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Rock Strength and Elastic Properties of Basement Granitoids from Koyna Region, Deccan Volcanic Province, India

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ABSTRACT

Unconfined compressive strength measurements on 20 borehole core samples constrain the elastic properties of basement granitoids underlying the Deccan basalts in the Koyna region for the first time. Test specimens were taken from the basement section below 1251 m depth in borehole KBH-7, which is located in proximity to the Donichawadi surface rupture associated with the 1967 M6.3 Koyna earthquake. Specimens of granite, granite-gneiss and migmatitic gneiss were tested in the laboratory under dry state and room temperature. Salient results of the study are as follows: (i) The granitoids are characterised by variable compressive strength in the range 22-98 MPa, (ii) Stress-strain response of the basement rock indicate varying degrees of deformation even for the same rock type. (iii) Young's modulus and Poisson's ratio of the granitoids, computed from the linear elastic portion of the stress-strain curves, vary in the range 8-23 GPa and 0.1-0.3 respectively, (iv) The low and variable rock strength of the Koyna granitoids when compared to granitic rocks from aseismic areas indicates their generally weak nature, probably induced by the recurrent seismicity in the Koyna seismogenic zone.

INTRODUCTION

Elastic properties of rock provide valuable constraints in understanding rock deformation. Elastic properties are determined from laboratory measurements of axial and lateral strain developed in a rock sample as a function of axial stress. A rock sample containing large number of weak planes, such as micro-fractures, foliations and joints generally shows large axial as well as lateral deformation at low axial stress (Lockner and Beeler, 2002). Strength and deformation behaviour of rock are primarily controlled by compaction, density of microcracks, grain size, interlocking between grains, and foliation/ lineation (Jaeger et al., 2007; Fossen, 2010). Studies also reveal that because of heterogeneity, same rock type may show variable rock strength and elastic properties (Lockner, 1995, Goswami et al., 2017). In general, deformed rocks are characterised by enhanced Poisson's ratio and reduced Young's modulus and compressive strength (Faulkner et al., 2006; Eberhardt et al., 1999).

The Koyna region, located in the Deccan Volcanic Province, western India (Fig. 1) is a unique site to study the influence of ongoing seismic activities on the strength and deformation behaviour of the rock strata. The region has been experiencing persistent earthquake activity since the past five decades, triggered by the Koyna and Warna artificial water reservoirs (Gupta and Rastogi, 1976; Gupta, 2002; Gupta, 2011; Gupta et al., 2015, 2016). The entire seismic activity is restricted in ~30 km x 20 km area to the south of the Koyna Dam. The great majority of the earthquakes are located in the granitic basement rocks underlying the Deccan flood basalt pile, generally below 1 km and up to about 10 km depth. Core drilling carried out during 2012-2014 penetrated the entire Deccan flood basalt pile and provided direct information about the nature of the basement granitoids for the first time (Roy et al., 2013; Gupta et al., 2016). The core samples obtained from drilling provide unprecedented opportunities to sample a few hundred metres of the basement granitoids and carry out laboratory measurements of elastic properties.

In the present study, the basement section from a vertical borehole KBH-7 at Panchgani, ~11 km SSE of Koyna Dam was chosen for laboratory measurements of mechanical properties. The borehole site is located in close proximity to the Donichawadi fault zone associated with the 1967 M6.3 Koyna earthquake. Soil-gas helium surveys conducted across the surface expression of the fault zone during the period 1996-1997 as well as extensive seismic monitoring during the past few decades from a dense network of seismic stations located in the region show that the fault has been seismically active even 50 years after the 1967 earthquake (Gupta et al., 1999, 2017). Borehole KBH-7 is 1500m in depth and passes through ~1251m of Deccan basalt and ~249 m of basement granitoids.

In this paper, laboratory measurements on 20 core samples from the depth range 1264–1498 m in borehole KBH-7 constrain the unconfined compressive strength (UCS) and elastic properties of basement granitoids in the Koyna seismogenic zone and shed light on their deformation behaviour in response to ongoing seismic activity.

SAMPLE DESCRIPTION

Rock samples in the present study comprise cores of Precambrian granitic basement below the Deccan flood basalt pile. The basement granitoids recovered from borehole KBH-7 are medium- to- course grained and include three major rock types: granite-gneiss, granite and migmatitic gneiss (Fig. 2). Twenty intact core samples representative of the basement granitoids were selected for studying unconfined compressive strength (UCS) and elastic properties of basement rocks. The sample details including depth and rock type are listed in Table 1.

Cylindrical test specimens were prepared from NQ size cores (47.6 mm diameter) for UCS tests. End surfaces of each sample were made flat (within 0.05 mm) and parallel to each other (within 0.002D, where D is the specimen diameter) by cutting, grinding and polishing. The length to the diameter ratio for each sample is 2:1. After preparation, all samples were dried in an oven at a temperature of about 100°C for about 12 hours before conducting the UCS tests.

UNCONFINED COMPRESSIVE STRENGTH (UCS)

Unconfined compressive strength (UCS) tests were carried out in a universal testing machine (UTM) at the Geomechanical Laboratory, CSIR-CIMFR, Dhanbad. Load was applied on the rock sample along

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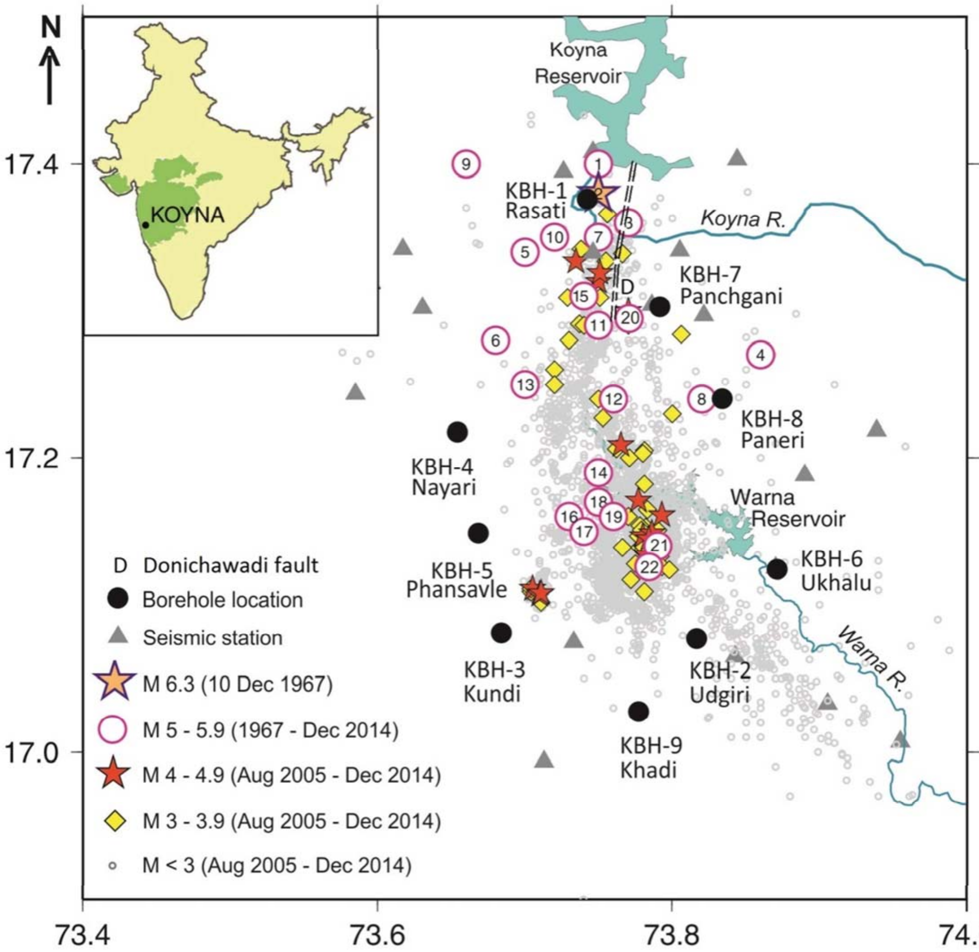

Fig.1. Map of Koyna-Warna area showing the distribution of cored boreholes vis-a-vis the seismicity (modified after Gupta et al. (2015) and Goswami et al. (2017)). The Koyna and Warna artificial water reservoirs are also shown. The trace of the Donichawadi fault zone, formed during 1967 M6.3 Koyna earthquake, is also shown. Inset shows the location of Koyna in the Deccan Volcanic Province (shaded green) on the outline map of India.

its axial directions by the action of a piston that pushes against the end of the sample. The lateral and axial deformation of the rock specimens are determined by using two pairs of linear variable differential transformers (LVDT), one pair measures the axial deformation whereas the other pair determines the circumferential deformation with an accuracy of 2%. The parameters obtained from the tests are the unconfined compressive strength and elastic properties of the rock sample. The axial strain (ε_a) and circumferential strain (ε_d) are calculated as follows:

$$\varepsilon_a = \frac{\Delta l}{l} \tag{1}$$

$$\varepsilon_d = \frac{\Delta d}{d} \tag{2}$$

where, l and d are the length and diameter respectively of the undeformed sample. Δl and Δd are the change in length and diameter of the test specimen respectively. The unconfined compressive stress (σ) is determined as:

$$\sigma = \frac{F}{A} \tag{3}$$

where, F is the compressive load on the test specimen and A is the cross-sectional area of the specimen before test.

Experimental UCS data are listed in Table 1 and the distribution of compressive strength of the basement granitoids are plotted as histograms in Fig. 3. Data vary in a wide range: 41-98 MPa for granite, 22-88 MPa for granite-gneiss and 41-67 MPa for migmatitic gneiss. Thus, all the three rock types representing the basement granitoids in the Koyna region are generally characterised by low but variable UCS values. Variation in strength within same rock type indicates that rock has experienced varying degree of deformation. Weak rock (low strength) generally indicates higher deformation as compared to strong rocks.

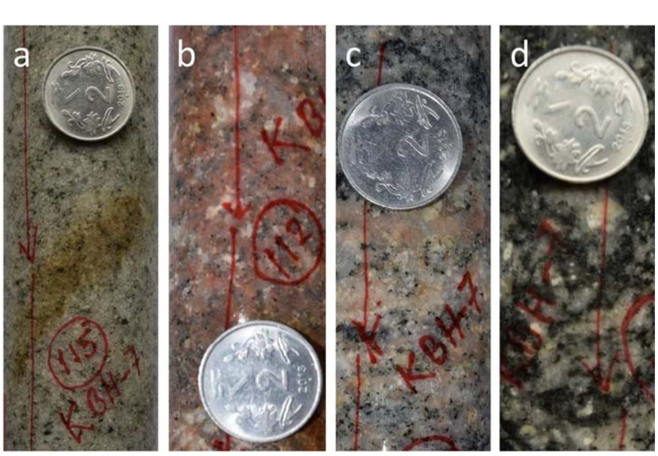

Fig.2. Photographs of representative test specimens used in the present work. (**a, b**) Granite, (**c**) Granite-gneiss, and (**d**) Migmatitic gneiss

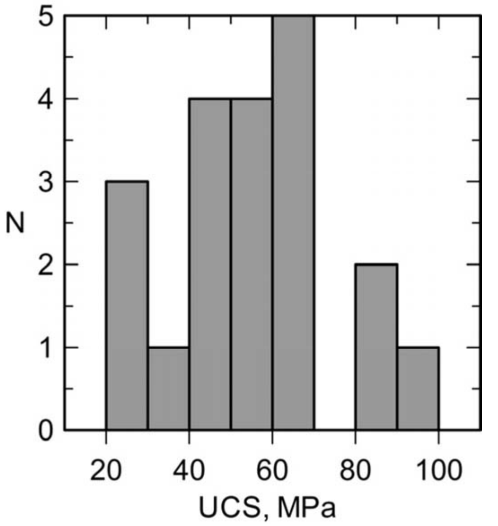

Fig.3. Histogram plots showing the distribution of UCS for 20 core samples of basement granitoids from Koyna region (present study).

DEFORMATION BEHAVIOUR FROM STRESS-STRAIN RESPONSE

Axial and radial deformation of the samples was measured under dry state and room temperature. Stress-strain response curves were obtained by plotting axial stress along Y-axis and strain along X-axis (Fig. 4). Deformation behaviours of granite, granite-gneiss and migmatitic gneiss samples are plotted separately. The positive side of the X-axis represents axial strain (axial shortening) whereas negative side represents radial or circumferential strain. Stress-strain curves are typically comprised of four sections: (i) an initial concave upward part indicating closing of pre-existing micro-cracks, (ii) a linear section representing the elastic deformation, (iii) a linear section indicating the initiation of stable cracks sub-parallel to the direction of applied load, and finally, (iv) propagation of fractures and failure. None of the tests shows post failure curve. Post failure behaviour of the rock could be obtained if stiffness of the load frame is comparable with the stiffness of the test specimen or higher. As the stiffness of the UTM was far below that of the test specimens, the strain energy stored in the load frame released violently during the failure of the specimens.

Data show that samples with large axial and lateral deformation generally fail at low axial stress and vice versa. Deformation is basically controlled by the rock heterogeneity. Larger the micro-crack in the rock specimen, higher is the heterogeneity. Deformation trends clearly show the varying degrees of heterogeneity among samples of similar as well as different rock types. Axial and lateral deformations of granite and granite-gneiss samples indicate slightly higher degree of heterogeneity as compared to migmatitic gneiss.

Table 1. List of test specimens of the present study showing rock type, depth, UCS, Young's modulus and Poisson's ratio. Poisson's ratio for two samples could not be determined.

Sample Desig-nation	Depth (m)	Rock type	UCS, MPa	Young's modulus, GPa	Poisson's ratio
KBH7_111	1264.8	Granite	98	22	0.21
KBH7_110	1268.26	Granite	55	16	0.11
KBH7_7	1279.64	Granite-gneiss	88	23	0.13
KBH7_113	1295.18	Granite-gneiss	47	12	0.25
KBH7_105	1303.96	Granite-gneiss	37	12	0.2
KBH7_103	1324.11	Granite-gneiss	53	20	0.22
KBH7_102	1331.52	Granite	42	17	0.22
KBH7_101	1339.06	Granite-gneiss	62	18	0.13
KBH7_114	1350.66	Granite-gneiss	52	17	0.26
KBH7_17	1357.65	Granite-gneiss	56	17	0.14
KBH7_115	1366.79	Granite	61	18	ND[@]
KBH7_116	1374.58	Granite-gneiss	22	9	ND[@]
KBH7_23	1388.16	Granite	41	13	0.29
KBH7_20	1407.12	Migmatitic gneiss	67	18	0.17
KBH7_108	1412.89	Migmatitic gneiss	41	14	0.15
KBH7_27	1434.89	Migmatitic gneiss	67	21	0.21
KBH7_107	1444.34	Migmatitic gneiss	61	19	0.14
KBH7_29	1460.67	Granite-gneiss	81	20	0.15
KBH7_32	1471.16	Granite-gneiss	27	9	0.17
KBH7_106	1497.67	Granite-gneiss	28	10	0.15

[@] ND: Not determined

ELASTIC PROPERTIES: YOUNG'S MODULUS AND POISSON'S RATIO

The linear, elastic deformation part of the stress-strain curve is used to calculate the Poisson's ratio (í) and Young's modulus (Y). Following relations are used to calculate the elastic parameters:

$$\nu = \frac{\Delta d}{\Delta l} \tag{4}$$

$$Y = \frac{\sigma}{\varepsilon_a} \tag{5}$$

where, Δd and Δl are the change in diameter and length of the test specimen respectively. The distribution of Poisson's ratio and Young's modulus are shown in Fig. 5a,b (red bars). Range of Young's modulus for granite, granite-gneiss and migmatitic gneiss is 13 to 22 GPa, 14 to 21 GPa and 8 to 23 GPa respectively. The corresponding ranges for Poisson's ratio are 0.11-0.29, 0.13-0.26 and 0.14-0.21 respectively.

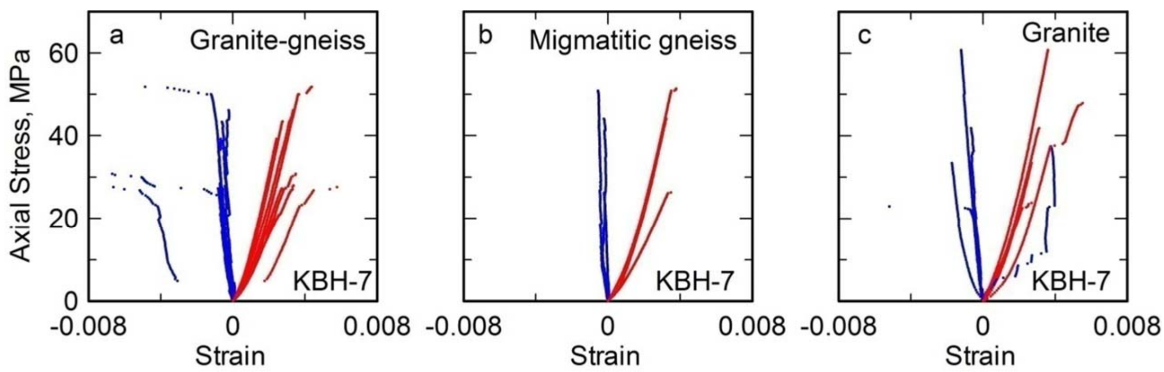

Fig.4. Plots showing axial deformation (red) and lateral deformation (blue) of KBH-7 basement granitoids of the present study. (a) Granite-gneiss, (b) Migmatitic gneiss, and (c) Granite.

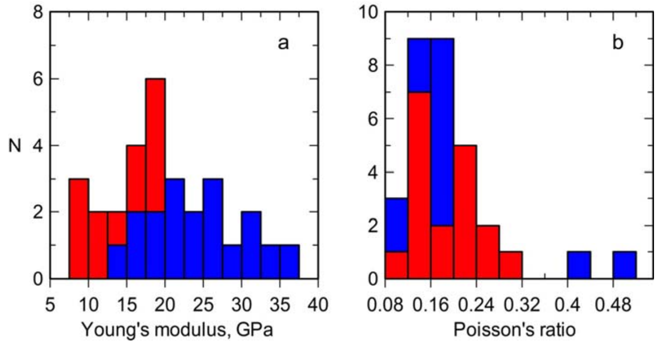

Fig.5. Histogram plots showing the distribution of **(a)** Young's modulus and **(b)** Poisson's ratio for 20 basement granitoid samples of the present study (red bars). The data for granitic rocks from other studies are also plotted for reference (blue bars): Young's modulus and Poisson's ratio data are taken from the compilation by Haas (1981).

DISCUSSION

Scientific drilling up to 1500 m depth in Koyna seismogenic zone has provided a unique opportunity to carry out laboratory mechanical tests on basement granitoids underlying the ~65Ma old Deccan flood basalt pile. Unconfined compressive strength (UCS), stress-strain response and elastic properties of 20 core samples were measured on a UTM. As the great majority of earthquakes in the Koyna region occur below a depth of 1 km from the surface, the dataset obtained from measurements on deep borehole samples provide valuable constraints to study the effect of ongoing seismicity on rock strength and elastic parameters.

The basement granitoids beneath the Koyna region are characterized by UCS values in the range 22-98 MPa. UCS range for individual rock types are 41-98 MPa for granite, 22-88 MPa for granite-gneiss and 41-67 MPa for migmatitic gneiss. Singh (1981) provides a large compilation of uniaxial compressive strength measured on 690 samples covering granitic rocks including granite-gneiss, biotite-rich granite and granodiorites from 16 sites in the USA (Wyoming, Vermont and California) and United Kingdom. The mean UCS values for individual sites range from 94.5±35.9 (SD) to 231.4±42.4 (SD) MPa, except 10 samples of granite-granodiorite from California which yielded mean UCS of 36.6±43.6 MPa. The mean values for the individual sites are plotted along with the mean of Koyna granitoids of the present study in Fig. 6. The UCS range obtained for Koyna basement granitoids is consistently lower than that of most granitic rocks listed in Singh (1981).

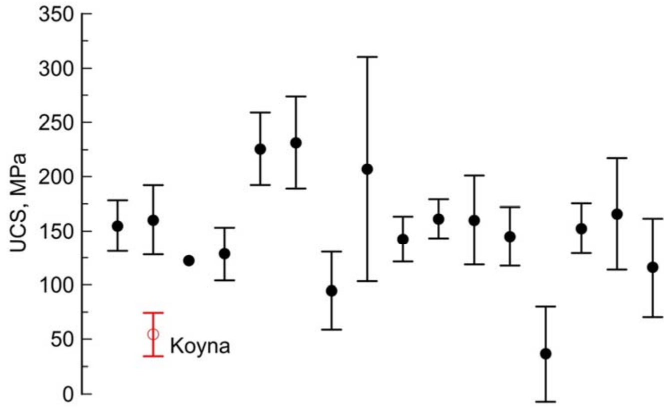

Fig.6. Comparison of mean UCS of granitoids from Koyna area (red open circle) and mean UCS of granitic rocks from 16 sites (690 samples) reported in the compilation by Singh (1981). The bars indicate standard deviation.

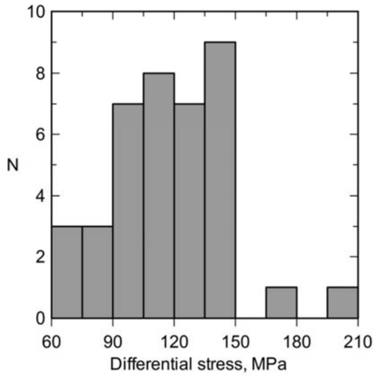

Fig.7. Distribution of differential stress of basement granitoids, measured at a confining pressure of 4 MPa, from four boreholes KBH-3, KBH-4A, KBH-5 and KBH-7 in the Koyna seismogenic zone. (Data from Goswami et al., 2017)

A recent study by Goswami et al. (2017) has reported the low failure strength of Koyna basement granitoids. The study involves the measurement of rock strength of several tens of basement samples from other boreholes in the Koyna-Warna region (KBH-3, KBH-4A, KBH-5 and KBH-7) under varying confining pressures up to 6 MPa by using a Hoek triaxial cell. The range of differential stress, measured at a confining pressure of 4 MPa, is 64-210 MPa (Fig. 7), which confirms the relatively weak nature of the basement granitoids. The low and variable UCS values obtained in the present study are consistent with the finding of Goswami et al. (2017) and may be attributed to the presence of heterogeneities induced by the recurrent seismic activity in the region.

Stress-strain response of the basement granitoids have been determined by measuring the axial and lateral deformation of the test specimens. The data indicate variable deformation behaviour among the test specimens. Young's modulus and Poisson's ratio of the granitoids range from 8 to 23 GPa and 0.11 to 0.29 respectively. Haas et al. (1981) provide a compilation of Young's modulus from 24 samples and Poisson's ratio from 14 samples of granite, gneiss and granodiorite from several studies. The data are plotted in Fig. 5(a,b) (blue bars) together with the data of the present study (red bars). For the Koyna basement granitoids, Young's modulus values are generally much lower when compared with the granitic rocks reported in the compilation by Haas (1981), whereas Poisson's ratio is found to be slightly higher.

Poisson's ratio and Young's modulus provide valuable constraints about rock deformation. A deformed zone is generally characterized by high Poisson ratio and low Young's modulus due to the higher density of micro-cracks, which substantially reduces rock stiffness (Eberhardt et al., 1999; Faulkner et al., 2006). Low Young's modulus of Koyna granitoids is attributable to low stiffness likely resulting from the ongoing seismicity in the region.

Rock strength data of the basement granitoids sheds new light on the frequent occurrences of low to moderate magnitude earthquakes in the Koyna region. Earthquakes generally occur when accumulated stress in the fault plane overcomes the breaking strength of the rock (Kanamori and Brodsky, 2004). Thus, rock strength should be high to generate large magnitude earthquakes. Low unconfined compressive strength of the Koyna basement granitoids indicates that fault(s) in the Koyna region are surrounded by relatively weak rocks, whose strength is not sufficient to build high stress levels within the fault zone. However, the region also experiences occasional moderate magnitude earthquakes for which the rock mass should regain its strength quickly. Re-strengthening of rock mass basically depends on the inter-seismic period between successive earthquake cycles and rate of healing (Marone, 1998). Higher the healing rate, quicker is the re-strengthening of rock mass. Statistics show that the seismic activity in the Koyna-Warna region includes one triggered earthquake of M6.3, 22 earthquakes of M≥5, 200 earthquakes of M≥4.0 and several hundred smaller earthquakes during the past five decades (Gupta et al., 2015, 2016). Mallika et al. (2012) have documented the occurrences of low to moderate magnitude earthquakes in the Warna region during the period August 2005 to December 2010. Earthquakes of magnitude 4 and above are generally infrequent, indicating longer inter-seismic period required to generate moderate magnitude earthquakes. Further detailed analyses of seismicity combined with rock friction experiments are essential to fully understand the control of healing rate in regaining the frictional strength of rock mass comprising fault/fracture zones in the Koyna region.

CONCLUSIONS

(i) Compressive strength and elastic properties of basement granitoids underlying the Deccan Traps in the Koyna seismogenic zone, western India, are measured for first time. Tests carried out on 20 specimens of granite, granite-gneiss and migmatitic gneiss yield UCS, Young's modulus and Poisson's ratio in the range 22 to 98 MPa, 8 to 23 GPa and 0.11 to 0.29 respectively.

(ii) Stress-strain response curves indicate significant variability in deformation behaviour of same as well as different rock types, likely due to heterogeneity induced by occurrence of frequent earthquakes in the region.

(iii) Low and variable strength and elastic properties of the basement granitoids in Koyna region compared to granitic rocks from other regions indicate that rock strength may have been modified by the recurrent seismic activity in the Koyna region over the past five decades. Low rock strength implies that rocks are not strong enough to build high stress levels in the fault zone to produce large earthquakes. The data therefore provide a plausible explanation for the occurrences of frequent low magnitude earthquakes in the region. Occasional moderate magnitude earthquakes occur depending on the inter-seismic period between successive earthquake cycles and the rate of healing of fracture/fault zones.

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