Report on ICDP Post–Operations International Workshop on "Scientific Deep Drilling in Koyna, India"

– Nagaraju Podugu[1], Amrita Yadav[1], Kothamasu Mallika[2], Deepjyoti Goswami[1] and M. Uma Anuradha[2]
([1]Borehole Geophysics Research Laboratory (BGRL), Ministry of Earth Sciences, Government of India. [2]CSIR-National Geophysical Research Institute, Hyderabad - 500 007)

Introduction

The Koyna region, located in the ~65 Ma old Deccan Traps of western India is a classical site of artificial water Reservoir Triggered Seismicity (RTS). Triggered earthquakes started occurring soon after the impoundment of the Shivaji Sagar lake formed by the Koyna Dam in 1962 and have continued till now. The seismicity includes the largest triggered earthquake of M 6.3 on December 10, 1967, 22 M≥5 earthquakes, more than 200 M~4 earthquakes and several hundred smaller earthquakes. A strong association of the earthquake activity is observed with the annual loading and unloading cycles of the Koyna and nearby Warna reservoirs (impounded in 1985). The entire seismic activity is restricted to ~20 km x 30 km area and there is no other earthquake source within ~50 km of the Koyna Dam. The depth of these earthquakes is limited to about 10 km with ~80% occurring between 2 and 9 km depths. Earthquakes of M~4 are found to be preceded by well-defined nucleation and real time identification of nucleation has led to short term forecasts. During the past few decades, a considerable shift in the seismic activity has been observed in the region to the south. However, it may be noted that even before the impoundment of the Warna reservoir in 1985, triggered earthquakes had occurred in the vicinity of Warna river as a consequence of loading of the Koyna Dam. Moment tensor inversion studies show that focal mechanisms are dominated by strike-slip faulting in the vicinity of Koyna Dam and immediately south of it and normal faulting in the Warna region.

A major programme on scientific deep drilling in the Koyna region was conceived by the CSIR-National Geophysical Research Institute (NGRI) and Ministry of Earth Sciences (MoES), Government of India in consultations with International Continental Scientific Drilling Program (ICDP), to investigate the causative mechanisms of the RTS. The first international workshop, held at Hyderabad and Koyna during March 21-25, 2011 provided the necessary impetus and inputs for development of the project on scientific drilling to study reservoir triggered earthquakes occurring in the Koyna region for the past five decades. A preparatory phase of the project was recommended. Under the programme, exploratory drilling and geophysical investigations were carried out during 2012-14. The second workshop held at Koyna during May 16-18, 2014 reviewed the work carried out during 2011-2014 based on the recommendations of the 2011 workshop and suggested the future course of action, including drilling of a 3km deep pilot hole in the Koyna seismic cluster and detailed planning for a full deep drilling proposal. In late 2014, Ministry of Earth Sciences initiated the setting up of Borehole Geophysics Research Laboratory (BGRL) at Karad. BGRL was mandated with the task of building necessary R&D infrastructure and expertise to carry out scientific drilling investigations, including planning and execution of the Koyna deep drilling programme. The drilling of a 3000 m – deep pilot borehole followed by downhole measurements have been completed recently.

After the successful completion of the pilot borehole drilling phase, an ICDP International Workshop was held during October 14-16, 2017 to discuss the results obtained from the pilot borehole and chalk out the future course of activities including setting up of a deep borehole observatory and down hole as well as laboratory measurements and modelling.

ICDP Post-Operations Workshop

The ICDP Post-Operations International Workshop on "Scientific Deep Drilling in Koyna" was held in Pune, Maharashtra during Oct 14-16, 2017. The Workshop was organized by the Ministry of Earth Sciences (MoES), Borehole Geophysics Research Laboratory (BGRL), Karad. The major themes of the workshop included:

1) Reservoir Triggered Seismicity in Koyna vis-à-vis Global Scenario: Key Lessons,
2) Review of Pilot Borehole Operations and Associated Studies,

Group photograph of the workshop participants

3) Design of Deep Borehole Observatory,
4) Key Knowledge Gaps: Areas of Future Work, and
5) Field Visit to BGRL-MoES, Karad (Core Repository).

The Workshop was attended by 67 participants including 48 delegates from earth science departments, institutes and universities within the country and 19 delegates from France, Germany, Italy, Japan, Czech Republic, South Korea, Spain, Switzerland, USA and Canada. Participants included geophysicists, seismologists, geologists and drilling and downhole instrumentation experts having experience in working on deep drilling sites globally. The workshop was supported by MoES and ICDP.

Structure of the Workshop

The first day of the workshop was dedicated to discuss Reservoir Triggered Seismicity in Koyna vis-à-vis the global scenario, and to review the drilling of the Koyna pilot borehole along with associated measurements. A day-long field visit to BGRL Core Repository and other facilities at Karad was planned on the second day. The third day was dedicated to identify key knowledge gaps and plan for the deep borehole observatory through break-out group sessions. The participants contributed to three break-out groups based on their expertise: (1) Downhole Instrumentation, (2) Downhole Geophysics, Stress and Thermal Regime, and (3) Fault Zone Studies.

Day-1, October 14, 2017

Session-1

Rahul Mohan, NCAOR welcomed the participants to the Workshop.

The inaugural session was chaired by Shailesh Nayak and Axel Liebscher.

Harsh Gupta set the ball rolling by providing a brief background of the project "Scientific Deep Drilling in Koyna", touched upon the scientific rationale of the project and traced its evolution to the present day.

Ulrich Harms (ICDP) made a crisp presentation on the association of ICDP with the Koyna Project and touched upon several fault zone drilling projects globally. He mentioned the uniqueness of the Koyna project among the active fault zone drilling projects supported by ICDP worldwide.

Shailesh Nayak discussed the perspectives for scientific drilling in a variety of geologic and tectonic settings in the country and highlighted the scientific drilling undertaken by India at Koyna and in the Indian Ocean. He added that Borehole Geophysics Research Laboratory is a unique institution and should be developed to cover all areas of Earth sciences.

Axel Liebscher, Executive Director of ICDP explained the rationale behind ICDP's total support to the Koyna Project. He termed the Koyna Project as a lighthouse in the ICDP portfolio and explained how the project has already set a new benchmark in terms of project execution.

B.K. Bansal, MoES, highlighted the significant achievements of Koyna project so far and touched upon the need to set up a deep borehole observatory. On behalf of the Ministry, he thanked ICDP for the successful completion of the pilot borehole drilling project and briefly presented the vision of MoES regarding future activities envisaged under the project. He also thanked NGRI for putting tremendous efforts for this project. He mentioned that ICDP-NGRI-MoES are three partners involved in this mega project. He further added that scientific activities undertaken by BGRL will be invaluable in going for 5-7 km deep drilling at Koyna, India, and looked forward to continuing the successful association with the ICDP in the coming years. Taking advantage of this workshop, he invited National and International agencies for collaboration with BGRL for future actions.

This was followed by detailed technical presentations on Koyna studies.

Harsh Gupta made a detailed presentation covering the reservoir triggered seismicity in Koyna during the past five decades and recent studies leading to drilling of the pilot borehole. Starting with the overview of reservoir triggered seismicity worldwide, he explained why Koyna is an ideal site to study the changes in physical and chemical properties of rocks at hypocentral depths before, during and after occurrence of earthquakes. He also discussed about the borehole seismic network deployed in Koyna to determine hypocenter locations of earthquakes with improved accuracy. He described how the seismicity recorded by the dense network gave the location for the first pilot borehole of 3 km depth. He concluded by referring to the address by Hon'ble President of India to both houses of Parliament during the Budget Session on 21 Feb 2013, which included a mention to the Koyna Scientifc Deep Drilling Project: **"The Government is setting up a dedicated Seismological Research Laboratory and has launched a first-of-its-kind research programme in the earthquake-prone Koyna-Warna region of Maharashtra to study precursor changes".**

V.M. Tiwari made a detailed presentation showing new results that throw light on the subsurface structure below Koyna-Warna region. He also discussed about the lithospheric density structure beneath Koyna region and 3D model of stress field in the region. He reported that the principal component stress is in NS to NNE direction. Seismicity has good correlation with high concentration of stress.

Pradeep K. Singh spoke on the deep borehole stability vis-a-vis strength and elastic properties of rocks around Koyna reservoir. He emphasized the significance of mechanical and chemical investigations to solve the borehole stability issues. Simulation of borehole by finite element method gives elastic properties and stress of rocks. Also we can determine where failure may occur.

Sukanta Roy presented an overview of the scientific drilling of a 3 km deep pilot borehole completed recently in the Koyna region and summarized the key accomplishments from drilling, coring and measurements. Starting with main objective of drilling of pilot borehole, he discussed how it will help to improve our knowledge to design deep borehole observatory. He showed preliminary results from on-site geological and gas sampling studies, geological studies on cores and cuttings, DIS, hydrological studies, downhole geophysical logs, and in-situ stress by hydrofrac measurements in the crystalline basement below Koyna. He explained that the pilot borehole is a fore-runner to the deep borehole planned in the Koyna region.

Seission-2: Pilot Borehole Operations and Associated Studies

The session was chaired by Marco Bohnhoff and N.K. Verma. Preliminary results obtained from the on-site experiments were covered in 7 presentations made by scientists of BGRL-MoES, IIT Kharagpur and ICDP, Germany. Presentations include results of geological, geophysical, geotechnical and geochemical studies. Additionally, Ujjal Borah (NGRI) presented the 3D conductivity structure below the Koyna-Warna region from magnetotelluric studies.

The session started with the presentation by R.B. Chakraborty on the various challenges faced during drilling of the borehole through Deccan basalts and crystalline basement rocks. He emphasized mainly on the drilling technology used to drill the hole, borehole stability and coring activities.

Surajit Misra presented detailed observations on basement geology from cuttings and cores of the exploratory boreholes and the pilot borehole, highlighting the deformation features observed in the granitic basement. He also indicated the areas for future work.

Thomas Wiersberg explained the set-up for online gas sampling and measurements made during drilling. OLGA lab was set up at the drilling site. Measurements were carried out jointly by ICDP and BGRL

scientists. He also presented key results obtained from study.

Full suite of downhole geophysical logs was acquired in the pilot borehole to study the physical and mechanical properties of Deccan basalt and the underlying basement rocks. Deepjyoti Goswami presented the rock properties obtained from the downhole logs and also discussed possible signatures of fault/deformed zones.

The state of stress in the Koyna region, obtained from wireline hydraulic fracturing tests, was presented by Vyasulu V. Akkiraju. He explained the challenges of making hydrofrac measurements in the crystalline basement at depth, the measurement techniques and data analysis.

Preliminary hydrological information obtained from drilling records and downhole geophysical logs were discussed by Nagaraju Podugu. Analysis of pulse test data carried out in the basement granitoids confirmed the low permeability of the basement granitoids.

Pinaki Sar brought out the science behind geomicrobiological studies carried out on the Koyna borehole cores. He also presented the first results on the microbial inventory of deep continental crust and threw light on possible implications for evolution of early life.

Ujjal Borah presented the results from magnetotelluric studies to delineate the resistivity structure in the Koyna-Warna region. The study found distinct electrical signatures in the basement along Koyna and Warna profiles which can be related to the presence of conductive Koyna fault zone in the region.

Seission-3: Global Trends

The session was chaired by Domenico Giardini and B.K. Bansal. There were a total of 7 presentations in this session.

A unique study on in-situ pore pressure variations in Koyna-Warna region carried out in mid-1990's was presented by H.J. Kuempel. The title of the talk was "In-situ pore pressure variations in Koyna-Warna region: A promising key to understand triggered earthquakes". He mentioned that out of 22 wells, 14 acted as pressure sensitive wells which showed co-seismic, aseismic and teleseismic pore pressure changes. In his opinion, determination of earthquake locations and monitoring of pore pressure changes are two essential parameters for better understanding of RTS at Koyna.

Marco Bohnhoff gave a talk on "Borehole seismic instrumentation: Benefits for detecting and locating microseismicity". He said that borehole seismology is used to achieve more accurate hypo-central locations. He opined that the experience gained from High Resolution Seismic Network (HRSN) in Parkfield needs to be taken into account for the present Koyna work. He talked about ICDP-GONAF project and bridging the gap between lab and field data. He also opined that acquisition of high-resolution downhole seismic waveforms as well as improvement of hypocentre locations can be possible by installing a downhole seismic sensor array.

William Ellsworth made a presentation on "Scientific exploration of induced seismicity and stress". He spoke on several aspects including passive fault zone drilling experiments, Long Valley deep borehole observatory, SAFOD, comparison between surface and borehole seismometers data, increasing seismicity in the central US due to consequences of new petroleum production methods, pore pressure variations with time and their effect on occurrences of earthquakes, experimental verification of the effective stress hypothesis at Rangely, Colorado, etc. He opined that stress measurements in focal zones, measurements of hydrological parameters in the basement and at the base of the Deccan Traps, pore pressure monitoring and study of radiated seismic waves are essential in understanding RTS at Koyna.

Ze'ev Reches delivered a talk on "Drilling target: Oklahoma induced seismicity". As is the case at Koyna, earthquakes in Oklahoma have occurred in the basement. In this connection, a project titled "Drilling investigation of seismogenic crust in Oklahoma (DISCO)" was approved by ICDP to drill into the seismogenic, igneous basement of Oklahoma near and across a causative fault of a M5+ earthquake. This will provide a better understanding the processes and conditions leading to the observed fluid induced seismicity. He spoke at length on a number of issues related to delineation of fault zones in the subsurface by scientific drilling, and threw light on potential studies to be taken up in Koyna region.

A presentation on "Fault stimulation and circulation experiments in deep tunnels under the Alps" was delivered by Domenico Giardini. He explained that CO_2 capturing and deep geothermal energy production leads to induced seismicity in Switzerland. He also mentioned that multi-scale experiments in laboratory, in tunnels and in deep boreholes followed by modelling approach would provide significant inputs to understand induced seismicity.

Hiroshi Ogasawara made a presentation on "Drilling seismogenic zones in deep South African gold mines (DSEIS), South Africa". DSEIS is a ICDP-funded project. Several times a year, small (M2) mining-induced earthquakes occur only a few tens of meters from active workings in South African gold mines at depths of up to 3.4 km. An earthquake of M 5.5 occurred in basement rock in a mining region near Orkney, South Africa on 5 August 2014, with the upper edge of the activated fault being several hundred meters below the nearest mine workings (3.0 km depth). The source regions of these events are accessible with short boreholes from the deep mines, and provide a very cost-effective method to directly study the earthquake sources. A ~800m deep borehole was drilled from the bottom of the ~3km gold mine to intersect seismogenic zone and unfortunately the hole was deviated from the target source zone. He mentioned that they are planning to drill again to intersect seismogenic zone.

In a brief presentation "Recent developments in fibre-optical sensing", Ernst Huenges highlighted the advancements in fibre-optic technology for borehole studies. He pointed out that Distributed Acoustic Sensing (DAS) delivers high quality data and he also talked on DAS monitoring at Reykjanes Iceland.

Day-2

A field visit to BGRL office and Core repository (under development) in Karad was arranged for the participants. A brief introduction to BGRL was given by Rahul Mohan. He spelt out the perspectives of the new research laboratory and the efforts put in by a young team of persons over a relatively short period of time to set up study facilities.

Scientific posters on the recent work were displayed at BGRL office and there was lively interaction between BGRL scientists, national and international experts. Participants also showed interest in visiting the core scanning laboratory, petrology laboratory and microscope studies established at BGRL.

In the post-lunch session, the participants were taken on a visit to Core Repository at BGRL campus in Hazarmachi near Karad, where the borehole cores from pilot borehole and exploratory boreholes were displayed. Borehole lithologs were also displayed. All the participants looked at the cores enthusiastically and appreciated the efforts put in by the Ministry of Earth Sciences. Several valuable suggestions for further work emerged from the interactions during the core display.

Day-3

Session-4: Future Plans / Inputs

The session was chaired by Ulrich Harms and Virendra M. Tiwari. The purpose of the session was to deliberate on the plans for deep borehole observatory proposed to be set up in the Koyna region.

Sukanta Roy laid out the plan for deep borehole observatory in the light of key science questions to be addressed by the project. He drew upon the plans outlined during the second International Workshop in 2014 at Koyna and expanded those ideas on the basis of

Display of cores from Koyna Scientific Drilling Project at BGRL-MoES Core Repository, Karad

experience acquired during drilling, coring and downhole measurements in the 3km-deep pilot borehole. The major components of the plan including (a) drilling target, (b) well design, (c) drilling technology, (d) sampling strategy/coring/spot coring, (e) downhole measurements, (f) casing plan/casing design, and (g) downhole instrumentation were discussed. Various options for each planning item were touched upon during the presentation and the advantages and limitations of each were highlighted.

The plan was put up for an open discussion. Experts provided several valuable inputs for future plans, both for further investigations in the pilot borehole as well as planning the deep borehole observatory keeping an eye on the major science questions to be answered.

This was followed by break-out group discussions on key issues regarding future areas of scientific investigations in Koyna region.

B.K. Bansal introduced the break-out group sessions and requested participants to deliberate on key scientific issues of the project and come up with specific action plans. The following were the break-out groups:

1) Downhole Instrumentation (Lead: Marco Bohnhoff and David Chapman)
2) Downhole Geophysics, Stress and Thermal Regime (Lead: Francois Cornet, Amalendu Sinha and Deepjyoti Goswami)
3) Fault Zone Studies (Lead: Ze'ev Reches and Prabhas Pande)

Lead coordinators for each break-out group were requested to consider the following during the breakout discussions: (i) Science objectives, (ii) Operational goals, and (iii) Tools, Constraints, Timing, Cost estimates, Developments.

Closing Session

The session was chaired by Harsh Gupta and William Ellsworth. The lead coordinators of the three break-out group sessions presented an account of the discussions in individual groups and highlighted the key recommendations for further work.

Break-out Group 1 (Downhole Instrumentation):

In this group, the following key science questions were put forth for detailed discussions.

- What is the fluid pressure and permeability within and adjacent to the fault zone(s)?
- What is the 3D/4D nature of the fault zone?

The major recommendations to answer the above questions through downhole instrumentation included:

a) Hydrological monitoring (pore pressure, fluid conductivity and temperature) in available exploratory boreholes.
b) Identification of target zones using available geophysical logs for perforation and place pore pressure sensors at perforated deepest parts in the pilot hole KFD-1 to study the state and temporal variations in pore fluid pressure.
c) VSP using vibroseis as source and 17-slot geophone chain at varying depth in pilot hole and reflection seismic surveys in the region to obtain velocity model and to image Donachiwada fault.
d) Deployment of a vertical string of borehole seismometers below 1500 m of pilot hole to obtain precise hypocenter locations.
e) Acquisition of Cement Bond Log (CBL) in KFD-1 is recommended before installation of borehole seismometer and VSP geophone chain. Deployment of fiber optic cable within the casing (Acoustic Distributed Sensing) could be an alternative for downhole instrumentation in KFD-1.
f) Permanent installation of seismometers behind casing in the main hole would be a big opportunity, which would allow campaign measurements of pore pressure, fluid sampling and installation of different seismic sensors in the main hole.

Break-out Group 2 (Downhole Geophysics, Stress and Thermal Regime):

The major recommendations are as follows.

a) Borehole geophysics and geochemistry studies in the main hole including real time gas monitoring, borehole image logs (UBI and FMI), dipole sonic (anisotropy analysis), natural gamma ray (for depth correlation), spectral gamma ray, density, neutron log and formation resistivity (for identification of zone of anomalous physical properties), temperature, mud resistivity, caliper, borehole orientation, and wireline fluid sampling. LWD is an option.
b) Hydro-frac tests and image logging in the main hole to constrain in-situ stress magnitude and orientation in the Koyna region. Deviated holes are better than vertical holes for stress measurements.
c) In-situ experimentations for large scale characterisation of hydro-mechanical properties.

Break-out Group 3 (Fault Zone Studies):

To know the character of the main fault zone (young/mature) and to locate appropriate sites for deep drilling, the following recommendations were made:

Surface geology and geophysics

a) Compilation of surface mapping at all scales, mainly 1:50,000.
b) Detailed mapping with searching suitable sites for paleoseismic trenching to identify past surfaces ruptures.
c) Shallow seismic profiles with high resolution on land/lake are needed
d) Utilize the existing LiDAR analysis to identify/verify fault features
e) "Regional" soil helium studies to identify fault zone(s).
f) Examine existing maps and data on basement structure and fabric in the exposures to the south of the study region.

Subsurface structural/tectonic analyses

a) Orient the cores with the image logs and gamma-ray log.
b) Comprehensive study of the brittle deformation in the existing cores to characterize the deformation fabric in the region.
c) Use logs to identify cutting depths for further study.
d) Use logs (primarily image logs) to create fracture intensity profile.
e) Possibility of sidewall coring as potential source for additional material.
f) Online gas monitoring while drilling should continue to be utilized.
g) A plan for collecting cuttings while coring needs to be instituted for future drilling.

The recommendations from three break-out groups were put up for open discussion. The recommendations were found to be valuable for future scientific investigations in Koyna region. Accordingly, it was decided to prepare necessary action plans for implementing the recommendations.

Major Recommendations

The following action points for implementation on priority were unanimously agreed upon:

1) **Development of Koyna RTS Information System**: It is necessary to develop a common data and information portal to provide a single point access to past field and bore-hole based geological, geophysical, geochemical and laboratory data as well current project generated geophysical data (seismic, gravity, magnetic, magenotelluric, etc.), core-descriptions, core measurements, logging data, publications and post-drilling data. It should be built around international standards and protocols for both metadata and data. To begin with metadata of all data should be developed, hosted and made accessible to all research workers of this project. ESSO-BGRL should take up this task.
2) **Detailed characterization of the Donachiwada fault** using seismic reflection studies in conjunction with VSP, geological and geochemical investigations and improved locations of hypo-centers.
3) **Deployment of a vertical string of borehole seismometers** below 1500 m in the pilot borehole KFD-1 to obtain precise hypocenter locations.
4) **Identify flow zones in pilot borehole KFD-1** using available geophysical logs and seriously consider perforation at target horizons for pore pressure monitoring and correlation with during pre-, co-, and post- seismic activities.
5) **Conduct hydrological monitoring** (pore pressure, fluid conductivity and temperature) in available exploratory boreholes, if possible.
6) **Subsurface structural/tectonic analysis** through detailed studies on cores and cuttings.
7) **Conduct experimental deformation tests** in the laboratory.
8) **Reference borehole outside Koyna seismogenic zone:** Drill one borehole in the depth range 1500-2000 m to serve as a reference borehole for geological studies and geophysical measurements outside the Koyna seismogenic zone. A suitable site could be inside BGRL campus, Hazarmachi, Karad, which is located ~60 km to the east of Koyna. Additionally, the borehole would be invaluable as a test hole for calibration and testing of downhole equipments, which is highly recommended for a laboratory specialising in borehole geophysics.
9) **Development of ESSO-BGRL**: There are many outstanding scientific questions, such as composition and structure of the Indian Lithosphere, Andaman Subduction Zone, etc., which will need scientific drilling. In view of this, the Borehole Geophysics Research Laboratory (BGRL), a unique institution in the country, needs to be fully developed in terms of scientific, administrative and financial resources. This lab should undertake experiments for providing exact, fundamental and globally significant knowledge of the composition, structure and processes in all areas of Earth Science. One of the important functions is to set up a state-of-art Core Repository and facilities to characterize the cores. The purpose of this laboratory is to build capacity (facilities and trained scientific manpower) to establish world-class facilities for advanced borehole geophysics studies to carry out scientific drilling studies for several other Earth Science problems.
10) **Detailed plan for the deep borehole observatory:** Planning for the deep borehole observatory, including obtaining necessary clearances, firming up design of deep borehole up to 7 km depth on the basis of studies detailed above, identification of drilling technologies and instrumentation, etc. should be initiated.

On behalf of Ministry of Earth Sciences, India, Sukanta Roy proposed a vote of thanks to ICDP for supporting the Workshop and to all the participants for their valuable contributions.