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Permanent Deformation Behaviour of Jointed Dolomite Rock Mass

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Abstract: Rock mass is a discontinuous medium with fissures, fractures, joints, bedding planes, and faults. These discontinuities may exist with or without gouge material. Reliable characterization of the deformation behaviour of jointed rocks is very important for safe design of civil structures on rocks. This behaviour depends on the orientation of joints with respect to loading direction, in-situ stress condition, spacing of joints and loading area. In-situ testing by means of uniaxial jacking is practiced to determine the modulus of rock mass. It is combination of recoverable and permanent deformations. Two cases viz. Anji Khad Bridge site (case-1) and Kuri-Gongri site (case-2) where jointed dolomites belongs to fair and poor rock mass respectively exist are considered for study. Five uniaxial jacking tests were conducted at both the sites and their results, with focus on the permanent deformation is discussed in the paper. The average permanent deformation in case-1 is 0.6 mm which is 33% of total deformation in 5th loading cycle. In case-2, average permanent deformation is 0.4 mm, which is 78% of total deformation in 5th loading cycle. The study revels that though the large portion of deformation is of permanent nature in case-2, the absolute value of deformation is less as compared to case-1. In addition, poor rock mass shows high deformation modulus than fair rock mass and the details are presented in the paper.

Keywords: Uniaxial Jacking Tests, Permanent Deformation, Jointed dolomite Rock

1 Introduction

An assessment of deformation and shear strength parameters of rock masses is required for the analysis and design of slopes, foundations and underground openings (Ramamurthy and Arora, 1994; Jade and Sitharam, 2003; Yang et al., 2017; Tiwari and Latha, 2019). Deformability characteristics are assessed using uniaxial jacking tests, large flat jack tests, or borehole jack tests (Bieniawski, 1978; Palmstrom et al., 2001). The deformation characteristic of a rock mass depends on the orientation of joint with respect to the loading direction, in-situ stress condition, spacing of joints and the size of loading region (Hari Dev, 2020). An appropriate interpretation of the in-situ tests data is essential for getting reliable design parameters i.e. modulus of deformation and modulus of elasticity (Rajbal Singh et. al., 2010). Usually, fresh and hard rock samples of laboratory scale may show elastic behaviour. In field situation, due to presence of fissures, fractures, bedding planes, zones of altered rocks and clays with plastic properties, the behaviour does not remain elastic any more. This causes the permanent deformations even after unloading the rock mass during in-situ deformability tests (Shashank Pathak et. al., 2014).

In the present study, the uniaxial jacking tests are conducted in jointed dolomites rocks to study the rock deformation behaviour during cycles of loading and unloading. Five equal incremental cycles of loading and unloading are applied and resulting deformations are measured. The total deformation consists of two parts (i) recoverable deformation upon unloading and (ii) permanent deformation. The elastic, permanent and total deformations are to be considered holistically for safe and economical design. In this paper, emphasis is given to get insight into the permanent deformation behaviour of the rock mass.

2 Uniaxial Jacking Tests

The uniaxial jacking tests were conducted following IS-7317 and ISRM suggested methods. The test results of two different projects in dolomite rock mass are discussed in this paper. The objective of testing at one project was to know the settlement of rock mass due to load of Railway Bridge whereas objective of the second project is to know the deformability characteristic of rock mass. Both the cases are dealt separately and discussed the test results with respect to permanent deformation. The deformation of a rock is partly elastic (recoverable) and partly plastic (permanent). It is mainly due to closure of joints existing in the rock mass, sliding along the fissures and deformation of rock, etc. Thus, the deformation of the rock mass is complicated and it includes elastic, plastic and time dependent behaviour.

The evaluation of deformation modulus is based on Boussinesq's equation for a point load on infinite homogeneous, isotropic and linearly elastic material. Modulus of deformation for loading cycle is calculated by considering total deformation of a particular cycle, whereas, modulus of elasticity is calculated by considering elastic deformation for the same cycle using Equation (1).

$$E_m = \frac{P(1-\upsilon^2)}{2\delta R} \tag{1}$$

where, $E_m = E_{dm}$, deformation modulus of rock mass corresponding to δ = total deformation during loading and $E_m = E_{em}$, modulus elasticity of rock mass corresponding to δ = recovered deformation during unloading in each cycle, P = Applied load in each cycle, ν = Poisson's ratio of rock mass and R = Radius of loading plate in contact with ground.

The values for modulus of deformation and modulus of elasticity were calculated for each cycle. IS 7317 may be referred for relevant application of values of E_{dm} and E_{em}. The deformations recorded in the first cycle may not be true representative of actual rock mass behaviour due to initial packing of surface undulations, modulus values obtained from the first cycle may not be used for design purpose. Hence, results obtained from the first loading cycle to be omitted.

3 Permanent Deformation Modulus

Plastic or Permanent deformation takes place when a rock, mineral, or any other substance is stressed beyond its elastic limit. The extent of permanent deformation plays an important role in design of structures in rocks. Permanent deformation is irreversible; the deformation stays even after removal of the applied forces, while the temporary deformation is recoverable as it disappears after the removal of applied forces. The permanent deformation depends on the number of loading cycles, stress levels and geological factors.

The permanent deformation in each cycle can be calculated subtracting the recovered deformation from the total deformation. In other words, total deformation = permanent deformation (plastic) + recovered deformation (elastic). Further, modulus of permanent deformation (E_{pm}) can be determined by substituting δ = permanent deformation in Eq.1 for each cycle. The higher the E_{pm} value represents, the material is behaving more elastically and permanent deformation is comparably less than the total deformation and vice versa.

In case the entire deformation is of permanent type, and no recovery of deformation obtained then, deformation modulus (E_{dm}) and E_{pm} will be equal. Further, when the permanent deformation = 50% of total deformation and remaining 50% is of elastic, and then modulus of elasticity of rock mass (E_{em}) and E_{pm} will be equal.

The uniaxial jacking tests results of two cases with detailed geological information are presented below;

3.1 Case-I: Anji Khad Bridge Project

This project envisages the construction of an arc bridge for Udhampur–Qazigund Railway Line, across Anji, a seasonal tributary of Chenab River, which is 186m high and 657m long. The proposed railway line alignment between Katra and Qazigund generally passes through Siwaliks and Pre-Tertiary rocks overlain by unconsolidated sediments of Recent to Sub-Recent ages. The study area comes within the sub-Himalayan zone, with outcrops of unfossiliferous limestone, Sirban limestone of Hazara of presumably Permian or Permo-Carboniferous/Meso-Proterozic age as inliers.

Massive to blocky Dolomite is exposed along both the banks of railway bridge project below the proposed arch foundation up to a height of 50 m with wide range of colours and different degrees of weathering and fracturing; rolled-down boulders and chips of dolomitic limestone and limestone with silt and clay material and siliceous limestone. The strata in the area are characterized by prominent one sub-horizontal foliation joint and two sub-vertical joints. The foliation joint strikes roughly N-S and dips 20^o to 30^o in East direction. The first joint strikes roughly NE-SW and dips 80^o to 85^o in NW direction and the second joint strikes SE-NW and dips 60^o to 70^o in SW direction. A few sub-vertical random joints are also present. The strata have major three sets of discontinuities, which are continuous and persistent. At many of the places, the foliation joint and the other two joints intersect each other forming cubical structure (Fig. 1). In weathered and fractured dolomitic limestone and limestone, the average spacing of the foliation joint is 5 to 10 cm and of the other joints is 10 to 15 cm. These joints are smooth to rough or irregular, planar to undulating and unaltered with occasional infilling of calcareous or siliceous material along them or very minor joint surface staining. The rock mass was characterized through RQD (49; Fair-Poor), RMR (48; Fair), Q (6.13; Fair), and Geological Strength Index (43; Fair) Classifications.

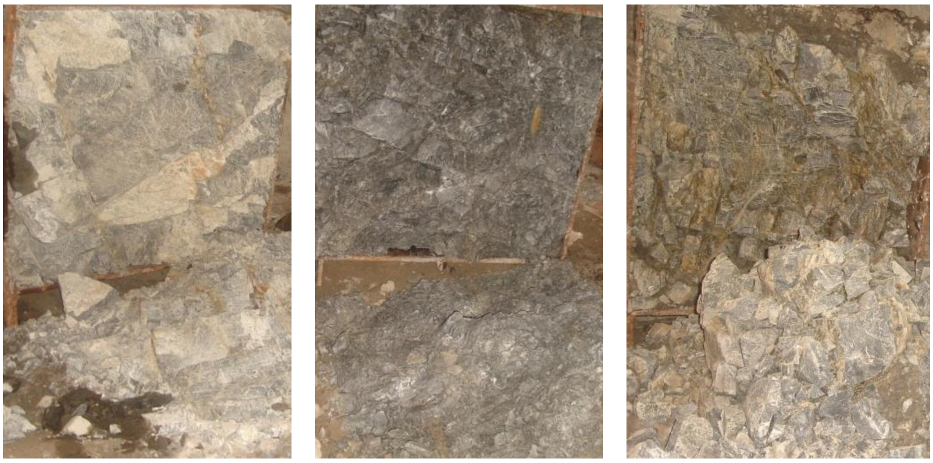

Fig. 1. Jointed blocky dolomite at Anji Khad Railway Bridge Project

The five uniaxial jacking tests were conducted in the left abutments, to know the settlement of rock mass by the load exerted due to proposed Bridge. The total deformation observed is varied from 1.56 to 5.66 mm and elastic rebound from 0.97 to 1.80 mm, the remaining deformations were permanent. The stress-deformation graphs obtained in one of the five tests is shown in Fig. 2. The minimum, maximum and average values of different modulus calculated based on total, recovered (elastic) and permanent deformation of five tests is shown in Table 1. The average modulus of deformation and elasticity were found to be 1.7 to 2.1 GPa respectively at 5th loading cycle. The permanent deformation modulus varies from 2.2 GPa to 16.2 GPa with average of 6.2 GPa at 5th cycle.

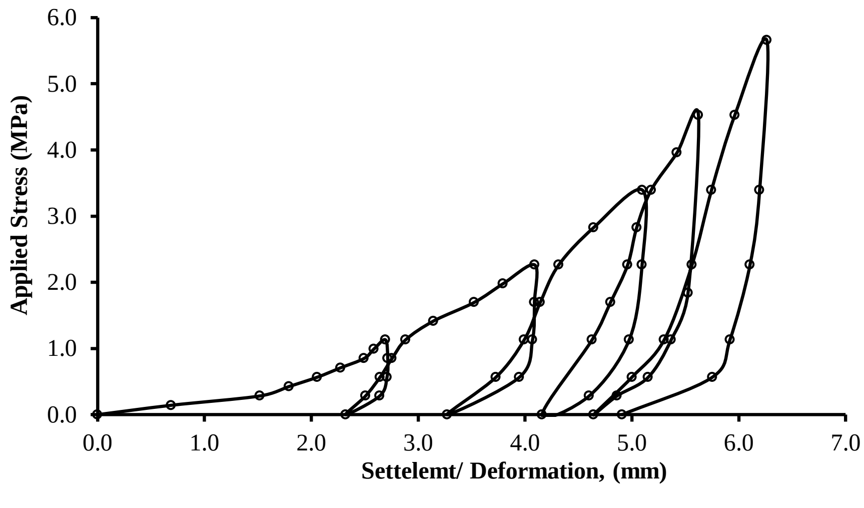

Fig. 2: Stress-Deformation graphs of Railway Bridge Project

Table 1. Average values of Moduli of deformation and elasticity (Case-1)

Stress Level MPa	Modulus of Deformation, E_{dm} (GPa)			Modulus of Elasticity, E_{em} (GPa)			Permanent deformation Modulus, E_{pm} (GPa)		
	Min	Max	Avg.	Min	Max	Avg.	Min	Max	Avg.
2.26	0.35	0.87	0.55	0.96	3.23	1.61	0.56	1.19	0.87
3.39	0.58	1.58	0.88	0.99	2.31	1.44	1.17	5.02	2.48
4.53	0.69	2.08	1.18	1.35	2.60	1.81	1.43	10.35	4.00
5.66	0.93	2.48	1.49	1.35	2.92	2.10	2.24	16.17	6.17

3.2 Case-II: Kuri-Gongri HE Project

The Kuri-Gongri HEP envisages construction of Rock Fill with Earthen Core dam of about 286 m high above river bed level, across Kuri-Gongri River to generate electricity with 2800 MW capacity. The project area is part of the lesser Himalayas of Neoproterozoic to Cambrian age bounded in the north by Shumar thrust and towards south by the Main Boundary Thrust. In the proposed project area rocks of Manas Formation comprising mainly dolomitic limestone, quartzite, phyllite / slate and carbonaceous phyllite are found. Different varieties of dolomitic limestone such as banded, dark grey, light grey are exposed in the major part of the project.

Rock type encountered in this drift is moderately to highly fractured dolomite with numerous calcite veins/lenses all along the drift (Fig. 3). The calcite veins are mostly parallel to the bedding joints, at places across to the bedding joints also. The bedding joints of the rocks are dipping 10°-35°/N025°-040°, however, variation in dip direction from NW to SE is also noticed may be due to warping, folding and some local deformation. Apart from bedding joint the rock mass is intersected with four joint sets. The joints are forming structural wedges at places. RMR value of rock mass in the drift ranges from 30 to 35 (Poor) and Q value varies from 2.0 to 3.8 (Poor).

Fig. 3. Jointed blocky dolomite at Kuri Gongri HE Project

Five uniaxial jacking tests were conducted in the right bank drift in the spillway area at different locations, to know the deformability characteristics of rock mass. The total deformation observed varied from 0.31 to 0.67 mm and the elastic rebound varied from 0 to 0.29 mm, the remaining deformations were permanent. The stress-deformation graphs obtained in one of the five tests is shown in Fig. 4. The minimum, maximum and average values of different modulus calculated based on total, recovered (elastic) and permanent deformation of five tests is shown in Table 2. The average modulus of deformation and elasticity were found to be 5.7 to 35.0 GPa respectively at 5th loading cycle. The permanent deformation modulus varies from 4.9 GPa to 9.8 GPa with average of 7.2 GPa at 5th cycle.

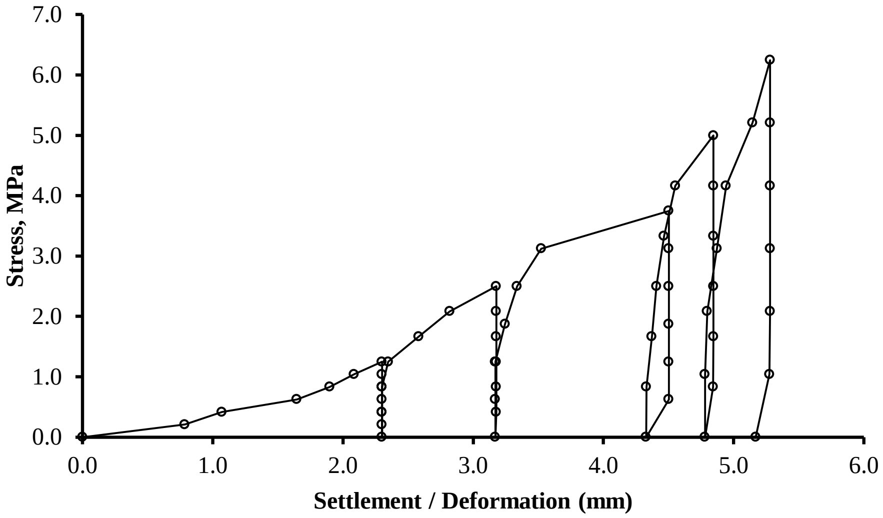

Fig. 4. Stress Verses Deformation graphs of Kuri Gongri HE Project

Table 2. Average values of moduli of deformation and elasticity (Case-2)

Stress Level	Modulus of Deformation, E_{dm} (GPa)			Modulus of Elasticity, E_{em} (GPa)			Permanent deformation Modulus, E_{pm} (GPa)		
MPa	Min	Max	Avg.	Min	Max	Avg.	Min	Max	Avg.
2.50	0.77	1.54	1.25	15.30	107.13	78.82	0.78	1.54	1.28
3.75	1.21	4.23	2.56	9.18	321.38	101.22	1.39	4.53	2.78
5.00	3.08	5.53	4.49	7.79	142.84	49.10	4.51	8.75	5.77
6.25	3.98	8.64	5.73	9.24	71.42	35.00	4.96	9.83	7.16

In case-2 it may be seen that, E_{em} values obtained were very high due to very less rebound. Even, at few cycles no rebound was recorded, which results infinite elastic modulus of rock mass. It indicates that the gradual accumulation of elastic strain is getting released due to highly jointed nature of dolomite present at the test sites. The parameter E_{em} should be used with careful engineering judgement. In general for designs E_{dm} at appropriate stress level is to be adopted. In other words, majority of the deformation were of permanent nature.

4 Results and Discussions

Two varieties of dolomites have been studied, the dolomite of Case-1 belongs to fair category of rock mass and the dolomite in Case-2 is highly jointed and belongs to poor category. The deformations total, recovered (elastic) and permanent (plastic) along with percentage of permanent deformation with respect to total deformation for case-1 and case-2 is shown in Table 3. The elastic and permanent deformation in each cycle for both cases is shown at Fig. 5. It is seen that percentage of permanent deformation reduces from 81% from cycle-1 to 33% in cycle-5 for case-1. In case-2, it reduces from 100% in cycle-1 to 78% in cycle-5. Through the permanent deformation percentage is more in case-2, value of total deformation and permanent deformation is less as compared to case-1.

Table 3. Average deformations of all tests in each cycle

Cycle	Case-1				Case-2			
	Deformation/settlement, mm			% of Permanent w.r.t total	Deformation/settlement, mm			% of Permanent w.r.t total
	Total	Recovered	Permanent		Total	Recovered	Permanent	
1st	2.70	0.50	2.20	81%	2.28	0.00	2.28	100%
2nd	1.94	0.72	1.22	63%	0.91	0.02	0.89	98%
3rd	1.87	1.10	0.76	41%	0.74	0.07	0.67	90%
4th	1.88	1.14	0.74	39%	0.50	0.10	0.39	79%
5th	1.85	1.25	0.61	33%	0.51	0.11	0.40	78%

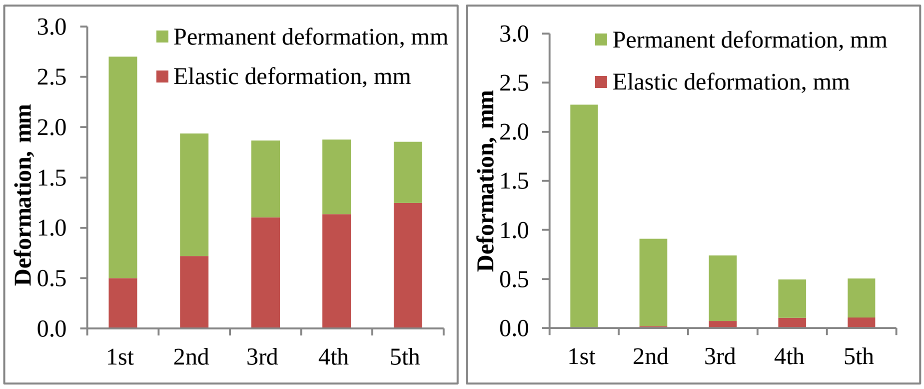

Fig. 5. Elastic and permanent deformation in each cycle (Left: Case-1, Right: Case-2)

The deformation modulus, elastic modulus and permeant modulus in each cycle calculated in case-1 and case-2 is plotted in Fig. 6. It is seen that in both cases the deformation modulus and permanent deformation modulus increases with stress level (loading cycle from 1 to 5). As the permanent deformation will be less or equal to total deformation, the permanent deformation modulus should be always higher than deformation modulus as evident from Fig. 6. In case-1, the value of permanent modulus increases steeply as the stress level increases shows that permanent deformation is decreasing and rock is behaving more elastically with increase in loading cycles (stress levels).

Further, the elastic modulus in case-2 is very high as compared to other modulus indicates the recovery is very less; or it can be said as the permanent deformation part is more. However, since the magnitude of the overall deformation is less, the deformation modulus in case-2 is higher that case-1. Though case-2 is poor rock mass, the deformation modulus and permanent modulus were higher than case-1 belonging to fair category rock mass. In case, the design is based on rock mass classification based on indirect approaches, the design for case-2 will be too conservative and uneconomical. This study also emphasise the importance of in-situ testing rather than empirical approaches.

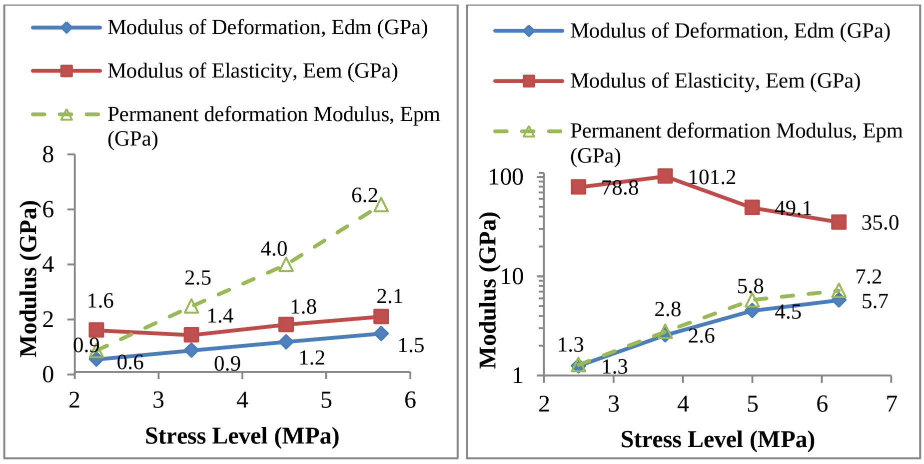

Fig. 6. Moduli Values with Stress Level (Left: Case-1, Right: Case-2)

5 Conclusions

The permanent deformation behaviour of two types of dolomite rock mass viz., (i) fair category (ii) poor category were studied. The permanent deformation is calculated by subtracting deformation recovered during unloading from total deformations during loading in each cycle. The following conclusions were drawn from the study;

(i) The percentage of permanent deformation w.r.t total deformation at 5th cycle is 30% in case-1 and 80% in case-2. However, the absolute value of permanent deformation in case-1 is 0.6 mm which is higher than 0.4 mm obtained in case-2.

(ii) Further, the modulus of permanent deformation in case-1 (fair rock mass) is 6.2 GPa, whereas in case-2 (poor category highly jointed) is 7.2 GPa corresponding to 5th cycle.

(iii) The deformation modulus of rock mass calculated based on total deformation at 5th cycle in case-1 is 1.5 GPa and in case-2 is 5.7 GPa.

(iv) The value of modulus of deformation and permanent modulus increases with increases in loading cycle from 1 to 5 in both cases. It shows that rock mass properties improve with increases in stress level.

(v) Overall, the study reveals that even though the major portion of deformation (80%) in case-2 (poor category rock mass) is permanent one, the value of both deformation modulus and permanent modulus is higher than case-1. In addition, the high modulus in poor rock mass than fair rock mass reminds us the importance of in-situ testing and limitations in rock mass classification based estimates.

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