Paper No. 149, Bulletin I.S.E.T., Vol. 11, No. 4, pp. 107-115, Dec. 1974

STUDIES ON ULTRA-MICROEARTHQUAKES IN FRACTURED ROCK FORMATIONS FOLLOWING RESERVOIR IMPOUNDING

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INTRODUCTION

It is well known that during the last few decades since the classical case history of reservoir induced seismicity at Lake Mead, U.S.A., there have been about two dozen cases uptil now (Rothe', 1970; Proc. COSERI, 1973; Guha et al, 1974), wherein significant seismic activities followed reservoir impounding. Though, in most cases, largest earthquakes observed following reservoir impounding were below magnitude 4.5, in few cases such as at Koyna. Kariba, Kremasta and Lake Mead, the magnitudes of largest earthquakes recorded were higher, even upto 6.5 (Koyna earthquake of 10.12.1967). It is evident from the above case histories that the number of reservoirs exhibiting seismic activities following impounding is insignificant compared to their total number as such. It is quite possible that seismic activities at much lower level could be more prevalent than observed so far and had escaped detection due to lack of close and proper instrumental observations near reservoirs. In a programme initiated immediately after the Koyna earhquake of December 10, 1967 to investigate existence of such low level seismic activities at various virgin reservoir sites in the Deccan trap region, seismographs suitable to record ultra-microearthqukes down to magnitude —2.0 were installed near some newly impounded reservoirs. Though a few of the reservoirs did not show even ultra-microearthquake activity, Mula reservoir situated in Deccan Trap region exhibited ultra-microearthquake activity significantly and the same did fluctuate with water level variations in the virgin reservoir.

SEISMOLOGICAL STUDIES

The Mula dam (19°22′ N, 74°37′ E) with the reservoir situated in the Deccan Trap area of the peninsular India, was impounded in 1972 monsoon season for the first time. Basalt lava beds in the area are known to be horizontally disposed like most other areas of Deccan Trap region. Immediately after the impounding of the reservoir in 1972, a long crack (400 m) was observed along the right bank of the reservoir about a kilometre upstream of the dam (Fig.1). Subsequent studies (Karmarkar, 1973) have confirmed that the crack was an old one and could not have been formed subsequent to impounding. Recent photogeological studies have also confirmed this crack to be only a part of a much elongated fracture zone along the course of the Mula river. In fact these photogeological studies have indicated other similar fracture zones throughout Deccan trap region specially on the Western side of continental divide. Significance of these fractures specially with respect to post-trap tectonic activities in the area is yet to be fully evaluated. But their predominantly north-south trends (Das and Ray, 1973; Karmarkar, 1973) and enhanced density along the west coast seem to be significant. Incidentally, western coastal strip of Maharashtra is moderately active as evident from geographical distributions of historical and recent earthquakes in the area. Thus, directions and density of these fracture zones in the trap region seem to be tectonically significant. But the area in the vicinity of the Mula river basin had not experienced any known earhquake activity in the historical period.

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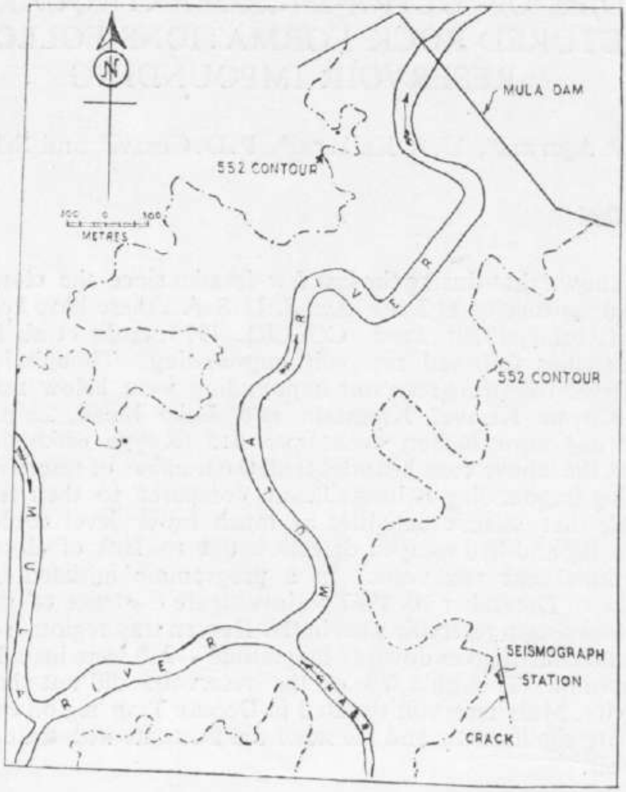

Fig. 1. Showing location of crack and seismograph station upstream of the Mula Dam, Maharashtra.

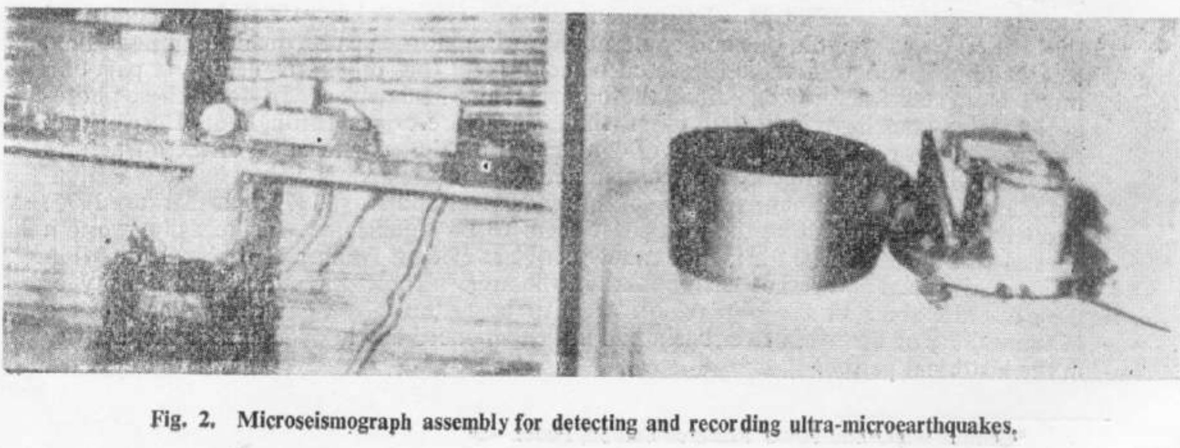

Fig. 2. Microseismograph assembly for detecting and recording ultra-microearthquakes.

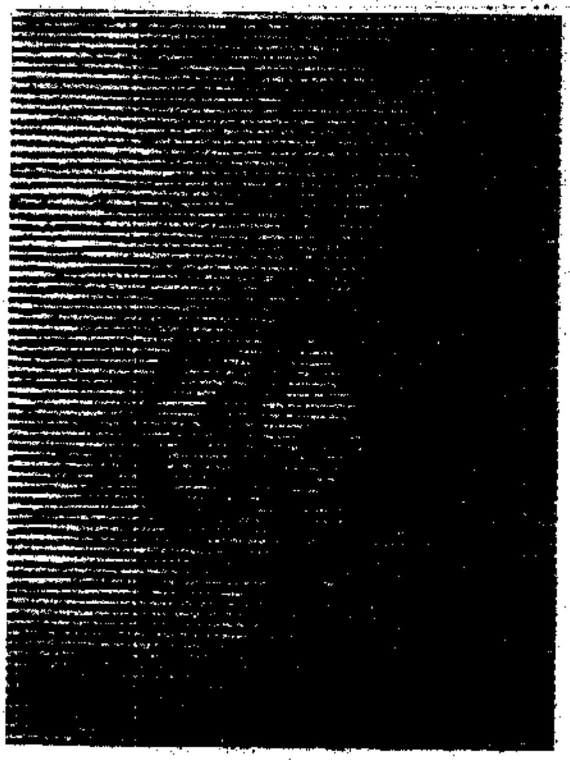

Fig 3. Sample record of ultra-microearthquakes recorded at the site of crack upstream of the Mula Dam, Maharashtra (Time Scale 5mm/sec.).

As mentioned earlier, this virgin reservoir at Mula exhibited seismic activities at ultra-microearthquake level during monsoon seasons. Fig. 1 shows the Mula dam, the course of Mula river, seismographic station and the crack. Fig. 2 shows the special micro-seismograph developed for recording the ultramicroearthquakes down to magnitude −2.0. The seismograph has a natural frequency of 10 cps while the pen-motor has a frequency of 35 cps. Thus the system has a reasonably flat frequency response between 10 to 40 c/s with magnification of a million to two. The system thus developed indegeneously is eminently suitable for recording ultramicroearthquakes down to magnitude −2.0 when the associated ground frequency could be as high as 40 cps or so. Figs. 3 and 4 show the sample records of micro-earthquakes detected in the area. Duration of these ultra-microearthquakes was between 0.1 seconds to 5 seconds while their frequency of occurrence varied considerably during the year. In view of large absorption of these high frequency earthwaves, ultra-microearthquakes are only recorded at very close range with Sg-Pg interval generally very small upto a few seconds only, while it could be as small as 0.1 second. For majority of ultra-microearthquakes recorded at Mula, Sg-Pg interval was less than 0.1 second indicating that most of the ultra-microearthquakes were in the neighbourhood of the crack where the seismograph station is also located. Thus the origin of the ultramicroearthquakes could be attributed to the activities at the crack zone following impounding of the reservoir and these activities are directly related with the water level variations, Fig. 5.

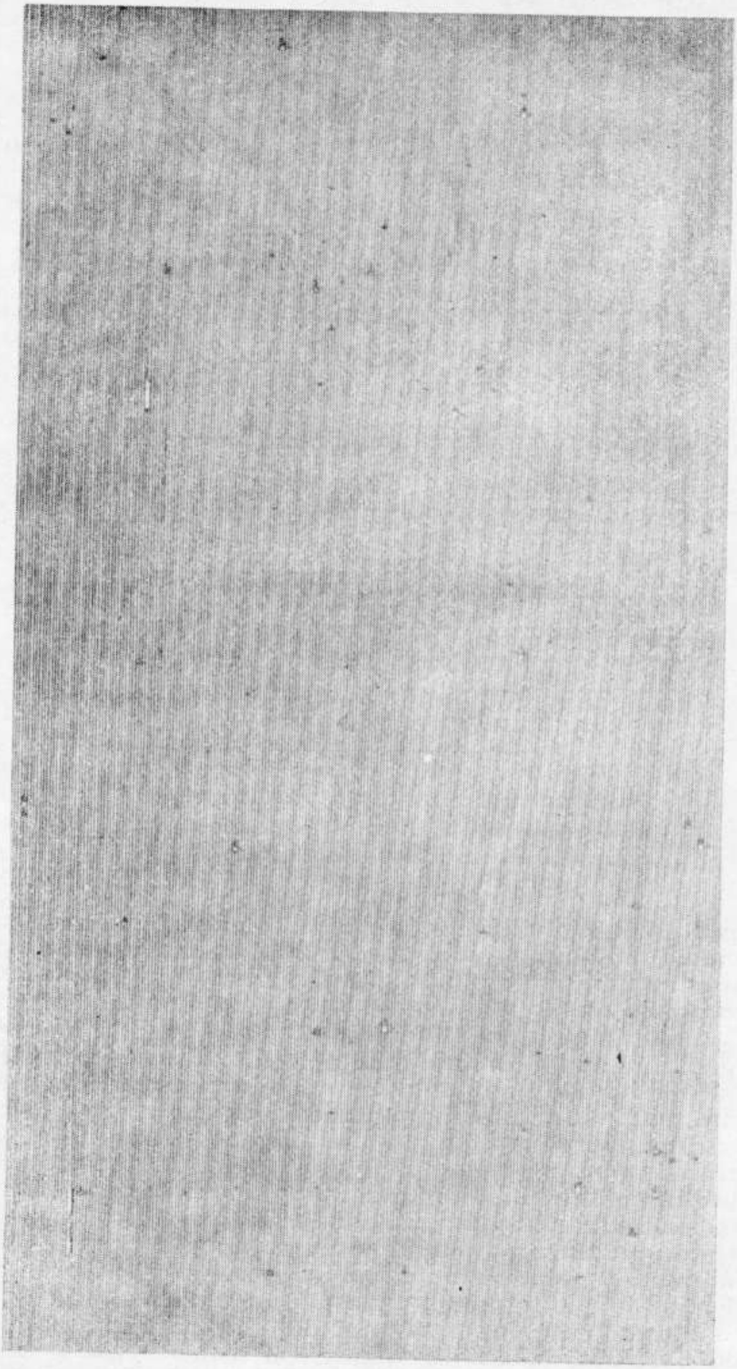

Fig. 4. Sample record of ultra-microearthquakes recorded at the site of crack upstream of the Mula Dam, Maharashtra (Time Scale 1 mm/sec.)

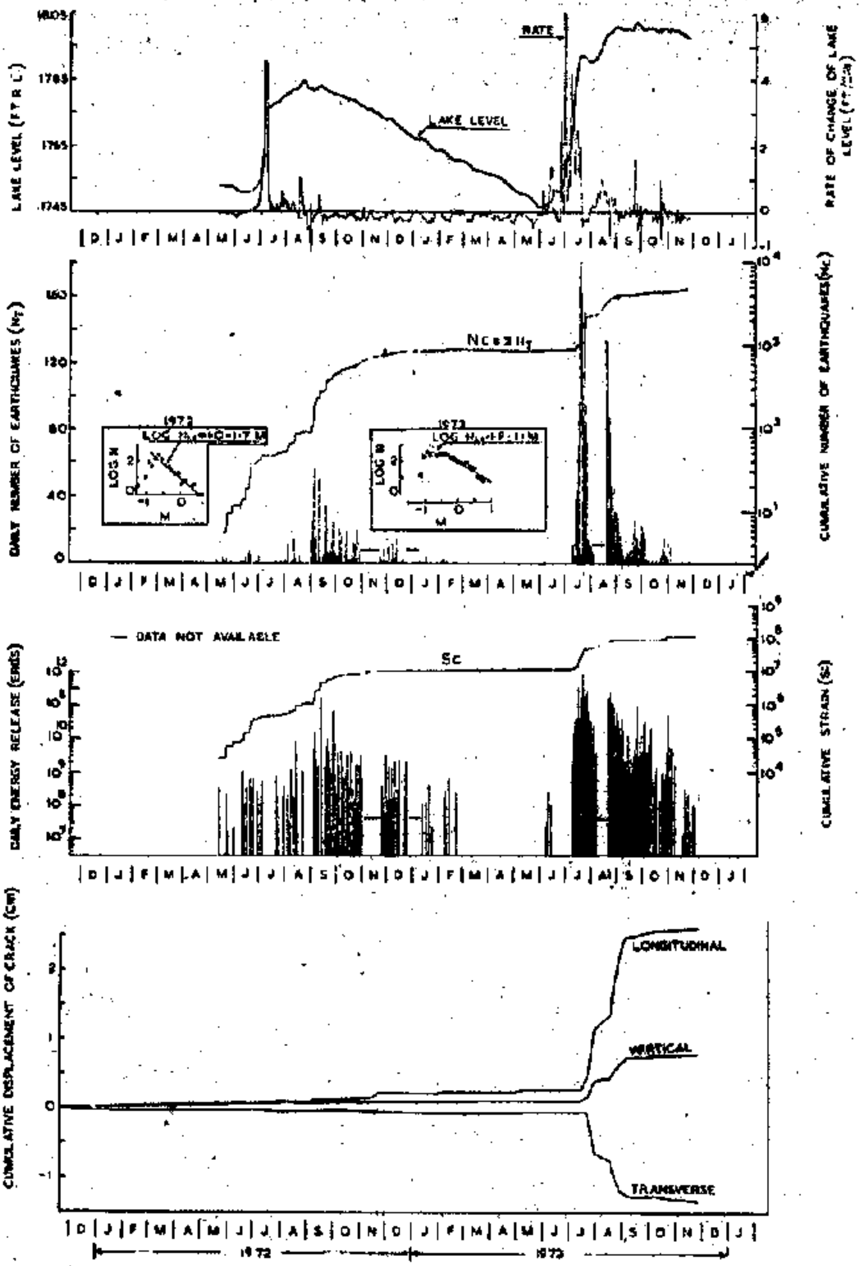

Fig. 5. Showing daily lake levels, rate of lake level variations, frequency of ultra-microearthquakes and their energy variations with cumulative displacements at the crack in three orthogonal directions for the years 1972 and 1973 at the Mula Dam, Maharashtra (Insets—recurrence curves.)

Magnitudes of these microearthquakes could be found out directly from the method of Brune and Allen (1967) though total duration method as advocated by Tsumura (1968) could be another efficient method for this purpose. Recently Tsushima (1968) had advanced somewhat better method of magnitude determination but in the present investigation, the equation advocated by Brune and Allen (1967) was utilised for determination of magnitudes of these ultra-microearthquakes.

Fig. 5 shows the lake level, rate of lake level variations, frequency of ultra-microearthquake and their energy variations with cumulative displacements at the crack in three orthogonal directions for the years 1972 and 1973. The data conspicuously depict that in dry months, the ultra-microearthquakes are absent while during monsoon months they are most prevalent. Moreover, the frequency of occurrence of ultra-microearthquakes shows an upward trend with larger rate of water level variations, which are accompanied by simultaneous displacements at the crack. Recurrence curves for each year, log N= a−b M, were obtained which yielded the values of a=1.0 and b=1.7 for 1972 and a=1.9 and b=1.1 for 1973. Lowering of b values from 1.7 for 1972 to 1.1 for 1973 also corroborates enhancement of the seismic activity from 1972 to 1973. Since all the conditions essentially remained same for both the years 1972 and 1973 excepting the rise of water level in the reservoir in 1973 over 1972 by an amount of about 5 metres, a major conclusion derived from these analyses is that the increase in reservoir level with consequent increase in pore pressure has possibly further activated the crack thus enhancing the ultra-microearthquake activity in 1973. Thus water level variations could be causative factor in initiating displacements and consequently fracturing at the crack thereby triggering the ultra-microearthquakes in the close vicinity.

DISCUSSIONS

Though presently there are about two dozen instances (Proc. COSERI, 1973) on reservoir induced seismicity observed in various parts of the world but as yet there is no case history so far reported where ultra-microearthquakes below magnitude zero were observed in so large a number following reservoir impounding in the vicinity of a fracture or crack zone. The reservoir induced seismicity at Mula is thus an unique instance where there are direct evidences of activation of a fracture zone due to influences of pore pressure. Complete absence of seismic activity during non-monsoon months so also large burst in ultra-microearthquake activity following high rate of water level variations with simultaneous movements at the crack could indicate direct influences of pore-pressure in initiating ultra-microearthquake activities associated with micro-fracturing. The micro-earthquake activities induced at the Rangely oil field, Healy et al. (1972) and at Rocky Mountain Arsenal disposal well, Denver Healy et al. (1970) U.S.A. following fluid injection cycle bear close parallelism with the activities observed at Mula following impounding. In all these cases, earthquakes of various magnitudes are initiated during artificial fluid pressurisation following reservoir impounding and fluid injections.

At present two types of theories are in vogue regarding mode of origin of reservoir induced seismicity (1) Triggering off seismic energy due to change in effective stress (6) on impounding (2) Accelerated rate of fracturing of rock due to high fluid pressures in porous and fractured brittle rock. There could be a third mode of origin viz. fracturing of rock due to high stress concentration around uneven and sharp underground geometry subsequent to water impounding. In order to test the relative efficacy of the above hypotheses in explaining the various case histories of reservoir induced seismicity observed in India and different parts of the world including specially the present case of ultra-microearthquake activity at Mula, seismic activities and associated geotectonic features of some of these case histories particularly those observed in India are discussed below.

A major part of aftershocks (about 60 p.c.) following Koyna earthquake of Dec. 10, 1967 have return periods of about a year indicating that the same are largely influenced by annual water load fluctuations in the reservoir (Guha et al., 1974). Recently, Hagiwara and Ohtake (1972) and Comminakis et al. (1968) have found correlation of earthquakes with lake levels for reservoirs at Kurobe dam (Japan) and at Kremasta (Greece) respectively. Such correlation of seismic activity with lake level variations indicates broadly influence of triggering in shallow underground favourable geological structures in initiating fractures, slips etc. in the form of earthquakes.

During the last two decades, number of water reservoirs situated in different geological and geotectonic regions were commissioned in India. Studies broadly indicate that the reservoirs situated in marginal areas of the Indian shield namely Kinnersani (Andhra Pradesh), Parambikulam (Kerala), Mangalam (Kerala), Sholayar (Kerala), Sharavathi (Karnataka), Koyna (Maharashtra), Ukai (Gujarat) etc. exhibit seismic activities following their impounding (Guha et al., 1974) while those situated well inside the shield and in Sub-Himalayan region namely Mettur (Tamil Nadu), Nagarjunasagar (Andhra Pradesh), Maithon (Bihar), Panchet (Bihar), Rihand (Uttar Pradesh), Bhakra (Himachal Pradesh) etc. are inactive. Largest earthquake occurred near the Kinnersani reservoir following impounding had a magnitude of 5.7 (Guha et al., 1970). The area surrounding Sholayar, Parambikulam and Mangalam reservoirs in Kerala rented with faults and fractures and exhibiting moderately induced seismic activities deserves special attention (Guha et al., 1974). This broad indication of seismic activity of reservoirs spread over diverse geological and geotectonic regions confirms that apart from local rock conditions, the prevailing geotectonic pattern and change of effective stress (σ) on impounding could also be dominant contributory factors in triggering seismic activity following impounding.

High fluid pressure in deep fractured rock below reservoir has been suggested by others also as a potential cause of progressive fracturing of the rock (Hubert and Rubey, 1959) thus possibly causing seismic events. Stresses at sharp geometry of faults, fractures, fissures, anticlinal features etc. below reservoirs at shallow depths of the order of reservoir widths could accentuate to a critical level of fracturing subsequent to their impounding. Gough (1969) had applied successfully Boussinesq's equation for computing stress field in rock below reservoir and had shown that significant fraction of applied stress is present upto depths of the order of reservoir width or so. The overall stress field in rock due to superimposed stress would then be accentuated significantly due to presence of sharp underground geometry at shallow depths. The local high stress field within rock would thus fluctuate considerably with seasonal variations in superimposed water load and similarly will be the resulting fracturing or seismic energy. This is what has actually been observed for earthquake frequency and energy specially for the post-earthquake (Dec. 10, 1967) period (1968-1971) in Koyna (Guha et al., 1974). This would not be the case if deep column of water in fractures would be the principal factor in enhancing seismic activity near reservoir. Most of the Koyna earthquake foci are situated within the 50% shear stress contour of Gough (1969) indicating that mechanism suggested herein may be a reasonable one (Guha et al., 1974). Fluid pressure changes and associated seismic activity at Rocky Mountain Arsenal Disposal well, Denver (Healy et al., 1970) also support the above mechanism broadly.

CONCLUSIONS

As stated earlier, Mula river basin is situated in a highly seismic belt where there is no historical record of earthquakes of any significance. The area could thus be broadly considered to be a seismic as such the fracture zones in the basin are stress-free or the tectonic stress in the area could be very low. Very low tectonic stress field in the area is also corporated from large b-values vide Fig. 5. According to following equation of Brune (1970)

$$\underset{\text{(effective stress)}}{\sigma} = \underset{\text{(tectonic stress)}}{\sigma_0} - \underset{\text{(frictional stress)},}{\sigma_f}$$

areas having low tectonic stress (σ_0) could be easily susceptible to seismic activity following impounding or pressurisation. From the geographic distributions of reservoirs exhibiting seismic activities in India (Guha et al., 1974) where low tectonic stress (σ_0) prevails, it is also confirmed that similar changes in effective stress (σ) in the area brought about by water impounding could be probable mechanism for triggering such seismic activity.

From the case histories of about a dozen reservoirs including that of Mula in India in respect of their seismic activities subsequent to impounding, change in effective stress (σ) and stress concentration around sharp geometry in shallow underground geological structures such as faults, fractures, shear zone etc. might be causative factors in initiating seismic activity, yet the exact mechanism specially for initiating the intense reservoir seismic activity could not be isolated. In this connection, it is very pertinent to mention that available measurements in tunnels, underground power houses, adits, etc. along the marginal areas of the peninsular India indicate rather low tectonic stress, compressional upto 50 bars or so. Thus, the sensitiveness of reservoirs situated in areas having low tectonic stress field could indicate dominant influence of prevailing low tectonic stress (σ_0) in triggering off seismic activities.

ACKNOWLEDGEMENTS

The authors record with great appreciation, the encouragement received from the Director and Joint Director, Central Water and Power Research Station, Poona, during the above studies and in preparation of this paper.

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APPENDIX

NOTATIONS

N_M = Number of Earthquakes of Magnitude M

M = Magnitude of Earthquake

a, b = Constants

σ = Effective Stress

σ_0 = Tectonic Stress

σ_f = Frictional Stress