman (1993) also obtained independently an empirical correlation to estimate the modulus of deformation of dry rock mass, as given below :

$$Ed = f.10^{(RMR - 20) / 38} \quad [GPa] \tag{2}$$

where, RMR = Bieniawski's rock mass rating

f = correction factor for the effect of overburden depth H (m) = $0.3\ H^{\alpha}$ and,

a = 0.16 to 0.30

The above correction is based on the back-analysis of the modulus of deformation from the Central Mining Research Institute data of support pressures and tunnel closures observed at several tunnel sections in the non-squeezing ground condition with RMR values ranging from 31 to 68 (Verman, 1993). Later experience suggested that Ed of poor rocks is highly pressure dependent and it may be as high as 0.50 like in soil.

It is interesting to note that for value of f=1, the Eq. 2 provides nearly the same correlation as represented by Eq.1. Thus, one may use Eq. 1 and 2 with confidence for "poor" and "fair" quality rock masses.

The effect of saturation has been further studied in detail through a series of separate tests performed on "poor" and "fair" quality rocks. Reduction factors have been worked out for both the cases. It has been found that the reduction factor (for saturation) bears a bilinear relationship with RMR (Fig. 5) as follows (Mehrotra, 1993),

$$Ed_{sat} / Ed_{nmc} = 0.01\ RMR - 0.1 \text{ (for RMR 21 - 40)} \tag{3}$$

$$Ed_{sat} / Ed_{nmc} = 0.016\ RMR - 0.385 \text{ (for RMR 41 - 60)} \tag{4}$$

The relationship as developed between the modulus reduction factor (ratio of modulus of deformation (Ed) to modulus of elasticity of rock material (Er)) and RMR shows that fortunately there is close comparison of modulus reduction factors at natural moisture content and Bieniawski's correlation (1975) as shown in Fig. 6. The curve for saturated rock mass is not in agreement with Bieniawski's relationship. The difference in the trend in "poor" and "fair" quality rock masses may be due to the variation in minerals and uncertainties of geological conditions which went undetected in the field.

It is seen that under saturation the reduction in Ed is as high as 90 per cent for poor rocks and 70 per cent for fair quality rocks. If insitu tests are carried out at natural moisture content, the correction factor as suggested by Eq. 3 and 4 may be applied to predict the design parameters for saturated conditions which shall prevail in the construction area after commissioning of the hydro-project.

Ideally the test should have been done in poor argillaceous rocks just after making drift so that weathering, stress relief and seepage erosion do not affect Ed adversely. Further, borehole extesometer below the plate should be used to get Ed values of undisturbed and confined rock mass, which will be much higher.

Rock mass gets saturated around a pressure tunnel in hydro-projects after its commissioning. The reduction in Ed after saturation tends to increase tunnel wall deformations which are resisted by nearly rigid concrete lining. As such, significant support pressures may be developed around the pressure tunnels (Verman, 1993). Consequently, the concrete lining is prestressed naturally particularly in argillaceous rock masses. This explains partly why unreinforced concrete lining in the pressure tunnels is functioning since 1980 in U.P., India. However, in the case of the penstocks, attention should be given to the effect of post-construction saturation on the design of steel liner.

4.0 CONCLUSION

A systematic and detailed study of six geostructural zones suggests that the effect of saturation on the modulus of deformation is significant. When saturated, the reduction in the modulus values may be as high as 90 per cent for "poor" and 75 per cent for "fair" quality rock mass with water sensitive minerals. Hence, it is important that the deformability data to be used for designs should be specified with water content i.e. humidity, state of saturation and the season when measurement were made in order that the effect of post construction saturation can be considered in the hydro-projects.

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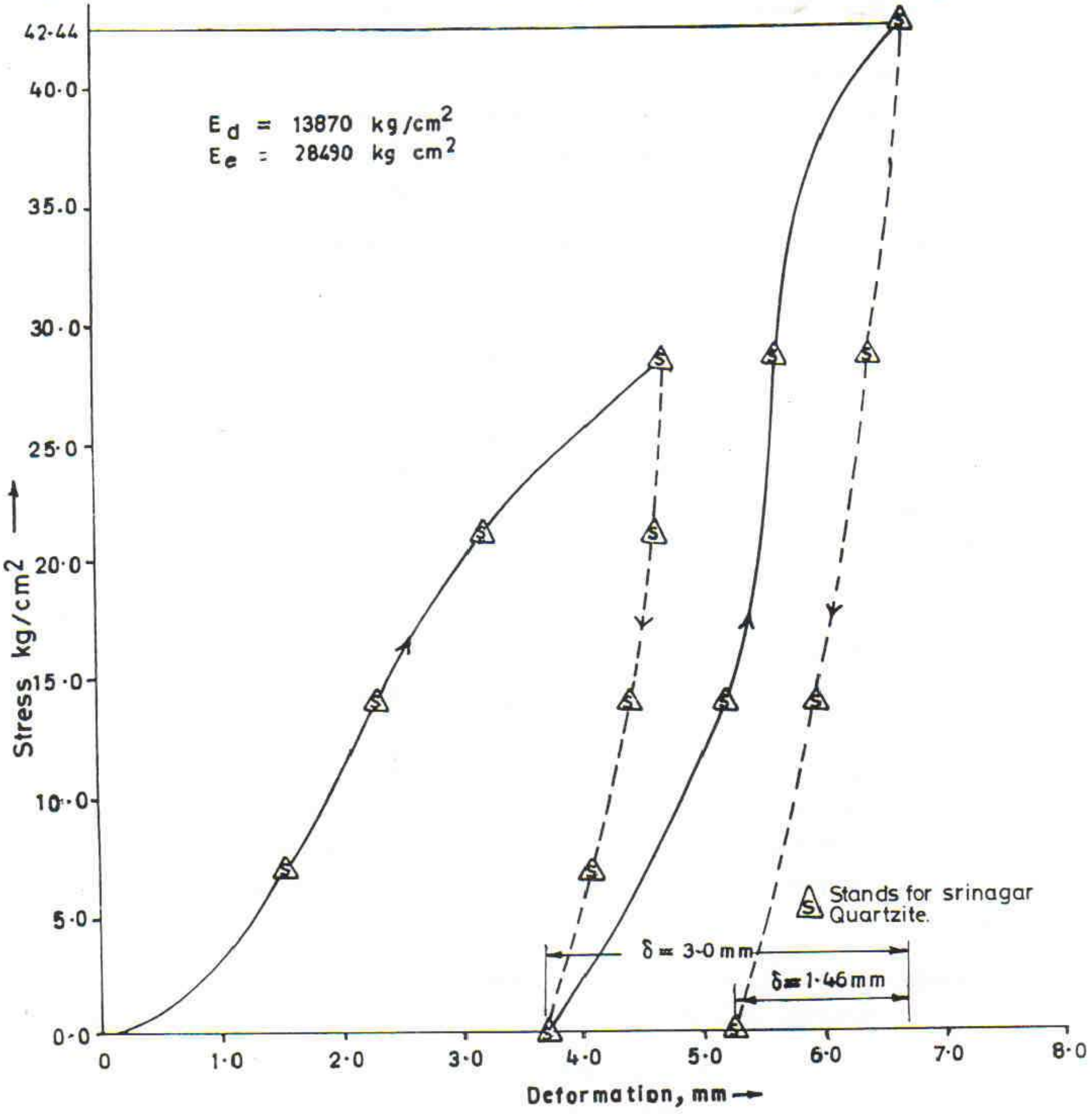

$$E_d = \frac{m(1-\nu^2)\times P}{\sqrt{A}\cdot\delta/2}$$ (Boussinesq's rigid punch equation)

Where,

P = Normal load (kg)

ν = Poisson's ratio (= 0·2, assumed)

m = Constant = 0·96 (circular plate)

A = Area of plate in sq. cm (2828 sq. cm. for 60 cm diameter plate)

δ = Deformation corresponding to load P (cm)

$$E_d = \frac{0{\cdot}96\,(1-0{\cdot}04)\times 42{\cdot}44\times 2828}{\sqrt{2828}\;\times(0{\cdot}3/2)}$$

$= 13{,}870$ kg/cm^2

$$E_e = \frac{0{\cdot}96\,(1-0{\cdot}04)\times 42{\cdot}44\times 2828}{\sqrt{2828}\times(0{\cdot}146/2)}$$

$= 28{,}490$ kg/cm^2

Fig. 1 Method of estimation of modulus of deformation (E_d) and modulus of elasticity (E_e)

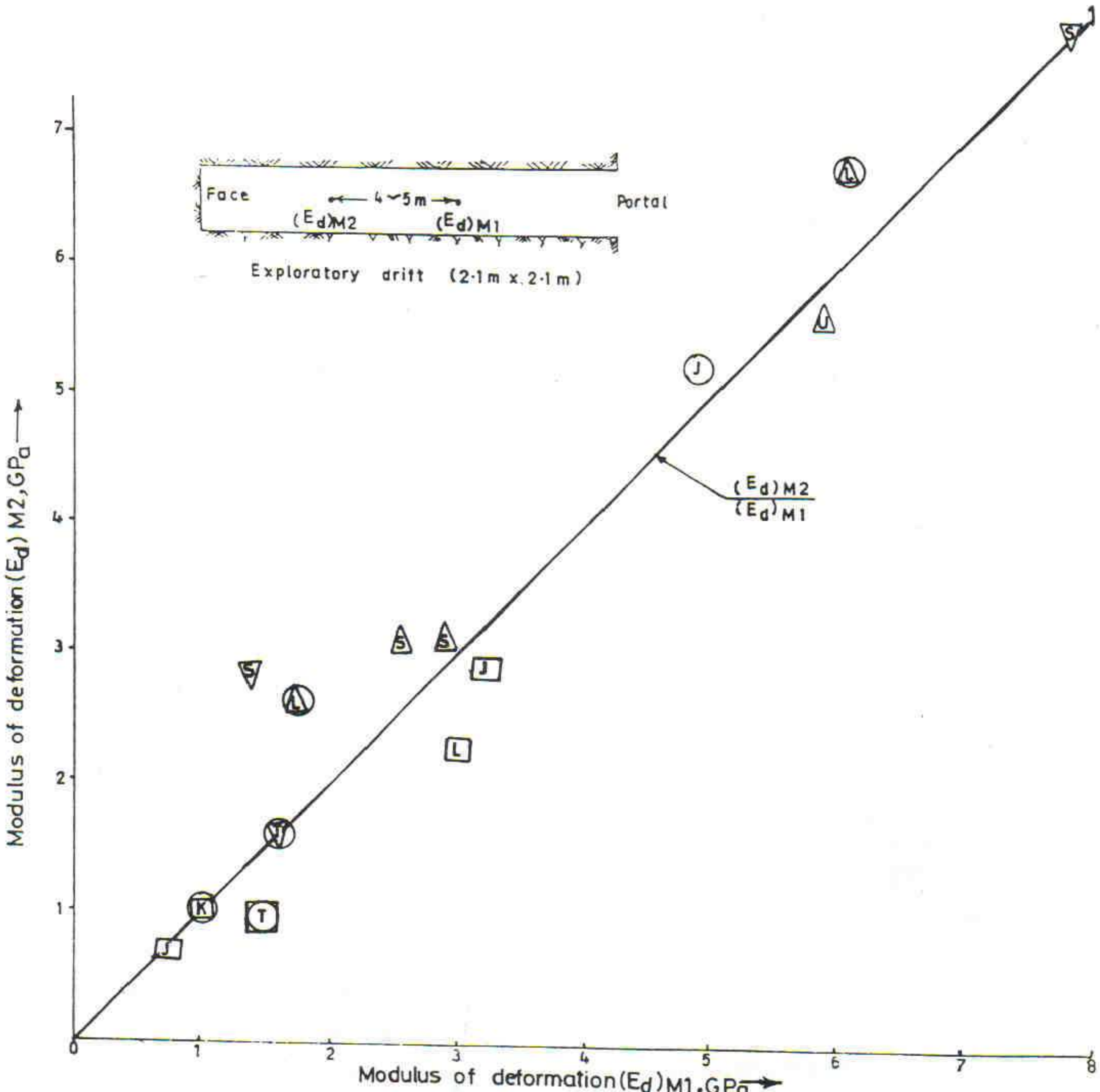

Fig 2 Modulus of deformation from uniaxial jacking tests [rock mass at n mc] (Mehrotra, 1993)

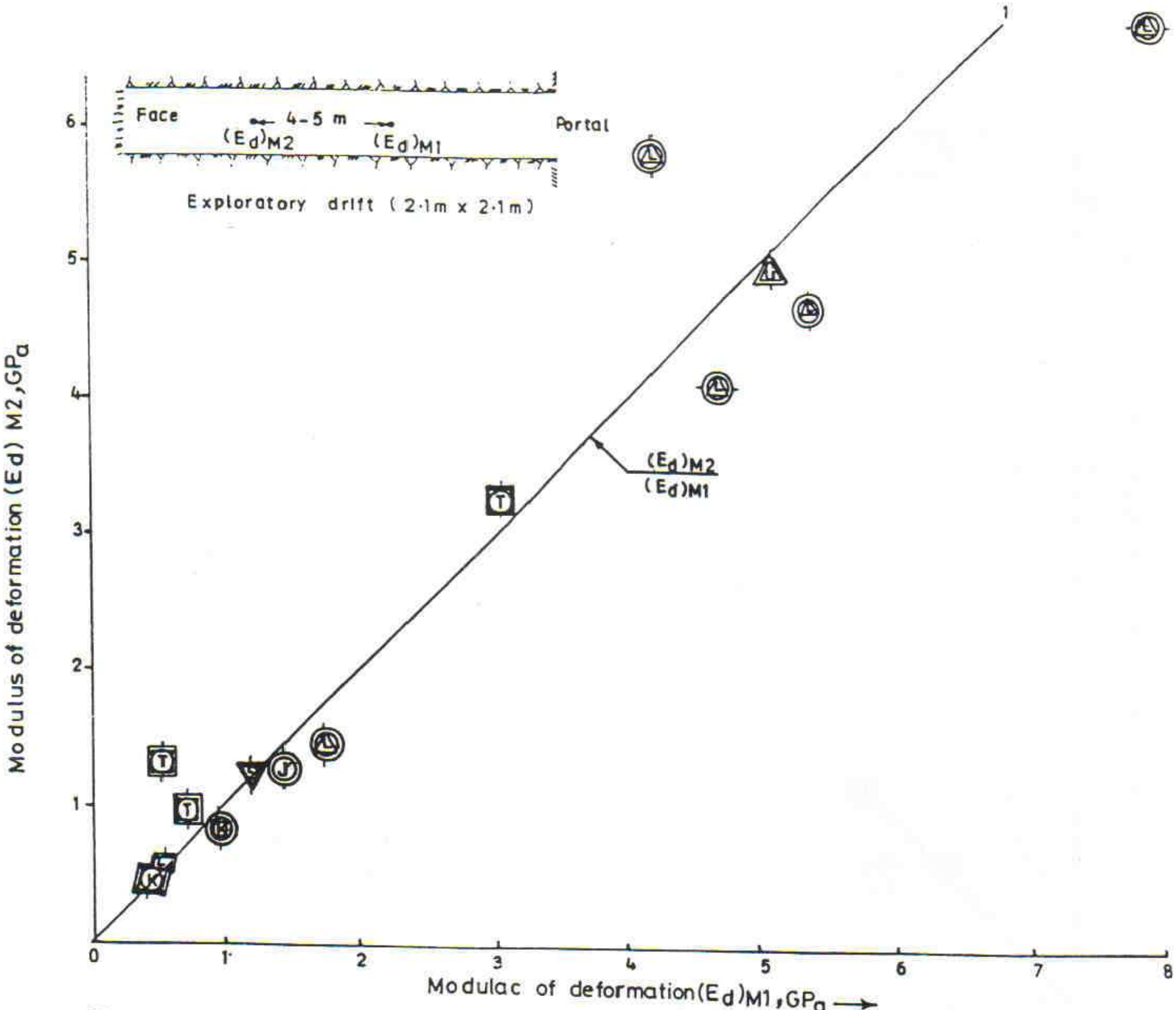

Fig. 3 Modulus of deformation from uniaxial jacking test (saturated rock mass) (Mehrotra, 1993)

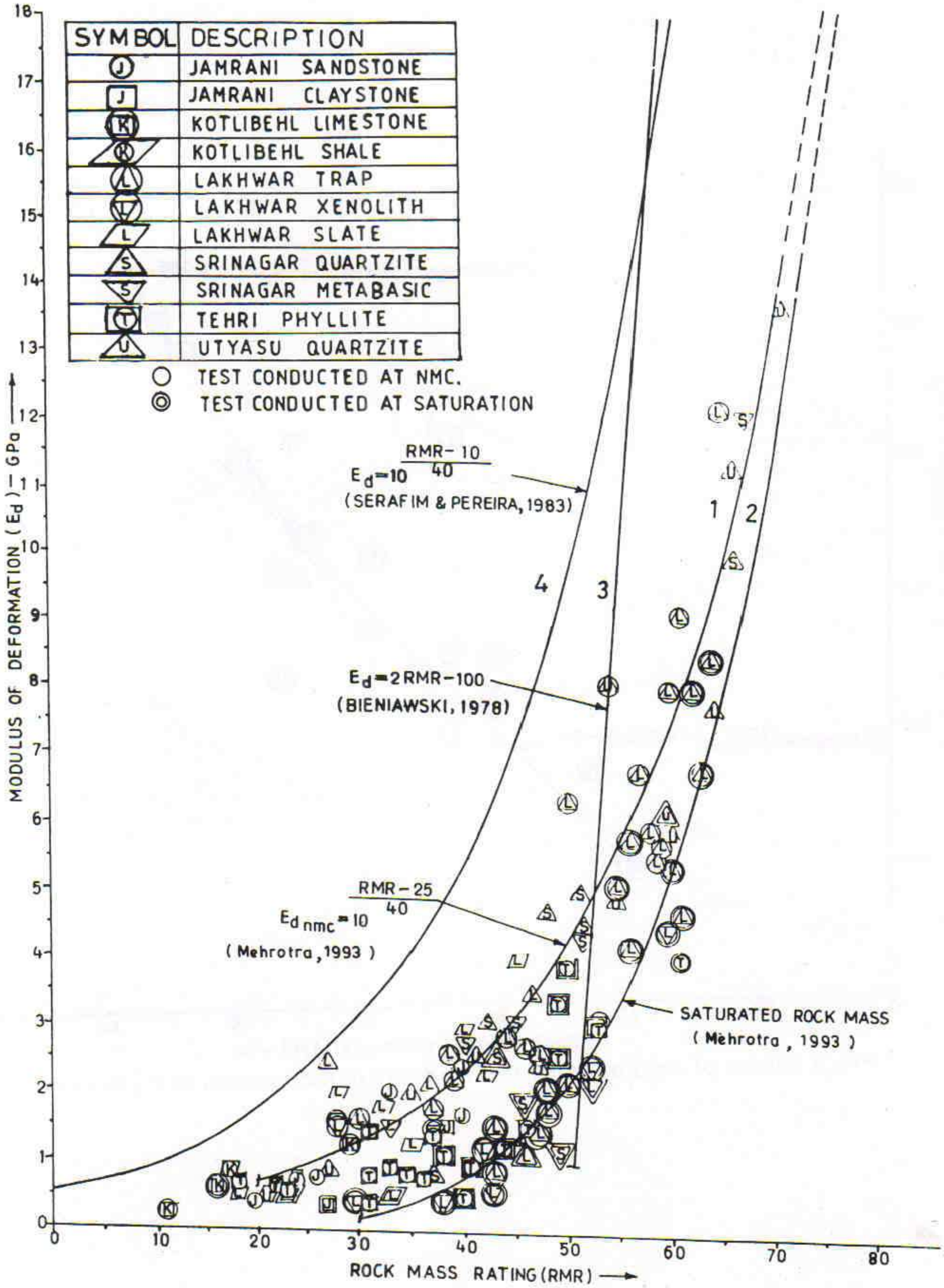

FIG. 4– CORRELATION BETWEEN ROCK MASS RATING (RMR) AND MODULUS OF DEFORMATION (E_d)

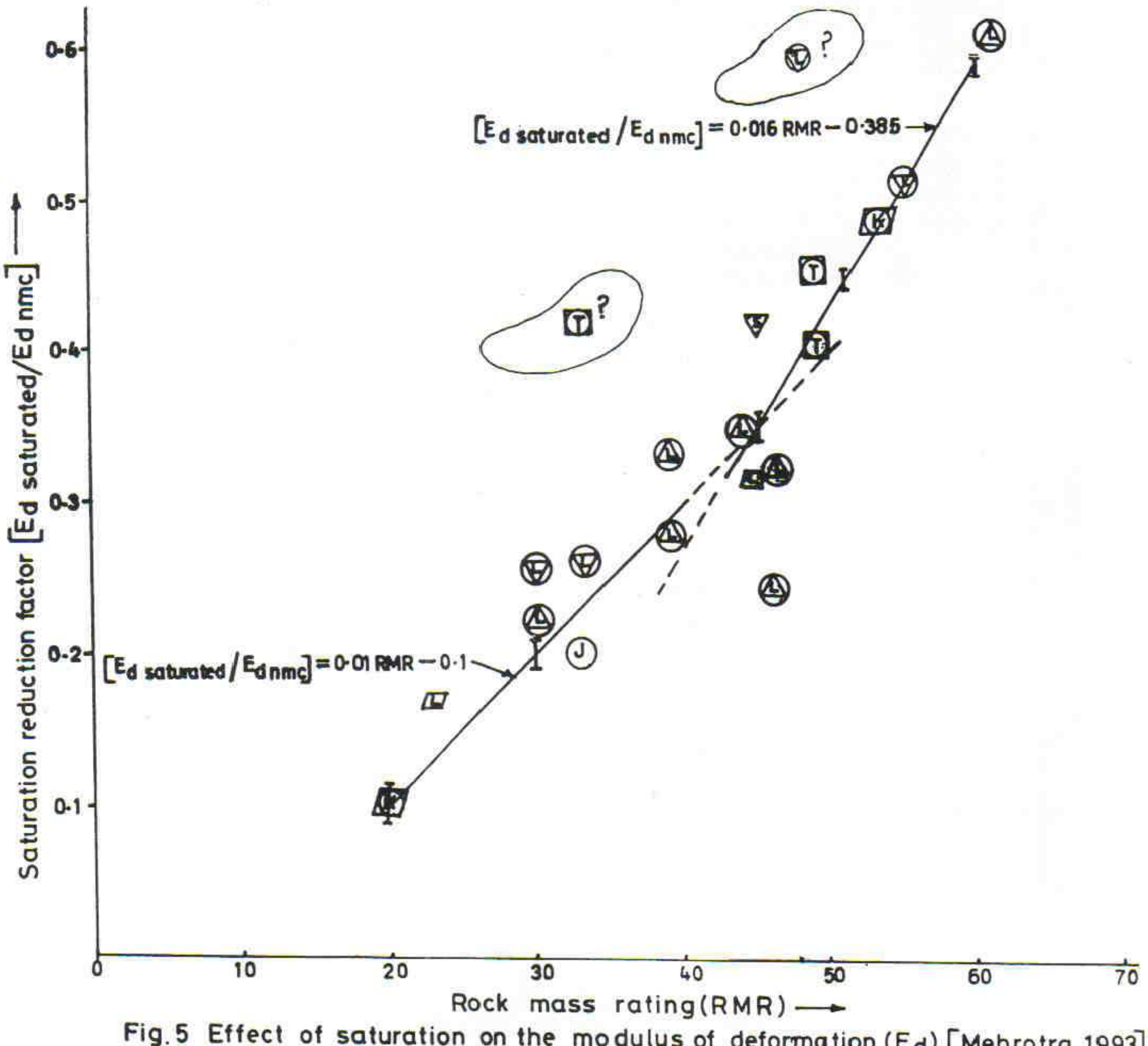

Fig. 5 Effect of saturation on the modulus of deformation (E_d) [Mehrotra, 1993]

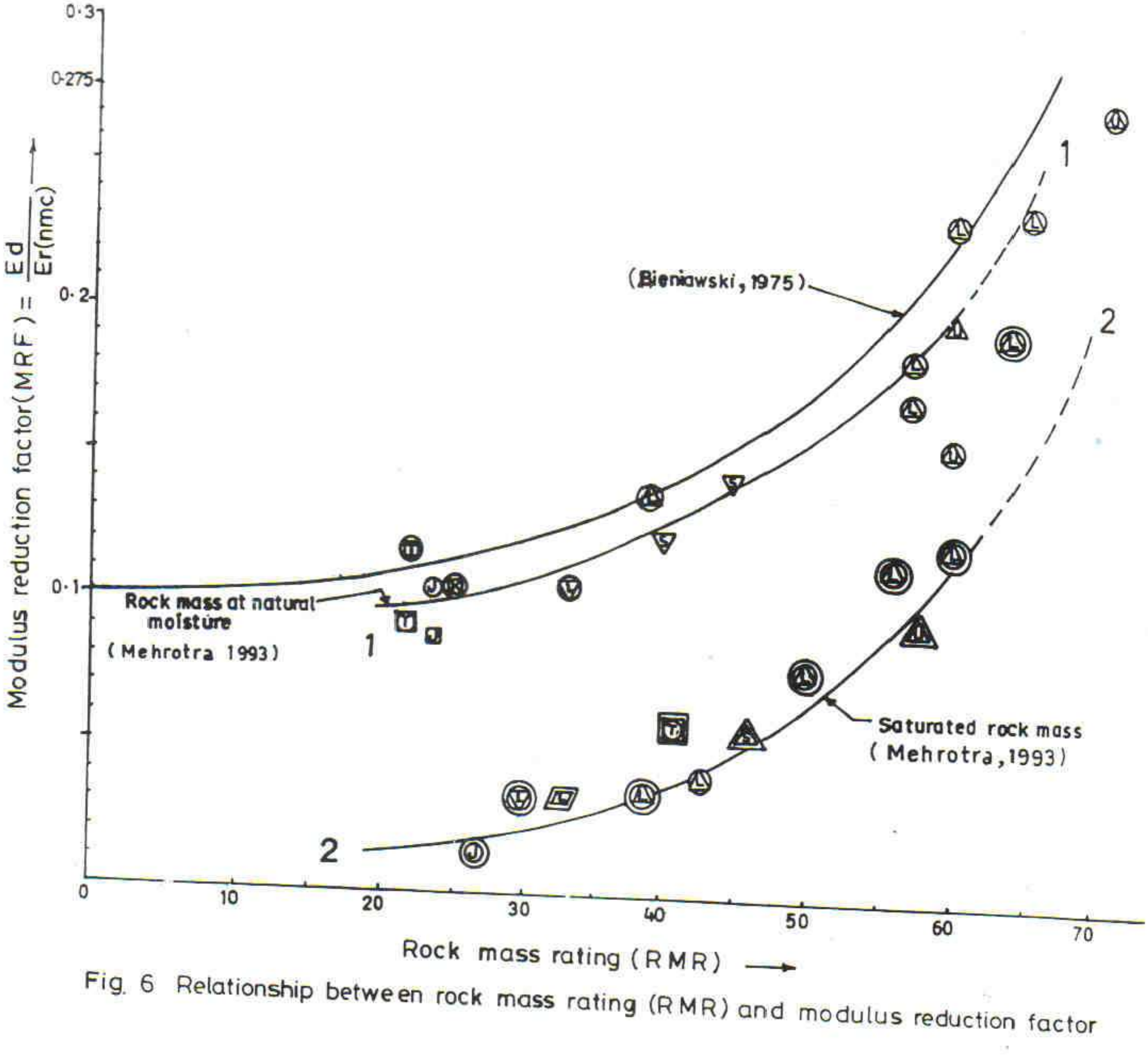

Fig. 6 Relationship between rock mass rating (RMR) and modulus reduction factor