Historical and future seismicity near Jaitapur, India

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Although India has a long written record, the shaking intensity of few damaging earthquakes that occurred before AD 1800, can be quantified. Since reliable estimates of future shaking near planned nuclear power plants depend on the extrapolation of historical earthquake data spanning many centuries, estimates of seismic risk to the planned Jaitapur nuclear power plant assessed from a short dataset of only the past few centuries, may not, therefore, represent the true risk to the plant.

Nuclear power stations can be engineered to withstand a high degree of shaking intensity, although the expense of the design increases with the severity and duration of the anticipated shaking. There is, therefore, significant interest in estimating the highest possible accelerations to be anticipated near Jaitapur, the proposed site of India's largest 9900 MW nuclear power plant on the west coast (16°35′N, 73°20′E). Jaitapur, however, has no record of local seismicity in the past century, although several $M \sim 3$ events cluster towards the Koyna seismogenic area over 100 km to the north-northwest. Specifically no earthquakes of $M > 4.5$ have occurred here since 1900, and definitely none since 1985 when good-quality local recordings became available. However, moderate earthquakes such as the M 6.4 Koyna earthquake of 1967 at distances <30 km and large ones at distances >100 km can also produce significant shaking. Indeed, Jaitapur has frequently experienced intensity VII shaking from such earthquakes. This level of shaking can be easily accommodated by most nuclear power plants, but a consideration of the tectonic setting of earthquakes in India suggests that Jaitapur lies in a similar setting to Latur and Koyna where earthquakes of $Mw \approx 6.5$ have occurred within the past half century, resulting in local accelerations exceeding intensity VIII. Such an earthquake in the close vicinity of Jaitapur may not occur for many thousands of years, but although unlikely, it could occur within the lifetime of the nuclear power plant.

Stable continental regions

India is considered to be a stable continental region – a region where earthquakes are rare, but can occur in special circumstances. Examples of these special conditions are: (i) ancient rift zones that may 'focus' regional stresses; (ii) coastal regions that may have been stressed by rising sea level since the last Ice Age; (iii) regions where friction has been reduced artificially on existing highly stressed faults by reservoir impoundment, and (iv) continental regions experiencing flexural stress.

(i) The nearest ancient rift zone to Jaitapur lies about 200 km offshore to the west. It is a large escarpment constituting the continental slope and is associated with the break-up of the western Gondwana. No large earthquakes are known from this region. The nearest continental rift to have experienced significant seismicity is the Bhuj region of Kachchh, 800 km to the north of Jaitapur. This was shaken by a Mw 7.7 ± 0.2 earthquake in 1819, and most recently by a $Mw = 7.6$ in 2001. Earthquake shaking at Jaitapur from this source is anticipated to consist of long-period undulations with MSK intensity less than or equal to IV.

(ii) Jaitapur lies on the Indian coastline. No large earthquakes in India are known to have occurred in a coastal setting alone, although the historical record is insufficiently long to exclude the possibility of one having occurred in the past thousands of years. A large tsunami with no known source rocked Vasco da Gama's fleet in 1524 near Daibul[1].

(iii) The Jaitapur site lies at a distance of ~110 km from the $Mw = 6.4$ Koyna earthquake of 1967, which was induced by the impounding of the Koyna reservoir. The main shock was unexpectedly strong in that no large earthquakes had been known to have occurred earlier. It was preceded by foreshocks and continues to generate $3 < M < 5$ earthquakes even to this day. The importance of this earthquake lies in the implication that stresses in the nearby Jaitapur region are likely to be sufficiently high to produce earthquakes, even though none is known historically.

(iv) In addition to the above considerations, there is one that singles out India tectonically from other stable continental regions. Due to its persistent 5 cm/yr northward motion relative to Asia, the Indian subcontinent is colliding with the edge of southern Tibet at approximately 16–18 mm/yr. The collision has bent the northern edge of the Indian Plate downward by approximately 4–6 km, raising the central Indian plateau elastically by >400 m. No other continental plate shares this special geometry and stress regime. The earth's mantle is also warped upwards beneath this bulge, as recorded by gravity measurements. The uplifted region has caused the area to its south to be buckled downward by roughly 40–60 m, and it is in this regional setting that Latur, Koyna and Jaitapur happen to be located. In plate tectonics terminology, this is known as the outer moat. In oceanic plates it is not well developed because they are thinner. In the Indian Plate the outer moat is broad (>300 km) and because of its thickness and stiffness, constitutes a region of intense north-south compression. Quantitative estimates of the amplitude of this surface compression depend on the elastic thickness of the Indian Plate which exceeds at least 40 km (ref. 2), but that it is capable of stressing moderate earthquakes is evident from the occurrence of the $Mw = 6.3$ Latur earthquake of 1993 (reverse faulting mechanism). This earthquake ruptured the surface of the Indian Plate, the only known surface rupture to have occurred at this latitude. The latitudinal correspondence between this earthquake and the Koyna earthquakes may in fact be related to these high surface compressional stresses. Vita-Finzi[3] using similar reasoning has proposed that the five belts of Indian seismicity have arisen as a result of the flexural buckling of the plate.

Since Jaitapur lies in the same compressional stress regime that has been responsible for generating both the $Mw = 6.3$ Latur and the $Mw = 6.4$ Koyna earthquakes in the past five decades, it can be argued that a similar sized earthquake could possibly occur directly beneath the power plant. The probability of this earthquake occurring is low but it is nevertheless possible, and is an important consideration in the analysis of power plant safety.

Historical seismicity

In the absence of a sufficiently long historical record, the task of estimating possible future seismicity at Jaitapur can, however, be approached in three ways: (i) by assuming that the rate of historical earthquakes is typical of the rate of future earthquakes; (ii) by examining the size and frequency of slip of mapped geological faults, or (iii) by examining the physics of earthquake processes. The last two approaches can indeed be greatly refined by a quantitative estimates of the accumulating strain rate in the area determined from precise geodesy (GPS measurements).

We first consider India's historical seismic record. A complete analysis of seismic risk requires a knowledge of likely shaking intensities within the lifetime of the power station, and its appurtenant structures and waste storage facility. For various reasons we do not consider that sufficient historical data exist to estimate the recurrence interval for moderate earthquakes in peninsular India. We also ignore the several hazard and seismic risk maps that have been issued by various authorities in the past several decades, since these assume that the seismic energy release of recent years is representative of the future.

At its simplest, most attempts to determine the rate of occurrence in a region, of earthquakes of a given magnitude, try to quantify b which signifies the rate of occurrence of earthquakes of a given magnitude, in the Gutenberg–Richter relation:

$$\log(N) = a + bM, \tag{1}$$

where N is the cumulative number of earthquakes of magnitude, M. These assume that the intercept of the resulting straight line, a, which is a measure of the total number of earthquakes in a given time – the seismic productivity – is a constant invariant over periods of millennia. Although this is a convenient assumption, there is no physical basis for assuming that a cannot slowly, or abruptly, vary especially in a flexural stress setting.

In regions where seismic productivity is high, the written record of earthquakes long and the stability of a in eq. (1) can be tested, it is possible to develop the statistics to characterize the probable rate of their future shaking. In Japan, China and parts of Europe and the Middle East, the >2000-year historical record of moderate earthquakes is sufficiently long for this approach. In India it is surprisingly brief (Figure 1). The written history of India regarding earthquakes is unreliable and incomplete before the arrival of the Portuguese in 1492. Some of the Jesuit records during 1500–1770 were lost in the Lisbon earthquake, and the duplicates of these records in India were burned by an ignorant captain charged to take them to Lisbon after 1775. Between 1500 and 1800, numerical data suitable for characterizing earthquake magnitudes and locations are sparse, except for large earthquakes described in Mughal archives or reported by traders or travellers. After 1800, the data become increasingly more useful due to numerous written reports archived in English, and progressively refined in the 20th century by data from seismometers and geodetic surveys. If we assume steady seismic productivity, we are missing quantitative and qualitative information concerning approximately 5000 earthquakes (Figure 1) since the edicts of Asoka were written in stone.

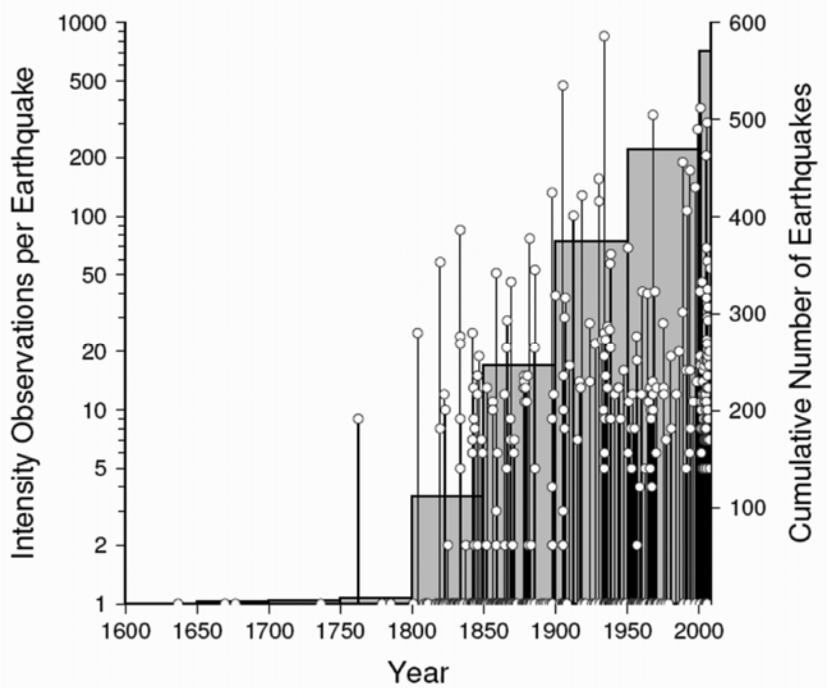

Figure 1. Historical record of felt earthquakes in India[5] after AD 1800. Felt earthquakes occur at a rate of more than 240 per century (shaded steps). The circles indicate the number of felt reports associated with each earthquake, and the bars, their cumulative number. Of considerable importance is the observation that none of these earthquakes is known to have recurred twice on the same segment of a mapped fault.

Catalogues of Indian earthquakes

Several earthquake catalogues are currently available for India. An historical Indian catalogue formed by the merger of several earlier ones is archived by the USGS on-line. The pre-1900 listing in this catalogue is judged to be unreliable in that it contains earthquakes that are duplicated, and which have been assigned magnitudes and locations evaluated uncritically or quoted from earlier catalogues. Their locations estimated from felt accounts in this catalogue are largely speculative. The USGS PDE catalogue since 1975 is quite reliable although earthquake locations and depths are no better constrained than 10–20 km. The catalogue by Engdhal *et al.*[4] includes improved locations and depths. A catalogue assembled by the Indian Atomic Energy Commission since 1985 is considered quite reliable, but is far too short to be of use for seismic risk analysis. Finally, a recent catalogue of felt observations indicating the severity of maximum shaking since 1600, offers helpful information[5]. However, their shaking data are more reliable than the locations and magnitudes of earthquakes that can be inferred to have caused the shaking, although an attempt was made by the authors to locate these earthquakes using quantitative methods. For most earthquakes, however, insufficient data exist to determine their locations.

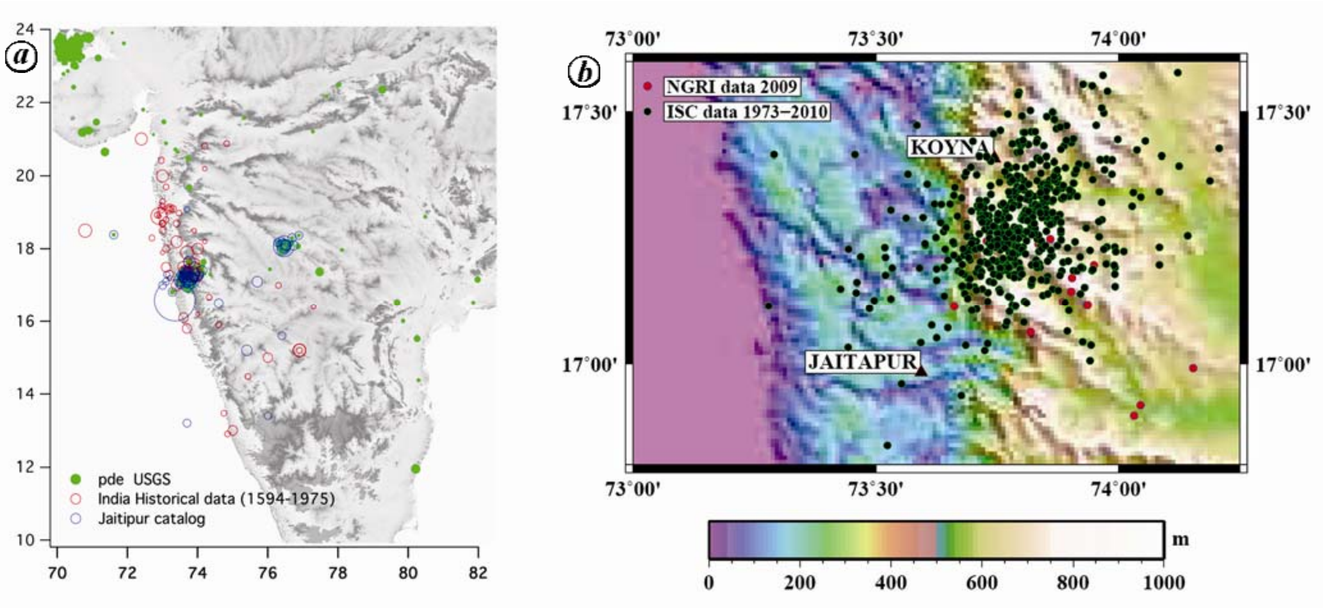

Figure 2. ***a***, Earthquake magnitudes from three catalogues: green – USGS PDE 1985; blue – Jaitapur catalogue, 1975 to present; red – historical earthquake catalogue (NEIC on-line). The red circles are from the least reliable of the catalogues and specific earthquakes are discussed in the text. The large blue circle is 100 km diameter (not an earthquake) centred on Jaitapur. ***b***, More recent earthquakes from the ISC catalogue and NGRI stations operated by S. S. Rai, NGRI, Hyderabad.

Catalogue length and infrequent seismicity

While the historical record in India is surprisingly short as noted above, an important question is: how long is sufficient for a statistical analysis of future seismicity? One answer to this question can be sought from the record of successful statistical risk studies elsewhere by multiplying the length of the records used for their analysis with the ratio of seismic productivity between that area and India. Thus if one concedes that the method has been successful in California with its roughly 200-year historical record and felt earthquakes every few weeks, one might require a 20–50 times longer history for India. viz. 4,000–10,000 years.

A similar answer may be obtained by questioning the duration of the complete earthquake cycle on a fault. Active faults are typically stressed for many years before they slip in a few seconds, or minutes, substantially relieving the accumulated interseismic stresses. The fault subsequently locks, and the cycle repeats again. At plate boundaries the recurrence interval is a century or two, depending on relative plate motion rates. In India we know of no fault that has historically completed this cycle of stressing and failure. The low observed geodetic strain rate suggests that it is possible that the earthquake cycle on faults on the Indian Peninsula exceeds 10,000 years[6]. Statistical studies of the behaviour of such faults may therefore require several thousands of years of data to be of reliable value.

As an example of the pitfalls of assuming that a 200-year history of seismicity is adequate to forecast future risks, consider the unexpected occurrence in 1993, of the $Mw = 6.3$ Latur earthquake, until then regarded as a region of low seismic risk. Had this earthquake not occurred, this region would still be considered as one of low seismic risk. Indeed, it is quite probable (see below), that having recently experienced an earthquake, the region has been destressed and can now be considered as one of low seismic hazard, contrary to indications on current seismic risk maps. Contiguous regions, on the other hand, which are marked with low mapped risk indices may be at a greater risk of future seismicity because of stress transfer from the destressed Latur area.

Historical shaking intensities near Jaitapur

Figure 2 *a* shows all known earthquakes from existing catalogues within 800 km of Jaitapur Green circles are those published by the USGS PDE. Blue circles with sizes proportional to their magnitudes are those listed by Indian agencies responsible for seismic hazard investigations near Jaitapur (here described as the Jaitapur catalogue), and the red circles are those listed in the historical felt catalogue of Martin and Szeliga[5]. The largest earthquake shown is the Bhuj earthquake of 2001, 800 km to the north of the area of interest. An even larger earthquake occurred here in 1819. Although this source region results in only low intensity (MSK III) long-period shaking (≈20 s) at Jaitapur, the narrative that accompanies the Jaitapur catalogue does not mention this intraplate cluster of earthquakes, which are much closer than the Himalayan plate boundary.

Figure 2 *b* shows the locations of recent earthquakes near Jaitapur, taken from the ISC catalogue as well as those recorded by S. S. Rai (pers. commun.) of NGRI.

Figure 3 shows the plot of earthquakes in Figure 2 *a* as a function of distance from Jaitapur. The plot illustrates the shaking intensity anticipated at Jaitapur from these earthquakes. The largest of Koyna earthquakes produced intensity ≈VI shaking at Jaitapur, and the Latur and Bhuj earthquakes resulted in intensity IV.

The magnitudes of many of the pre-instrumental earthquakes are speculative, and Szeliga *et al.*[7], were able to quantify only 235 of the 570 earthquakes felt in

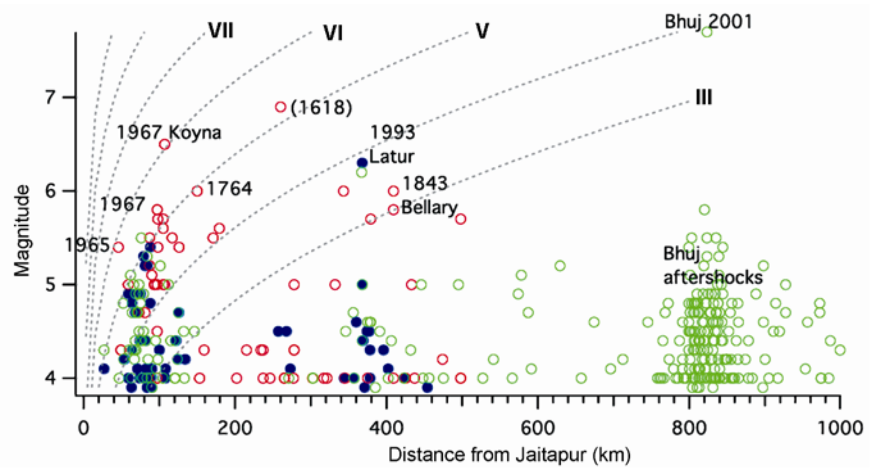

Figure 3. Earthquake magnitude versus distance from Jaitapur from three catalogues. (Blue circles – Jaitapur 1985 catalogue; red circles – historical catalogue (NEIC on-line merged India catalogue) and green circles – USGS PDE 1975 catalogue). The dashed lines indicate the intensity of shaking anticipated at Jaitapur from these indicated earthquakes, e.g. the Bhuj 2001 and Latur 1993 earthquakes which produced intensity III–IV at Jaitapur, and the 1967 Koyna earthquakes resulting in intensity VI shaking at Jaitapur. Attenuation curves were calculated from the attenuation parameters derived by Szeliga *et al.*[7]. The 1618 event in parentheses is a storm with no evidence for intense shaking and should be removed from historical catalogues.

the past 400 years. Some of these listed in the historical catalogue giving both magnitudes and epicentral coordinates include those rejected by Szeliga *et al.*[7]. A striking example is the 1618 Bombay earthquake attributed in the historical catalogue to Oldham (1883), who does not quote his source. This earthquake is of doubtful authenticity at any magnitude, because the event described[8], like the 1737 Calcutta event, appears to be a storm. The account is reproduced below:

> 'In May 1618, six years after the settlement of the English at Surat, "a general and diabolical storm" occurred in the neighbourhood of Bombay (Bombaim as it is termed by old writers). It began at Baçaim on the 15th of that month, and continued with such violence that the people hid themselves in cellars, in continual dread lest their dwellings should be levelled with the earth; The sea, according to the historian of the time, was brought into the city by the wind; the waves roared fearfully; the tops of the churches were blown off, and immense stones were impelled to vast distances; two thousand persons were killed; the fish died in the ponds; and most of the churches, as the tempest advanced, were utterly destroyed. Many vessels were lost in the port. At Bombaim, sixty sail of vessels, with their cargoes and some of their crews, foundered. At Agaçaim, a boat was blown by the force of the wind from the sea into a house, where it killed a woman and her child, and the trees were torn up by their roots.'
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> [Faria Y. Souza *Ásia Portugueza*, Lisbon, 1666–75, translated under the title *The History and Conquest of India by the Portuguese* by J. Stevens, London, 1695. The text was researched by Stacey Martin, who identifies the location of Agaçaim with Agashi, and Baçaim with Bassein.]

The intensity predictions of Figure 3 at Jaitapur are theoretically derived for 17 calibration earthquakes in India using the attenuation curve of Szeliga *et al.*[7], for which both intensities and instrumental magnitudes and locations were available:

$$\text{Intensity (MSK)} = 3.67 + 1.28Mw - 0.0017R - 2.83 \log(R),$$

R being the distance from the earthquake.

An instructive way to view historical shaking intensities is to plot the maximum intensity recorded in each area of India (Figure 4). In this view, the reported intensity data for Jaitapur lie within a region of intensity VI shaking. Many of these earthquakes are associated with the reservoir-induced 1967 $Mw = 6.4$ Koyna earthquake and its aftershocks, and may be considered anomalous. We note, however, that the Koyna earthquake signifies a region that prior to reservoir impoundment was highly stressed. As the stresses in the region are likely to be similar over hundreds of kilometres, the Jaitapur region must be considered to be similarly stressed.

Geodetic strain in India

Rocks fail to create an earthquake rupture at a failure strain value of approximately one part in 10,000 (10^{-4} strain = 100 microstrain). The rate at which earthquakes recur (seismic productivity) thus depends on the tectonic strain rate in a region. For example, the mean rate of strain at a 100-km wide plate boundary where relative motions of 10 cm/yr occur, is of the order of 1 microstrain/yr, and an earthquake on a given fault will repeat every 100 years or so. A strain rate of 1 nanostrain/yr would extend this renewal time to 100,000 years. In the interior of the Indian Plate there are numerous faults, but the rate of strain evaluated using GPS methods, is very low[6,8] – 0.3 ± 0.05 nanostrain/yr. The replenishment of failure strains on an existing fault at these low strain rates would thus take 300,000 years. This means that no fault in the Indian subcontinent should slip more frequently than three times in a million years, accounting for the fact that earthquakes have never been observed to rupture the same fault twice in India – the historical record is far too short.

In some areas of India the rate of seismic productivity appears to be higher than elsewhere, apparently defying the above conclusions. For example, the Kachchh region experienced a $Mw = 7.9$ earthquake in 1819 and a $Mw = 7.6$ earthquake in 2001. However, the two earthquakes were not on the same segment of the fault, and the 2001 earthquake was shifted by at least one fault rupture length to the east. These earthquakes are therefore not repeats of each other. To explain their close occurrence, it is necessary to invoke either an underlying weakness or a local excess in stress that selectively prefers this part of India to rupture. Several explanations have been proposed for these local conditions.

Elsewhere in India, the low strain rate and the rare incidence of recent or

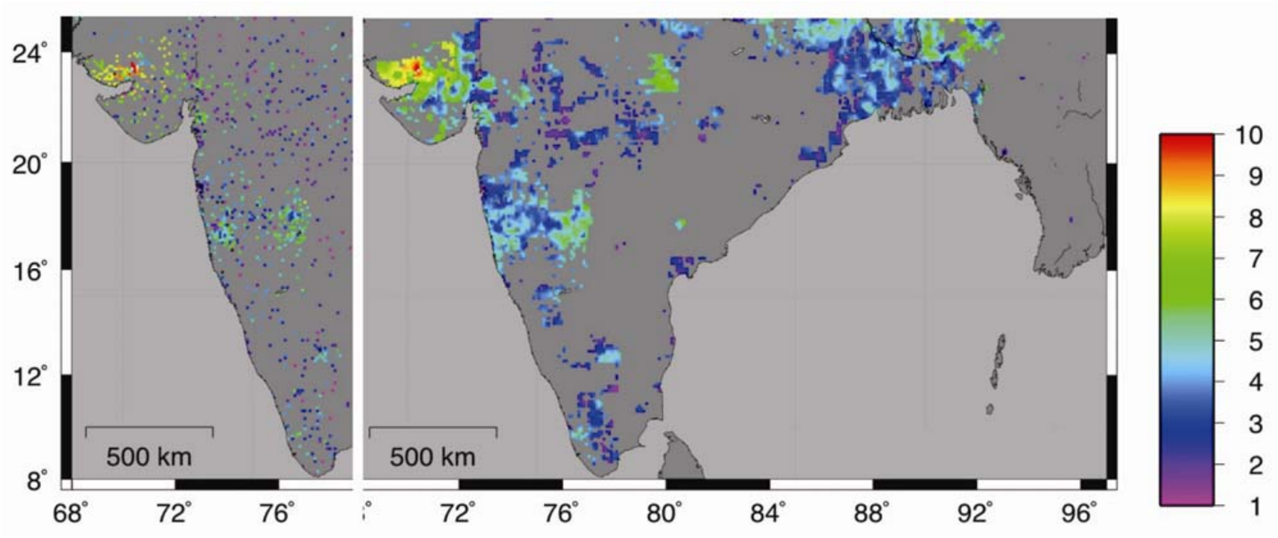

Figure 4. Raw intensity observations (left) and maximum intensities per 20 km box (right) from Martin and Szeliga[5]. The Jaitapur region using a 'nearest neighbour' analysis (right) has historically experienced MSK intensity VII (scale on the right). It is probable that the band of high intensity shaking between latitudes 16° and 20°N will eventually extend across India in response to the flexural downwarping.

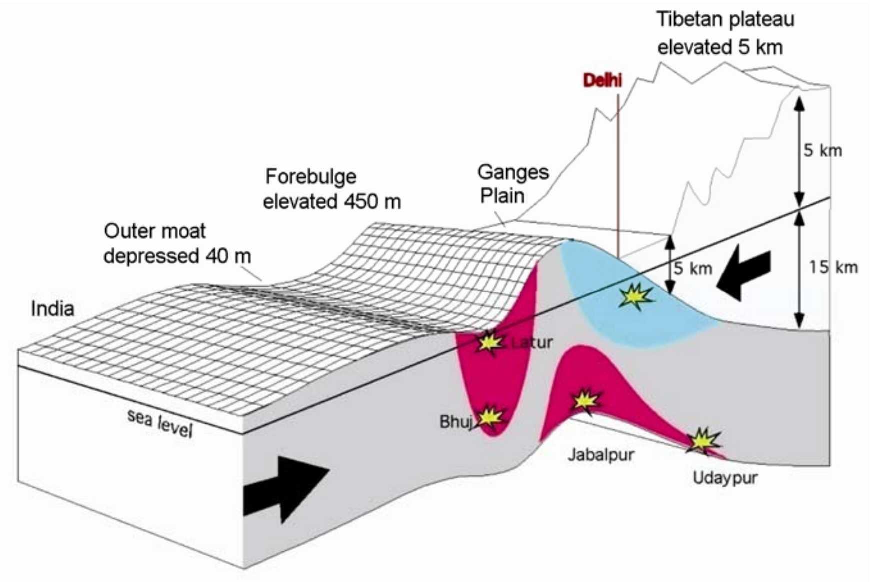

Figure 5. Cartoon showing schematically the flexure of India caused by its collision with the southern edge of the Tibetan Plateau. Jaitapur lies in the flexure trough that is the locus of the Latur and Koyna earthquakes (from Bilham *et al.*[2]).

historical earthquakes means that we must expect many thousands of faults to be close to failure. These faults presumably can experience earthquakes at any time, triggered by minor variations in stress loading, or by minor reductions in friction. The main Koyna earthquake of 1967 was triggered by the first of these effects, and its continuing sequences by the second. It is unlikely that the Jaitapur region is immune from subsurface faulting, but it is not known whether the subsurface hosts any faults sufficiently large to permit rupture in an earthquake similar to the 'unexpected' earthquakes of Latur and Koyna.

Flexure of India

As explained earlier, the Indian Plate is unique among the world's continental plates in that it is flexed by its collision with the Tibetan Plateau resulting in belts of buckling parallel to the Himalaya that extend southward, deep into the plate interior (Figure 5). The northern edge of the plate is depressed by several kilometers, placing its upper surface in tension and its lower surface in compression. The wavelength of buckling is large (>600 km) and is less manifest in its topography than in the gravity field for it has raised the earth's denser mantle beneath the central Indian plateau. The stresses associated with this large wavelength flexure account for normal faulting near Delhi and beneath the Ganges plains, and for thrust faulting and strike-slip faulting at depths beneath Jabalpur. South of the crest of the flexural bulge the Indian Plate is depressed ≈40 m in the form of a wide trough. The amplitude of the trough is too small to be seen amid the topographic roughness of the plate. This flexural depression, however, results in high compressional stresses near the surface of the plate and tensile stresses at the base of the plate. These high compressional stresses are believed to be responsible for the thrust faulting that produced the Latur earthquake, and are presumably also responsible for the faulting in the Koyna region. The Jaitapur region lies in this same compressional downwarp.

The flexural shape of India takes the form of a wave that is static in space, locked to the southern edge of the Tibetan Plateau, whereas the rocks of India stream through this wave at a rate of roughly 2 cm/yr. Thus as the surface rocks of southern India move northwards, they first encounter compressional stresses near the latitudes of Mangalore to Madras, and after many million of years as they approach the central Indian plateau, they encounter tensile stresses. The rate of stressing is less than 1 bar/millennium, so that earthquakes are slow to be brought to failure conditions; yet because the process has been operative for tens of millions of years, numerous faults are expected to be currently close to failure throughout India[2].

Using the assumption that stress is at a critical level everywhere in India, the length and depth of a geological fault can provide a measure of the largest possible earthquake that can occur in the region. This assessment of the capability of a fault is based on physical laws[9] and empirical relationships[10] established for faults elsewhere. A knowledge of the distribution of surface and subsurface faults near Jaitapur is therefore an important factor in characterizing local seismic hazards, although it is not considered in this review because we have found no published geological studies characterizing surface or subsurface faulting in the region. Mapped surface faults in India are rare and their absence in geological maps may be inconclusive since they are commonly associated with insignificant slip, that has accumulated at infrequent intervals. Traces of recent activity are quickly covered by surface soils. The Latur earthquake, for example occurred on an unmapped surface fault[11]. Subsurface faults (deeper than 5 km, say) are difficult to study using traditional paleoseismic methods. We have found no publically available information on seismic imaging near Jaitapur that may have mapped its subsurface structures.

Although it is possible that the marine terrace underlying Jaitapur is the flank of an offshore normal fault system, Vita-Finzi interprets[3] this long wavelength marine terrace as the expression of one of several long wavelength buckles indicating India's active flexural deformation.

The combined consequences of the high incipient state of stress in India and the observation that the rate of stressing is so slow that no fault has yet been observed to slip twice in its recent or extensive history, means that there presumably exist numerous faults that represent seismic hazards that as yet we know nothing about. In a plate boundary setting such as California, alternative methods can be devised to examine faults that slip at long intervals. These largely depend on excavation of their surface traces. Many of India's faults, however, do not reach the surface, and their examination using traditional palaeoseismic methods is not feasible.

Discussion

We show that earthquakes in central India in the past few centuries have frequently shaken the Jaitapur region with intensity VI ($\approx 0.1\ g$) and a statistical analysis suggests that intensity VII shaking is not an unreasonable expectation, although it has not been recorded directly. These low levels of shaking result from earthquakes at moderate distances from Jaitapur.

In the past few decades no microearthquakes have occurred in the immediate vicinity of Jaitapur, a circumstance that can be interpreted in two ways. Jaitapur may be located on a strong core of unfractured rock, or it could be a region of high stress like the neighbouring parts of India, with low ambient seismicity, but subject to slowly varying flexural stresses, close to failure levels. On the one hand, the absence of microearthquakes at the time of large shocks elsewhere, suggests that the Jaitapur region acts as an aseismic block[12]. On the other, absence of aftershocks in Jaitapur can be interpreted as an indication that no large earthquake, i.e. stress relief has occurred in Jaitapur within the past several centuries, since aftershocks in stable continental regions are long-lived indicators of a previous large earthquake[13].

In contrast to these comforting possibilities, the occurrence of earthquakes of up to $Mw = 6.5$ on faults near Koyna and Latur at approximately the same latitude as Jaitapur is of considerable concern, since the stress regime near Jaitapur cannot differ substantially from these two areas when viewed from a flexural perspective. Moreover, the occurrence of the nearby Koyna earthquake has presumably loaded the Jaitapur region closer to failure as a result of Coulomb stress transfer[14].

Vita-Finzi[3] concurs that the sub-peninsula is flexed but offers an alternative geometric interpretation of the crests and troughs, and the wavelength of buckling applicable in the Indian plate. Specifically he interprets the Ratnagiri marine terrace, which at Jaitapur is manifestly 25 m above sea level, as a flexural high.

Conclusion

The historical seismic record near Jaitapur extends reliably back for only 200 years, with scant additional data prior to 1800. Due to the long interregnum between earthquakes in continental India (millennia), historical seismic data from a few hundred years cannot be taken as a guide to future seismic hazard. Because of low strain rates and therefore low seismic productivity in the plate interior, reliable hazard figures are difficult to be estimated as these require a knowledge of earthquake history for at least a 1000 years, preferably more. Geological studies are unavailable to characterize the millennia-long seismic history.

Unhappily, however, the apparent seismic quietness of Jaitapur does not mean that a severe earthquake cannot occur there. If stress in the region is sufficiently mature to have brought an existing subsurface fault close to failure, an earthquake may be imminent. It is our opinion that insufficient data are available to exclude this possibility. With the possible exception of Koyna and Latur, which have recently been relieved of local tectonics stresses, no shallow fault between lat. 16°N and 19°N may be invulnerable to future $M \geq 6$ rupture. While this may be considered of low probability, it is nevertheless possible, and as the recent earthquake in Japan has demonstrated, it is relevant to plan for all possible futures in the design of nuclear power plants.

Appendix 1. Catalogues available for the study of the Jaitapur region.

India, 1063–1984

http://earthquake.usgs.gov/earthquakes/eqarchives/epic/code_catalogue.php

From the USGS webpage, 'This is a combination of four catalogues (Tandon, A. N. and Srivastava, H. N., 1974; Chandra, 1977; Rao and Rao, 1984; Srivastava, H. N. and Ramachandran, 1983). See the authority column for the catalogue identification. The entries that could be identified as duplicates from the four catalogues have been eliminated from the final listing. The abbreviations that identify the magnitude source are listed in the publication by Rao and Rao, 1984.'

The catalogue is untrustworthy in that several events listed may be spurious. As an example, an earthquake near Mumbay in 1618 is listed with a magnitude of 6.9 and attributed to Oldham (1883). The entry in that catalogue reads '26 May 1618–Bombay, etc. accompanied by severe hurricane. 2000 lives and 60 vessels lost at Bombay', without authority. A modest earthquake in 1668 ($M << 7$) now known to have occurred near Nasirabad in Sind Province is attributed a magnitude of 7.6 and assigned an incorrect location.

USGS/NEIC, 1973–present

PDE catalogue of earthquakes located by the USGS NEIC and its predecessors in the US Coast and Geodetic Survey, the National Oceanic Survey, and the Environmental Research Laboratories of the Department of Commerce. Listings are from three different publications. PDE, Preliminary determinations of epicenters, monthly listing. This list is the most complete computation of hypocentres and magnitudes done by the USGS NEIC. It is normally produced a few months after the events occur. The publication is called 'preliminary' because the 'final' computation of hypocentres for the world is considered to be the *Bulletin of the Internation Seismological Centre* (ISC), which is produced about two years after the earthquakes occur. The NEIC PDE programme contributes about one-third of all data used by the ISC.

Martin and Szeliga

This list of almost 8000 uniformly assessed intensities for more than 400 years of earthquakes provides the raw data for the assessment of pre-instrumental earthquakes.

http://www.seismosoc.org/publications/bssa_html/bssa_100-2/2008328-esupp/TableS1.html
file:///Users/rogerbilham/Sites/public_html/Martin&SzeligaTableS2.webarchive (S2intensity observations)
file:///Users/rogerbilham/Sites/public_html/Martin%20and%20Szeliga.webarchive (article)

Jaitapur catalogue

This is an earthquake catalogue from 1973 onward, collected by Koyna Bandkam Vibhag and India's Marine Engineering and Research Institute, supplemented by the Nuclear Power Coorporation of India-funded micro-earthquake array around Jaitapur installed by the National Geophysical Research Institute, Hyderabad.

India Meteorological Department catalogue

The NDI database for India is searchable on-line from 1998 onward at the ISC website. The catalogue includes several $M > 3.5$ earthquakes within 50 km of Jaitapur for which focal mechanism solutions are available. The dominant mechanism appears to be shallow normal faulting on north striking faults.
http://www.isc.ac.uk/search/bulletin/index.html

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