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Reservoir Induced Seismicity in the Koyna–Warna Region, India: Overview of the Recent Results and Hypotheses

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Abstract—The state of the art in the geological and geophysical study of the region of Koyna and Warna water reservoirs is reviewed. The probable geodynamical factors of induced seismicity are discussed. The detailed geophysical surveys, satellite geodetic data, and time history of the seismicity in the region reveal a complicated pattern of the structure and recent geodynamics of the region. The existing data suggest that the induced seismicity is here most likely to be caused by the regional (intraplate) stresses driving the displacements along the orthogonal network of the faults whose strength has dropped and continues decreasing due to the reservoir impoundment and operation processes. The evolution of the seismicity which started immediately after the rapid filling of the Koyna reservoir in the region of the dam, then rapidly expanded southwards and eventually became concentrated in the region of the subsequently constructed Warna reservoir shows that seismic events can be initiated by a number of factors whose contributions may vary with time. The key ones among them include reservoir loading and its seasonal variations; water saturation of the faults which guide the propagation of the front of fracture, increased permeability, and, probably, mineral transformations (hydrolysis) under the water level fluctuations in the reservoirs; and displacement of the front of the high pore pressure down to the main source zone of the earthquakes at a depth of 6–8 km. Based on the analysis presented in the paper, we outline the directions of the future research aimed at studying the nature and dynamics of induced seismicity in the region of large water reservoirs.

Keywords: reservoir triggered seismicity (RTS), triggering process, satellite technologies, Koyna, Warna, laboratory modeling

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INTRODUCTION

Seismicity during the filling and operation of large water reservoirs has been detected in more than one hundred regions in the world (Gupta, 1992; 2002). Building reservoirs affects the Earth's crust and changes the seismic regime in the seismically active regions. Cases are known when active seismicity and devastating earthquakes emerged in aseismic regions several years after reservoirs were filled (Malik, 2005). Reservoir operation is typically accompanied with seasonal water level variations which create cyclic loading. As of now, the influence of static loading (the weight of the water reservoir and its seasonal variations) on the processes of water diffusion through the network of faults has been studied on simple models describing the attenuation of the amplitude of the pore pressure oscillations as a function of the distance to the reservoir across the fault networks and the period of these oscillations (Roeloffs, 1988; Talwani, 1997b; Pandey and Chadha, 2003; etc.).

The Koyna–Warna region of intraplate seismicity is one of the most promising areas for fundamental studies in the physics of induced earthquakes. Here, earthquakes with the magnitude above 4 have regularly occurred within an area of 500 km^2 for more than 50 years after the impoundment of the Koyna reservoir in 1962 and after the Warna reservoir was filled in 1993. The earthquake of December 10, 1967 with magnitude 6.3 was the strongest known induced earthquake in the region of the artificial reservoirs (Gupta, 2002).

The structure and dynamics of this region have been thoroughly studied by a number of geological and geophysical methods, including monitoring the seismicity, ground surface displacements by GPS, and water level monitoring in 20 specially equipped wells. Fundamentally new information will certainly be obtained by the measurements in the deep borehole which is expected to penetrate the source zone of earthquakes at a depth of 6–8 km. There are plans to install instruments for measuring the temperature, heat flow, fluctuations in the gas and water flow, pore pressure, and many other parameters. The fact that the reservoir water level (the main triggering factor) in this region has been tracked for many years simultaneously with the thorough exploration of the responses of the medium to this impact makes the process of studying the Koyna–Warna region close to the laboratory physical experiments. For a complete analogy, it is also required to have the data on the dynamics of the regional displacement field and tectonic stresses, which will be discussed below.

The questions concerning safe operation of water reservoirs just as the other hazardous objects are also fairly important for the Russian Federation and the CIS. Indeed, in accordance with the Explanatory note to the set of the general seismic zoning maps for the Russian Federation as of 2016, more than 25% of its territory pertains to seismically hazardous regions, which are prone to earthquakes with intensity 7 and higher (*Obshchee* ..., 2016). The zone of shaking intensity 7 accommodates large hydroelectric and thermal power stations, nuclear plants, and many highly ecologically unsafe enterprises; frequently, subterranean waste water pumping into the Earth's interior is practiced in this zone. Hence, the studies of the risk factors of induced seismicity and the development of the physical basis and the techniques for monitoring the induced seismicity remain topical.

The aim of the present paper is to analyze the geological and geophysical data for the Koyna–Warna region, to discuss the achievements and challenges in studying the regularities and origin of the reservoir-triggered seismicity, and to substantiate the directions for future collaborative research conducted by the Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences (IPE RAS) and National Geophysical Research Institute (NGRI), Hyderabad, India. In particular, this analysis is important for preparing and jointly monitoring by the methods of seismology and satellite geodesy using the GPS and GLONASS global navigational satellite systems (GNSSs) and satellite radar interferometry.

1. GENERAL INFORMATION

The Koyna and Warna dams and the water reservoirs formed as a result of their construction are located in the Western Ghats Mountains, within the western margin of the Precambrian Indian shield (Fig. 1), in the region where seismic events had not been detected before the reservoirs were filled. The earthquakes (shown in Fig. 1 by different markers depending on the m_b magnitude) started to occur with the commencement of the impoundment of the Koyna reservoir in 1961; however, since the middle of 1963 the seismicity began to grow rapidly. For monitoring the seismicity, a network of four seismic stations were installed in 1963; since then these stations started recording the earthquakes at shallow depths beneath the reservoir in the dam's region. On December 10, 1967, the region was hit by a catastrophic earthquake with magnitude 6.3, which caused numerous fatalities and severe damage. This seismic event was preceded by five strong aftershocks one of which (September 13, 1967) had the magnitude of 5.5 (Gupta, 2002; Gupta et al., 2007).

The seismic network was gradually expanded and recently equipped with downhole geophones (Shashidhar et al., 2016). As of now, seismic activity in the Koyna reservoir region is decreasing; however, the region of the Warna reservoir still remains active. The analysis of the migration of seismic events with $M > 4$ (Talwani, 1997a) revealed their systematic drift southwards. In 1964–1967, the events mainly occurred in the area of the dam on the Koyna River. In 1967–1973, the events migrated towards the Warna River. Most of the events of 1974–1982 occurred between the Koyna and Warna rivers and south of the Warna River, although the Warna reservoir had not been constructed at that time. The seismicity significantly increased after the beginning of the filling of the Warna reservoir in 1985; and the events of 1983–1992 occurred in approximately the same area as the events in 1974–1982. The Warna reservoir was filled slower than the Koyna reservoir and probably that is why the peak of seismic activity fell in 1993–1994. We note that it is exactly 1993 when the water level in the Warna reservoir rose from June 11 to August 4 by 44.15 m and reached its maximum of 60 m on August 4 (Gupta, 2002), after which two earthquakes with magnitudes above 5 and a series of weaker events occurred on August 18.

2. GEOLOGICAL STRUCTURE AND TECTONICS OF THE KOYNA–WARNA REGION

The geological structure and tectonics of the Koyna–Warna region is still not known with sufficient detail since the territory is entirely covered by a thick layer of basalts—the Deccan traps. Some conclusions can be inferred by studying the structures on the periphery of the traps where the Archaean and Early Precambrian rocks outcrop. The last stage of the orogeny in the region of the recent Indian shield had been completed in the Precambrian, before the Vendian. This stage was marked with intense folding and emplacement of granite intrusions. It is believed that the subsequent folding and vertical displacements were low-amplitude, perhaps except for the Carboniferous when a system of faults and grabens was formed within the Precambrian shield (Gupta, 1992). The traps of the Deccan plateau were formed at the end of the Cretaceous–in the Eocene as a result of a series of subaerial eruptions through a system of numerous fractures in the Earth's crust. The first lava flows filled the topographical depressions above which the basaltic layers are nearly horizontal. The traps' thickness reaches 2 km in the Konkan coastal lowlands and

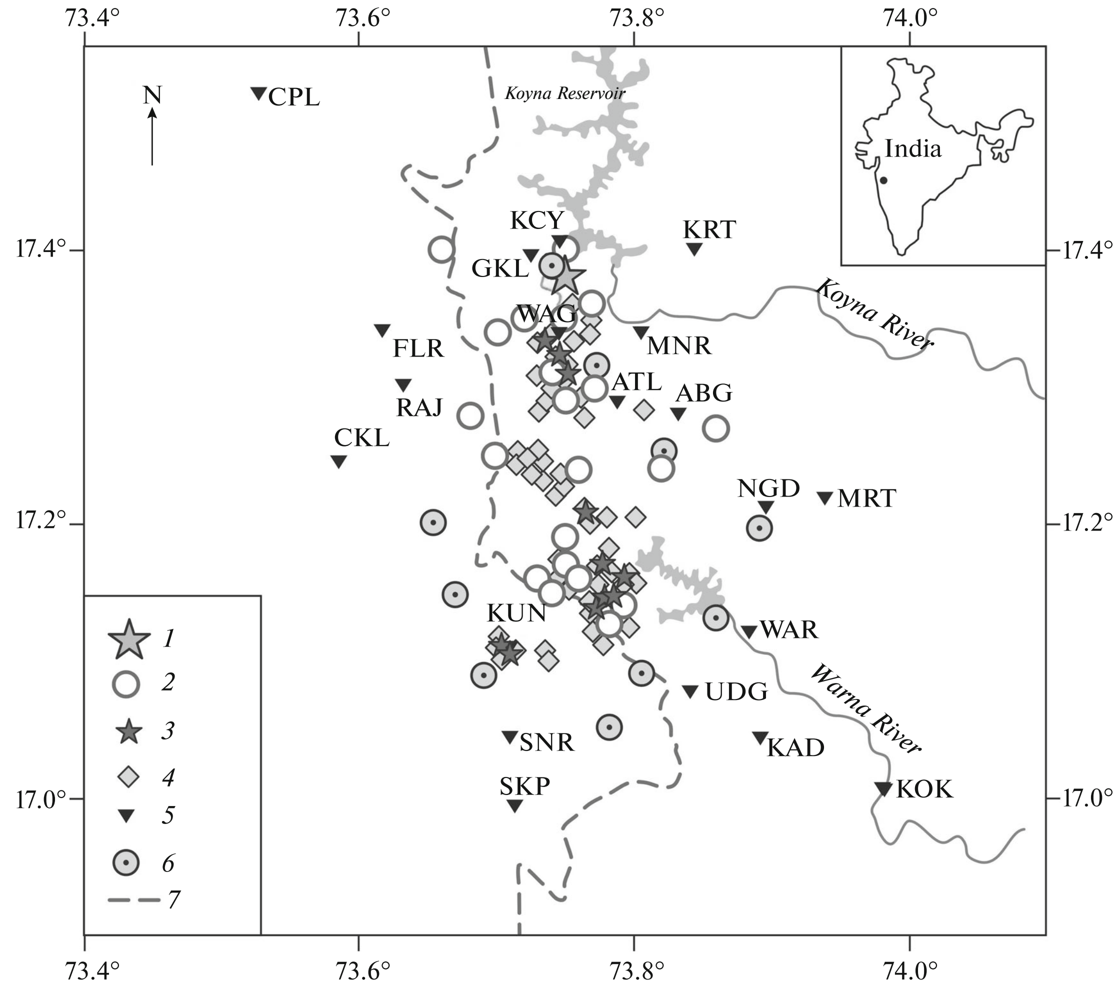

Fig. 1. Epicenters of earthquakes in Koyna–Warna region and locations of broadband seismic stations and deep boreholes. Inset in upper right shows positions of reservoirs in map of India (after (Arora et al., 2016; Srinagesh et al., 2016, with additions)). (*1*) $M = 6.3$ (December 10, 1967); (*2*) $M = 5.0–5.9$ (1967 to February 2015); (*3*) $M = 4.0–4.9$ (August 2005 to February 2015); (*4*) $M = 3.0–3.9$ (August 2005 to February 2015); (*5*) broadband seismic stations; (*6*) deep scientific boreholes; (*7*) scarp separating Western Ghats from more westerly Konkan lowland.

Western Ghats Mountains. In the escarpment separating the Western Ghats from the Konkan lowlands (shown by the dashed line in Fig. 1), a 1300-m series of basalt flows are outcropped (Gupta, 1992). The Deccan basalt eruptions occurred simultaneously with the commencement of rifting in the Arabian Sea, which resulted in the formation of the Carlsberg Ridge, separation of the Seychelles microcontinent, and creation of the volcanic Chagos-Laccadive Ridge, also referred to as the Maldives Ridge (see the discussion and bibliography in (Mishra et al., 2014)).

The thickness and structure of the Indian shield's lithosphere are presently active debated. The crustal thickness in the Koyna–Warna region is about 40 km (e.g., (Shasindar et al., 2011)). It has been traditionally believed that the thickness of the lithosphere there is about 250–350 km and the heat flow is largely generated by the decay of the radioactive elements in the Earth's crust, whereas the mantle heat flow is relatively low (a review and bibliography on the subject are presented in (Pandey, 2015)). The heat flow measured in the KBH-1 borehole, which has been drilled in the Koyna region to a depth 1522 m through 933 m of the Deccan basalts and 589 m of the underlying granites, is 45 mW/m^2, i.e., slightly above the values that were previously registered for the southern part of the Indian Shield. An important fact is that beneath the traps the borehole encountered granulites and amphibolites (Roy et al., 2013), which have a high density and high seismic velocities and are identified as midcrustal rocks that are depleted in radioactive elements and were drawn up to the surface as a result of the deep erosion of the upper crustal layers. Based on the new data, including the low concentration of the radioactive elements, the temperature at a depth of 6 km is estimated at 130–150°C and at 10 km it is only 165–

225°C. This prompted Pandey (2015) to conclude that the Indian Shield's lithosphere is not at all thick and rigid but, instead, it has a thickness of about 100 km, is heated, and, as a result, deformable. It is fairly challenging to explain the high seismicity that emerged within a huge craton after building relatively small reservoirs; therefore, the hypothesis suggested in (Pandey, 2015) surely merits attention. There are a number of questions to be solved there. One of them is whether it will be possible to integrate the existing seismic tomography data with the new model of the Indian Shield's structure. The solution of these questions could be promoted by the petrographical and strength studies of the rocks cored from the deep borehole which is expected to penetrate the source zone of the earthquakes (Rao et al., 2013).

3. FAULT TECTONICS

The presence of the regional active faults within the Deccan Plateau still remains debatable. In the opinion of some scientists, the large scarp which has a length of 450 km and borders the Western Ghats Mountains in the west is a fault; however, most authors tend to considering it as an erosional landform. We note however that the tectonic origin of this scarp is supported by the presence of more than 30 hot springs confined to this zone (Gupta, 2002). The Koyna River valley with a depth of 500–600 m, which does not follow the trend of the main geomorphologic structures of the region, was probably formed along the fault zone. The sharp eastward turn of the Koyna River south of the dam is perhaps also guided by the fault (Gupta, 1992).

The Deccan traps are frequently observed to be cut by tectonic dislocations which are filled by the brecciated rocks; however, only rarely is it possible to find signs of displacements. Quite a number of such dislocations are revealed in the region of the Koina reservoir. These NNW- to NNE-striking dislocations with a length up to 20 km cut the basalts down to a depth of 800 m without visible signs of the displacements. Such faults are also revealed during the construction of the tailrace tunnel near the Koyna dam. The fault zones are filled with clastic rocks cemented by clay and have a width of 1 to 20 m (Gupta, 2002).

It is worth noting that the mechanism of the intraplate earthquakes in the Indian Shield is dominated by thrusting on the latitudinal faults, which results from the collision between the Indian and Eurasian plates. In the Koyna region, the displacements occur as the left-lateral shears on the faults that are predominantly oriented in the NE–SW direction parallel to the scarp. The displacements in the Warna region are mostly normal dip-slip movements taking place on the fault oriented from NW to SE. This distinguishes the Koyna and Warna region from the other areas of the Indian Shield (see the discussion and bibliography in (Rao and Shashidhar, 2016)). The kinematics of the displacements on the Koyna and Warna faults show that the regional stress field differs here from the simple compression along the motion of the Indian–Australian plate (from SW to NE in this area). Here, the regional stress field is probably also controlled by the geodynamics of the structures of the northwestern Indian Ocean, i.e., the Carlsberg and Sheba rift zones and the Owen Fracture (transform) Zone separating the Indo-Australian plate from the Arabian one.

With the progress in studying the structure of the Koyna–Warna region, the fault tectonic schemes have become increasingly more complicated. The first detailed schemes relied on the data from the network seismic stations installed in this region. Based on the refined epicenters of 39 earthquakes that occurred from 1967 to 1973, Rastogi and Talwani (1980) concluded that the seismic events can be grouped into three zones. The first one, subsequently named the Koyna seismogenic zone (KSZ), has a length of more 40 km. It trends from NE to SW, passes through the dam and the southern part of the Koyna reservoir, and further extends to the western part of the Warna reservoir (shown in Fig. 2). The second zone was identified 30 km west of and parallel to KZS; however, in the later versions of the scheme, it was not considered. The earthquakes in these zones have left lateral strike-slip focal mechanisms. These two zones are connected by the third one, approximately trending from NW to SE and passing south of the Warna reservoir, which had not been constructed at the time of writing the cited paper (1980). These three zones coincide with the lineaments identified from the Landsat satellite images. Within these zones there is a Donechiwada fault (shown by the letter D in Fig. 2), which has been for the first time described in (Harpster et al., 1979). The helium survey on a number of profiles intersecting this fault revealed a noticeably increased He flux at a depth of 1.5 to 5 m. Two slant wells cutting this fault zone allowed its dip angle to be estimated at 60° WNW (Gupta, 2002).

Simultaneously, Gupta et al. (1980) have analyzed 12 events with magnitudes above 4 and their aftershocks over the period from October 1973 to December 1976. Significant part of these events is concentrated along the N–S trending line which passes through the epicenter of the earthquake of December 10, 1967. It was found that the events along the 75°45′ east longitude, north of the 17°15′ north latitude had the left lateral strike-slip mechanism. South of this latitude, approximately at the sharp westward turn of the Koyna River, the earthquake mechanisms are dominated by normal faulting.

Later, Talwani (1997a) carried out a detailed analysis of the seismological, seismic, seismotectonic, aeromagnetic, and other data obtained up to that time and considerably elaborated the system of tectonic dislocations in the Koyna–Warna region. In the cited work, he again distinguished the Koyna fault zone

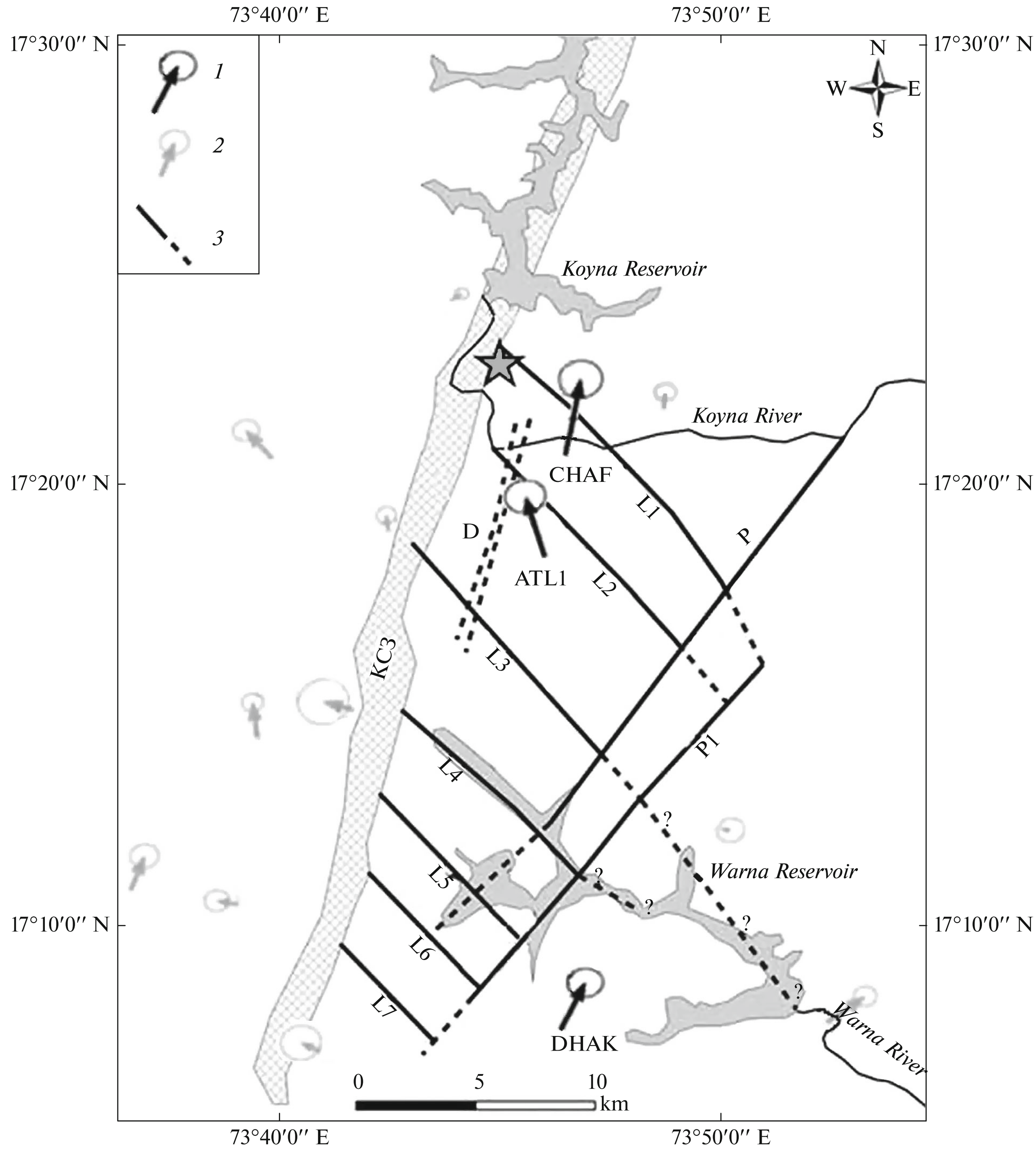

Fig. 2. Scheme of tectonic dislocations and positions of GPS sites according to (Durá-Gómes and Talwani, 2010; Catherine et al., 2015 with additions). (*1*) GPS sites where displacements are larger than measurement accuracy; (*2*) GPS sites where displacements are not larger than measurement accuracy; (*3*) tectonic dislocations; D, Donechiwada fault; P, Patan fault; KSZ, Koyna seismogenic zone.

which borders the seismically active zone in the west. In the east, the seismicity is limited by the NE–SW trending Patan fault (shown in Fig. 2), which is located east of the Koyna zone. The fault dips 45° northwest. Between the Koyna zone and Patan fault there are several disjunctive dislocations including the Donechiwada fault, which trend from NNE to SSW and plunge from the surface to the depth of the seismogenic zone (6–8 km). According to the cited paper, these faults steeply dip and probably serve as the pathways guiding the fluid flows towards the seismogenic depth.

The structure of the upper crustal layers of the Earth and the positions of the faults in the region of the reservoirs were recently studied by seismic tomography (Dixit et al., 2014). In particular, the cited study revealed an area of high *P*- and *S*-wave velocities. This zone stretches by more than 15 km to the north from the Warna reservoir; its depth reaches 8 km. The revealed structure is interpreted as a water-saturated fault zone. Considering the fact that the earthquakes mainly take place in the periphery of this zone, the authors conclude that seismic events occur on the faults feathering this zone and are associated with the increased pore pressure. The seismic tomography data also demonstrate a series of northwesterly trending faults north of the central part of the Warna reservoir and the meridional main fault zone coinciding with the previously revealed KSZ.

For studying the activity of the faults in the region of the reservoirs, geodetic measurements have been conducted since 2003 at the repeated GPS sites, which total 16 (Catherine et al., 2015). The GPS sites are installed both above the seismogenic zones and in their closest vicinity (Fig. 2). According to the estimates in (Catherine et al., 2015), the displacements relative to the Indian Plate are determined in this network as accurately as up to 1.5 mm per annum, and this value was only exceeded by the displacements at the three GPS sites shown by the thick arrows in Fig. 2. The maximal average displacement velocity is 2.1 mm per annum. The obtained results were compared to the seismological data (Srinagesh and Sarma, 2005) according to which the length of the KSZ zone was assumed to be 22 km and the length of the seismogenic zone that is located south of the Warna reservoir and referred to as the Warna seismogenic zone (WSZ) is assumed to be 15 km. In modeling the displacement field, the upper edge of the faults was assumed at the surface, and the lower edge, at a depth of 8 km. The dip angle of the faults was specified at 70°. For achieving displacements close to those observed at the three GPS sites with displacements of more than 1.5 mm per annum, Catherine et al. (2015) assumed the average displacement velocity to be 7 mm per annum and the focal mechanism to be left-lateral strike-slip faulting at KSZ and normal faulting at WSZ.

Since the measured displacements are small, these data need subsequent verification by analyzing the longer time series of the geodetic data and applying satellite radar interferometry. Indeed, the present-day satellite radars with synthetic aperture (InSAR interferometry) under favorable conditions are capable to reveal the displacement fields or time series of ground displacements with the accuracy sufficient for monitoring the dynamics of the deformation regime in the seismically active regions (a few cm when two radar images are analyzed and average displacements by a few mm per annum in the case of analyzing a time series of SAR images). Moreover, the SAR technology does not require deploying an expensive network of ground-based observatories and stations in the study region. At the same time, the success in applying the SAR interferometry depends on a number of factors, which are discussed in detail in the Russian-language literature, e.g., in (Mikhailov et al., 2014). The recent investigations of the spatiotemporal correlation between the seismicity and surface deformations highlighted the critical importance of studying the fields of these geophysical parameters (Sobolev et al., 2010).

It should be noted that the displacements measured at the GPS sites are related to long-lasting processes and may reflect the crustal deformations caused by reservoir loading and intraplate stresses but not the effects of seasonal variations in the groundwater levels. Gahalaut and Kalpna (2001) estimated the deformations caused by the changes in the water volume in the reservoirs. The calculated seasonal horizontal displacements induced by the seasonal variations in the water level by 30 m were estimated for a homogeneous elastic crustal model at 0.7–0.8 mm per annum.

Recently, Rao and Shashidhar (2016) analyzed the instrumental data on the focal mechanisms of the earthquakes that have occurred during the past 45 years in the Koyna–Warna region. These authors used both the data of the previous studies and their own results of the moment tensor inversion using the broadband stations starting from 2005. Just as the previous works, their analysis also revealed the Koyna and Warna seismogenic zones. The focal mechanisms are dominated by the left lateral strike-slips in the first zone and by normal faulting in the second zone. At the intersection of these zones, both event types have been observed. The source depths reach 13 km in the KSZ, whereas they are at most 4–6 km in the WSZ.

In the past decade, numerous of geophysical studies have been carried out and a series of boreholes were drilled (Gupta et al., 2015) in the Koyna–Warna region, which allowed more detailed schemes to be constructed for this territory (Gupta et al., 2015). For instance, according to (Durá-Gómez and Talwani, 2010), at least eleven large fault zones are now identified within a small (30 × 20 km) region. These zones, shown in Fig. 2, include four subvertical faults striking in the NNE–SSW azimuths in the west and in the NE–SW azimuths in the east. From the west to the east, these are the KSZ, Donechiwada, and Patan faults, and the fault referred to as P1. These faults are intersected by the systems of the NW–SE striking normal faults denoted by indices L1 to L7. Among the latter, the L3 fault identified from the Landsat data is the largest. From the KSZ zone it strikes southeast, probably up to the dam of the Warna reservoir. Faults L1 and L2, which are located north of L3, are identified from the seismological data; and faults L4 and L5 located south of L3 are revealed by the airborne magnetic surveys. Faults L6 and L7 coinciding with the WSZ were recognized from the seismological data (Sringaresh and Sarma, 2005; Sarma and Srinagesh, 2007).

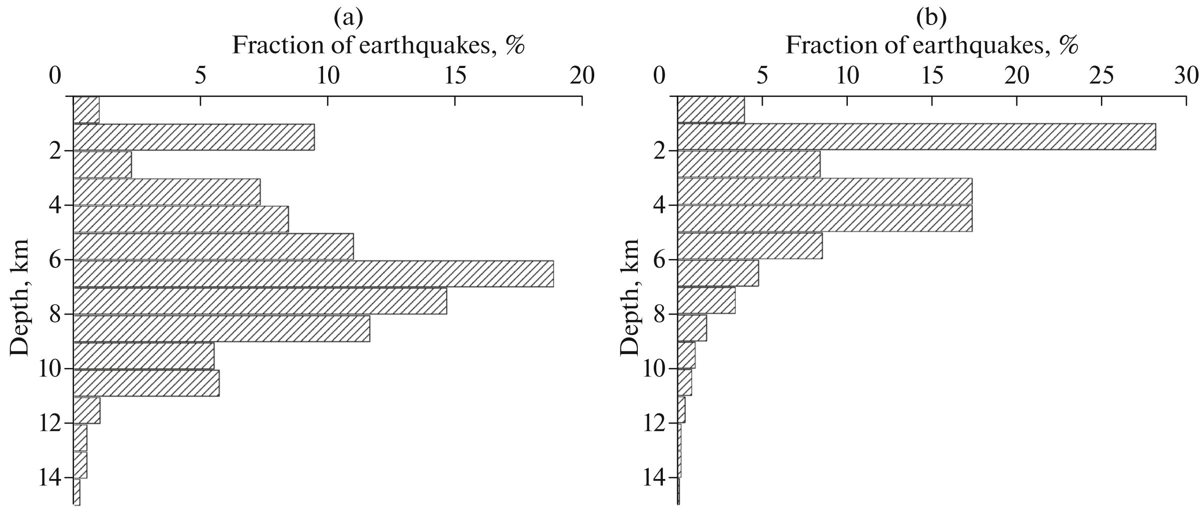

Fig. 3. Depth distribution of earthquakes (% of total number of events) according to local seismic catalog for MERI broadband stations for 2005–2015 starting from $M \leq 2$: (a), north of 17°25′ N lat (region of Koyna reservoir); (b), south of 17°25′ N lat (Warna reservoir).

4. THE ANALYSIS OF SEISMIC ACTIVITY

By comparing the frequency of the seismic events with the water level and the rate of its variations in the reservoir, Gupta (1992) concluded that the seismic events occurred with a certain delay after the seasonal filling of the reservoir. In 1967, the water level had been very high all year, which could have initiated the earthquake of December 10, 1967. Gupta's other conclusion is that the events with $M > 5$ frequently occurred when the water level rises faster than 12 m per week. The subsequent studies with the borehole seismometers (Shashidhar et al., 2016) established the growth of the weak seismicity during the fast water intake in March 2015. These data show that the response of the medium to the change in the water level in the reservoirs varies with time: during the first few years, the enhancement in the seismicity occurred during the accelerated growth of the load, whereas in March 2015, weak seismicity was activated during the reservoir's drawdown.

The depth distribution of seismic events is nonuniform (Mandal et al., 1998). The events are concentrated above 1 km and in the depth interval from 5 to 10 km, whereas in the interval from 1 to 5 km events are rare. The maximal number of the events is confined to the depth interval from 6 to 8 km, where seismic velocities according to the deep seismic sounding data are low (Krishna et al., 1989). Figure 3 illustrates the depth distribution of the seismic events in the region of the Koyna (north of 17°15′ N, Fig. 3a) and Warna reservoirs (south of 17°15′ N, Fig. 3b), which we calculated using the catalog of the Maharashtra Engineering Research Institute, India—MERI (*Maharashtra* ..., 2015) for 2005–2015. The depth distribution of the events generally agrees with the data for the previous periods. The key events in the KSZ take place in the depth intervals from 1 to 2 km and from 5 to 9 km with the predominance of the deep events. In the southern segment, the events occur at the shallower depths ranging from 1 to 5 km with the appreciable minimum at 3 km. It is fairly characteristic that the events in the upper 1-km layer (i.e., in the Deccan traps) are very scarce.

Generally, the described regularities are also observed in the other regions. For instance, based on the analysis of the global data, Simpson et al (1988) concluded that large seismic events are frequently delayed relative to the periods of a high water level in the reservoir. These events do not occur in the immediate proximity of the reservoir; instead, they take place at a distance of up to 10 km and at a large depth, and frequently there are facts testifying to the connection between the seismogenic fault and the water reservoir. There are numerous works providing the estimates for the propagation velocity of the pore pressure front along the porous half-space (Rice and Clearly, 1976; Roeloffs, 1988; Talwani, 1997b), including the case of the heterogeneous half-space (Gahalaout and Gupta, 2008; Pandey and Chadha, 2003).

By analyzing the time distributions of the focal mechanisms, Rao and Shashidhar (2016) revealed periodical alteration of the predominant strike-slip mechanism of the earthquakes and normal faulting. The authors of the cited paper propose explaining the origin of the induced seismicity and the revealed periodicity in the changes of its mechanisms by the fact that the existing fault system is loaded by the intraplate stresses caused by the collision between the Indian and Eurasian plates and is presently close to critical limit. It is hypothesized that intraplate stresses vary with time so that their growth is associated with strike-slip displacements on the system of the meridional faults, whereas their decrease leads to normal faulting on the latitudinal faults under the loading of the reservoir weight. The difference of the displacement mechanisms in the regions of the Koyna and Warna reservoirs (strike-slip and normal faulting, respectively) can probably be accounted for by the fact that sliding occurs on the faults that have already existed up to the time of construction of these reservoirs. The dynamics and operation of the water reservoirs are disregarded in this model.

There are also other hypotheses. For instance, in (Gahalaut et al., 2004) the authors correlated the seismic activity to the interactions of the faults. They numerically calculated the Coulomb stresses and showed that the left-lateral strike-slip displacements in the KSZ can initiate normal-fault displacements in the Warna seismogenic zone and vice versa. In (Catherine et al., 2007), the authors relate the seismicity to the stresses caused by the bending of the lithosphere under the gravity loading of the water reservoir. The weak point of the last hypothesis consists in the fact that the additional stresses induced by filling the deepest reservoirs are at most 1 MPa (100 m of water), whereas the stress released by the reservoir-triggered earthquakes is many times higher (Gup[ta, 2002). The estimates of Mandel et al. (1998) have shown that that the stress release by most events in the Koyna and Warna region was 3 MPa; however, for some events, it reached 19 MPa. Perhaps, the additional loads associated with the reservoir's weight and its dynamics do not directly cause the earthquakes but create the triggering impact; therefore, in the joint analysis of the seismological and satellite geodetic data, one should consider all the mechanisms discussed above.

Talwani (1995; 1997a; 1997b) proposed a model in which the system of the intersecting faults is a concentrator of the intraplate stresses, whereas the seasonal variations in the groundwater level give rise to fluctuations of the pore pressure in the faults and, consequently, the fluctuations of the Coulomb stresses on the faults. Based on the analysis of the long time series of the observations in these papers, it is asserted that the seismicity with a certain delay reflects the water level variations in the reservoirs. The impoundment of the reservoirs in July–August initiates the seismic events in such a way that about two-thirds of the annual released seismic energy falls in September–December. In the discussion of this model in (Gupta, 2002), the author notes that in this case the earthquakes should have been only concentrated at the intersections of the faults during the entire interval of the observations, which is not the case in the real data.

An important result is obtained in (Pandey and Chadha, 2003) by analyzing the pressure variations at the depth of the earthquake sources induced by the changes in the reservoir water level. By solving the problem of the propagation of the pressure front in a porous medium, the authors show that when the water level at the surface of a vertical permeable fault with impermeable walls changes by one meter per 5 days, the pore pressure front propagates to a depth of 6–8 km. The front of the pore pressure in the cited work is defined as 5–15% of the initial water load. In the opinion of the authors of the cited paper, even small variations in the pore pressure are sufficient to cause displacements on the Koyna–Warna faults, which are close to the loss of stability.

The times of 19 seismic events with $M > 5$ from 1967 to 2000 with the operation of water reservoirs have been compared in (Durá-Gómez and Talwani, 2010). The authors of the cited work used the one-dimensional diffusion model in a porous medium suggested in (Roeloffs, 1988). It is shown that the water level variations due to the reservoirs' filling could create at the epicentral distances the changes in the pore pressure that were sufficient for initiating earthquakes. For instance, according to the estimates of these authors, for initiating the seismic events, the pore pressure in the region of the Koyna reservoir should have increased by about 300 kPa since the beginning of its impoundment up to 1980; the corresponding growth in the pore pressure for the Warna reservoir is estimated at 600 kPa. Among the triggering factors, the authors note the rise of the water level by at least 40 m, the high velocity at which the reservoirs were filled, and the high rate of the pore pressure variations with time. The excess of the water level (and, correspondingly the stresses) above its previous value is also considered as an important, although probably not the leading factor. This memory effect which was established in the laboratory experiments and referred to as Keizer's effect, according to the data (Durá-Gómez and Talwani, 2010) also contributes in forming the pattern of seismicity in the Koyna–Warna region. The cited work also presents the data indicating that the sources of the large earthquakes move away from the water reservoirs with time.

Rajendran et al. (1996) asserted that the earthquakes are initiated by the violation of the equilibrium due to the reduction in the strength of the fault zones. This idea has been further developed in (Rajendran and Harish, 2000), where it was hypothesized that water passes through the basalts broken by the meridional faults and penetrates into the fault zone with the highly permeable upper part, which is located in the region of the Koyna reservoir. As the fluid pressure increases, the rocks in the fault zone become damaged, and the zone of fractured and highly permeable material propagates to the deeper horizons. As a result of the weakening of the fault zone, even small fluctuations in the intraplate stresses may lead to the loss of stability. In this model it is assumed that the vertical walls of the fault are impermeable and therefore the pressure front moves only downwards along the fault.

In their keynote lecture, McGarr and Simpson (1997) concluded that the growth of normal and shear stresses with the increase of the reservoir loading, the increase in the pore pressure due to water diffusion into the fault zones, and as a result of the reduction of the porosity of the rocks under the growth of stresses can be a triggering mechanism of induced seismicity. Just as many other authors, McGarr and Simpson infer that the reservoir loading is too small to be the cause of the observed earthquakes. Therefore, the induced seismicity takes place in the areas where intraplate stresses are fairly high. For the generation of earthquakes with magnitude 5 and higher, it is also required that sufficiently long faults exist in the vicinity of the reservoir.

5. PROBABLE DIRECTIONS FOR FUTURE RESEARCH

Summarizing all this, one should admit that despite the significant progress made in studying the structure and the dynamics of the seismic process, the surface displacement fields, groundwater level, and many other factors associated with the seismicity of the Koyna and Warna regions, the problem of elaborating models that describe the key features of induced seismicity overall and specifically in this region is still topical. For instance, the relative contributions of the regional intraplate stresses and local factors, such as reservoir loading and its variations with time, the changes in the limiting strength of the faults due to water diffusion through them, cyclic changes of the pore pressure and probably mineral transformations (hydrolysis) in the rocks of the fault zones, the role of the Kaiser effect and the changes in the permeability of the rocks, remain unclear.

In our opinion, important information can be yielded by the joint analysis of the seismological data, together with the ground surface deformations and water level variations in the reservoirs and boreholes. The numerical analysis of the changes in the water level in the boreholes drilled under the Indian–German project on studying the earthquake-related fluctuations in the groundwater level was started in (Gahalaut et al., 2010). Based on the analysis of the equations for a poroelastic medium (Rice and Cleary, 1976) and Okada (1992) formulas for a homogeneous elastic half-space, the authors of the cited paper concluded that in wells having a sufficiently high sensitivity (the ratio of the change in the water level to the bulk deformation), there is a 100% agreement between the sign of the actual water level fluctuations and its calculated change after the earthquake. In many cases, the actual and predicted amounts of this change also coincide. In the cited work, only events with $M > 4$ are studied and the first-approximation formulas are used; therefore, the coincidence of the real and predicted values is remarkable. In the future it would be reasonable, in addition to the coseismic change of the water level, to investigate the dynamics of the water level fluctuations for several weeks or months after the seismic event. This will made it possible to take into account the finite velocity of the propagation of the pore pressure front which was estimated in (Frank et al., 2015) at 1 km per day. As was noted, the distance from the reservoirs to the epicenters of the large earthquakes increases with time. For instance, according to (Chadha et al., 2003), seismic events with magnitudes above 4.3 are now detected as far as 24 km from the reservoir. The further studies should also take into account the results of Gahalaut and Gupta (2008) where it is shown that allowance for the rock's high permeability in the fault zone compared to the homogeneous half-space increases the pore pressure estimates in the faults by more than a factor of three.

The necessity to jointly analyze the variety of the processes initiating the induced seismicity is also demonstrated by the results of Durá-Gómez and Talwani (2010) where the integrated model of the seismic process was suggested. This model incorporates the propagation of the pore pressure front along the network of the faults, the memory effects, and the rate of change of the water level. The total effect of these factors generally accounts for the time of the generation of 19 earthquakes with magnitude m_b above 5.

It is also worth noting that the physical properties of the rocks in the region, particularly those located beneath the basalt traps, are still relatively poorly known. Therefore, it would be reasonable to conduct a series of laboratory experiments with samples from the deep boreholes in the Koyna–Warna region. In these experiments, it would be important to explore the contributions of fluid saturation, loading velocity, and excess stress above its previous level (the Kaiser effect).

The laboratory testing of the cores of rocks directly from the source zones of earthquakes are a relatively new and highly promising direction of the studies into the nature and mechanisms of induced seismicity. These experiments were carried out with the samples obtained in the projects of continental deep drilling in the fault zones. These are the widely known SAFOD project on the San-Andreas fault; the Nojime project in the region of the Kobe earthquake of 1995 in Japan; the TCDP project in the region of the Chi-Chi earthquake of 1999 in China; the WFSD project in the area of the Wenchuan (Sichuan) earthquake of 2008 in China; and the CRL (Corinth Rift Laboratory) project, executed on the southern coast of Corinth Bay in the area of high local seismicity.

The latest results of the laboratory testing revealed the important role of many processes which drastically change the permeability of the medium and friction conditions on the contacts of different scales, and initiate physicochemical transformations of the rock material in the relatively low pressure and temperature conditions (Carpenter et al., 2015; Morrow et al., 2014; Kocharyan and Ostapchuk, 2015). Indeed, a significant part of the seismic events in the region of the

Warna reservoir occurs at a depth of about 2 km, whereas the events around the Koyna reservoir take place at a depth of 5–7 km (Fig. 3). These depths are critical for the actuation of the processes of kaolinite hydrolysis (conversion into water saturated smectite) in the first case and feldspar hydrolysis (dissolution into hydromicas) in the second case, which lead to the significant weakening of the faults (Di Toro et al., 2004; Khrunina and Cheban, 2015).

CONCLUSIONS

Based on the problem-oriented analysis of the accumulated experimental and theoretical dataset on the reservoir-triggered seismicity in the Koyna–Warna region, their comparison with the geology and tectonics of the region, and with the support of the wide spectrum of the relevant publications, we can formulate the priority tasks for the future research. Solving these tasks will promote understanding the nature of the induced seismicity observed in different regions for building the regional geodynamical models and selecting the ecologically safe regime of the operation of the reservoirs.

In our opinion, the following research will promote understanding the cited processes.

(1) The analysis of seismic catalogs aimed at refining the spatial association of the earthquakes and the dynamics of their migration in space and time and enable more accurate determination of the positions, lengths, and depths of the main seismically active faults.

(2) The study of the regularities in the seasonal variations of induced seismicity which are caused by the significant intraannual water level fluctuations in the Koyna and Warna reservoirs based on the detailed up-to-date seismic catalogs compiled from the observations by the regional, local, and borehole seismic networks.

(3) Studying the variations in the strain sensitivity of the medium with the use of the calibrated tidal impacts. The response of the medium to tidal perturbations can be estimated both from the deformation-related components of the water level fluctuations in the boreholes and from the seismic activity itself (e.g., in the LURR model (Yin et al., 2006)).

(4) Conducting specialized laboratory experiments on the cores from the source zones of the Koyna and Warna region for studying the rock fracture processes under the conditions of the varying hydrostatic pressure and loading velocities, under the changes in the level of effective loads, and periodical fluctuations of the pore pressure, which change the strength, permeability, friction conditions on the contacts on different scales, and the related physicochemical transformations in the medium.

(5) Estimating the surface displacement field by SAR interferometry, its comparison with the GPS data, and correlation to the positions of the seismogenic faults and their activity in the course of time. This is a fairly difficult task since the displacements are small and since the Koyna–Warna region is covered with dense vegetation. The use of the images with a long wavelength (ALOS-1 satellite) should mitigate the effect of the vegetation; however, these images are less sensitive (the sensitivity is determined in terms of fractions of the wavelength which is 22.4 cm for the ALOS-1 satellite). The radar survey by the ALOS-1 satellite was conducted in the Koyna–Warna region in 2007–2011. The area of both reservoirs is covered by the images from 536 tracks which were taken at different time intervals from January 12, 2007 to March 10, 2011. There are 26 images overall; they were obtained from January to April and from June to October, i.e., during the seasonal filling and emptying of the reservoirs. Under the favorable conditions, based on this series of images, it is possible to reveal the seasonal and long-period displacements.

(6) Estimating the size of the displacements on the faults over the periods covered by GPS and satellite radar interferometry. Calculating the Coulomb stresses in the Koyna–Warna region for these periods under different hypotheses of the orientation of regional stresses.

(7) Joint statistical analysis of the data on seismic activity, surface deformations, and water level fluctuations in the reservoirs and boreholes for revealing the time delays between the probable initiating impacts and the response of the geological medium.

Based on the previous results, it would be reasonable to carry out the joint analysis of the seismological and satellite geodetic data (GPS, InSAR) in models that take into account the propagation of the fracture fronts and high pore pressure along the faults under cyclic reservoir loading with time-varying amplitude. The initial stressed state of the faults under the action of the external (intraplate) stresses can probably be assumed to be close to the critical strength. Bending of the lithosphere under reservoir loading should hardly be considered as a seismogenic factor in this case. Indeed, the presence of the large KSZ fault zone which stretches west of the Koyna reservoir suggests that for solving this problem it would be reasonable to use the model of bending of an elastic cantilever resting on a low-viscous base. It is qualitatively clear that this model will yield displacements of the type of normal faulting along KSZ instead of the left-lateral strike-slip movements observed here. At the same time, the reservoir load will certainly be the triggering factor.

The synthesis of the listed results with the data of the previous studies will promote progress in understanding the nature and dynamics of induced seismicity in the Koyna–Warna area and other similar regions.

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