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Earthquake Safety for Tall Statues Higher than 100 m

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ABSTRACT

Seismic considerations about the tall statues (taller than 100 m) in the world have been brought out. These include the tall structures of Gautam Buddha in China and Myanmar, Sardar Patel statue and proposed ones at Mumbai (Chhatrapati Shivaji Maharaj) and Ayodhya (Sri Ram) in India. Emphasis has been given to the proposed statue at Ayodhya, District Faizabad, Uttar Pradesh due to significant tectonic features and liquefaction potential. Keeping in view the extension of Lucknow fault up to Faizabad ridge or a fault along the Saryu (Ghagra) river near the junction of Faizabad ridge and adjoining alluvium, maximum magnitude of earthquake near the site has been assessed as 6 making this area near seismic zone IV instead of zone III according to the seismic zoning map prepared by the Bureau of Indian Standards. In addition, a great earthquake (Mw 8) originating in the Himalayan thrust may generate secondary meizoseismal area near Ayodhya on the banks of river Saryu with a possibility of liquefaction. A range of possible scenarios are discussed with respect to the peak ground motion (PGA) at the proposed site. However, there is a need for further investigations for its reliable estimate.

Keywords: *Earthquake resistant, Significant tectonic features, Tall structures and Peak ground motion.*

1. Introduction

Several very tall statues higher than 100 m have been built in different parts of the world like (i) Sardar Vallabhbhai Patel at Narmada district, Gujarat, India (182 m), (ii) Buddha (Vairocana) at Leshan, China (128 m), (iii) Buddha (Gautama) at Khatakan Taung, Sagaing region, Myanmar (116 m). Tall statues at Mumbai and Ayodhya are also under consideration. The proposed tallest statue (221 m) of Shri Ram in Ayodhya, District Faizabad in Uttar Pradesh near the banks of the Saryu river is susceptible not only to earthquakes originating at nearby faults like Lucknow and Patna but also the great earthquakes originating in the Himalaya. Hough and Bilham (2008) reported that seismic intensities are 1 to 3 units higher near the major rivers as well as at the edges of the Ganga basin based on the data recorded during 1905 Kangra and 1934 Bihar Nepal earthquakes. Major liquefaction in the Gangetic plains was reported during the 1934 Bihar Nepal earthquake (Dunn et al., 1939). The epicentres of the earthquakes of 1505 and 1803were possibly located in Uttarakhand and its neighbourhood but they produced large scale liquefaction features more than 300 km away up to Mathura and Agra respectively due to proximity of Yamuna River (Srivastava et al., 2013a). The 2001 Bhuj earthquake caused damage to multistoried buildings as far as Ahmedabad and Surat (Srivastava et al., 2013b). The possibility of the development of such secondary meizoseismal areas (Srivastava et al., 2010) near Ayodhya from the epicenters of great earthquakes and their seismological characteristics need discussion. In the design of the Sardar Patel statue on Narmada river banks, wind effects caused by the tropical cyclones were also included but their influence is less important at Ayodhya. The effects of severe winds caused by the low pressure areas or depressions during the southwest monsoon will be much less as compared to the tropical cyclones and hence need not be considered for statue in Ayodhya. Only if a tornado forms in the vicinity of the statute, the violent winds could affect the structure but the possibility of such occurrence is very rare.

The objective of this paper is to review the seismological aspects in the regions of the large statues in the world namely China, Myanmar and India where statues taller than 100m have been designed or under design. More emphasis has been given to the seismological aspects for the proposed tallest statue of Sri Ram keeping in view earthquakes likely to occur at nearby faults as well as distant major/great earthquakes in the Himalaya. Besides the possibility of soil liquefaction due to its proximity to the Saryu River is also examined.

2. Geology and Tectonics around the Tall Statues

(i) The tall Buddha statue in Leshan, Sichun, China is located in a region with active faults like the Longmenshan fault, Xianshuihe fault, and Anninghe fault. The 2013 Mw 6.8 Leshan earthquake in southwest Sichuan province, China occurred in the southwestern end of the Longmenshan fault zone and is attributed to blind thrust fault. Another very large and destructive earthquake in the region occurred on May 12, 2008 (Mw7.9) which ruptured the same fault for over 240 km causing very large number of geohazards. However, the statue was undamaged by this earthquake.

(ii) Buddha (Gautama) at Khatakan Taung, Sagaing region, Myanmar is located in a seismically active region where the eastern boundary of the Indian plate passes from Indo Myanmar border to the Andaman Islands. Inside Myanmar, the second most active tectonic feature is dextral strike slip Sagaing fault towards east of the tall Buddha statue in Monywa township, Sagaing where destructive earthquakes have taken place in the past. An earthquake of magnitude 6.0 occurred in the Saigiang region on 31 August 2019 but without causing any damage to the Buddha statue.

(iii) The statue of Unity of Sardar Patel has been located on Sadhu hills close to Sardar Sarover Dam in Narmada River in Gujarat. There are three failed rifts of Kutchch, Cambay and Narmada in Gujarat. The largest earthquake of magnitude near 8 occurred in the Kutchch region. Along Narmada rift zone, severe earthquakes of magnitude around 6 occurred in 1970 at its western end and further east in 1927 (Son), 1938 (Satpura) and 1997 (Jabalpur).

(iv) The statue of Chhatrapati Shivaji is located on a rock outcrop in the Arabian Sea close to Bombay i.e. 2.4 km west of Nariman point and 1.2 km from Raj Bhavan. The penvel flexture is a significant tectonic feature in the region. The NS trending Mumbai High East fault is the major tectonic trend along which the higher fracture density is inferred. The Mumbai Basin formed due to extensional tectonics during rifting of the Indian plate from Madagascar in the upper-Jurassic lower-Cretaceous and is characterized by longitudinal extensional faults giving rise to a series of horsts and graben features. Some effects of the Koyna earthquake, 1967 (M6.5) have been recorded at Mumbai.

(v) The statue of Sri Ram has been proposed at Ayodhya in Uttar Pradesh near Saryu River. The alluvial plains of the Ganga extend between the Himalayas to the north and the shield to the south. The Ganga basin is surrounded on the north and south by positive gravity anomalies (Sastri et al., 1971). The foredeep of the Himalayan arc is covered by very deep alluvial deposits. Faizabad ridge is the northeast extension of the Bundelkhand granitic massif with a thin Neogene cover into the central part of the Ganga basin. It extends further towards the Himalayan foot hills. The NE-SW trending Faizabad ridge is the most prominent structure of the Ganga basin (Figure 1). The Ganga basin is divided into sub-basins by the Faizabad ridge (Dasgupta et al., 1987). This ridge meets the Lucknow fault which intersects the course of Ganga. (Valdiya, 1973; Sinha et al., 2005). Figure 1 also shows Ayodhya fault whose extent needs further study. Basement depth map of Ganga basin is discussed by Ahmad and Alam (1978). The proposed statue at Ayodhya falls under Faizabad district in the central Ganga plain and is overlain by thick pile of alluvium made up of clay, silt, kankar and sand.

The tectonic features for this region are the main boundary thrusts in Himalaya, Lucknow and Ayodhya faults (Figure 1). Since detailed tectonic mapping of the area has been constrained due to thick alluvium cover, it is difficult to estimate hidden faults in the region. However, geophysical investigations have been suggested to work out a reliable seismic hazard assessment of the site.

Catalogue of earthquakes (IMD, USGS, ISC or Tandon and Srivastava, 1974) do not show the occurrence of a significant earthquake near Ayodhya. However, significant earthquakes are noted in the nearby Himalayan region (Figure 2).

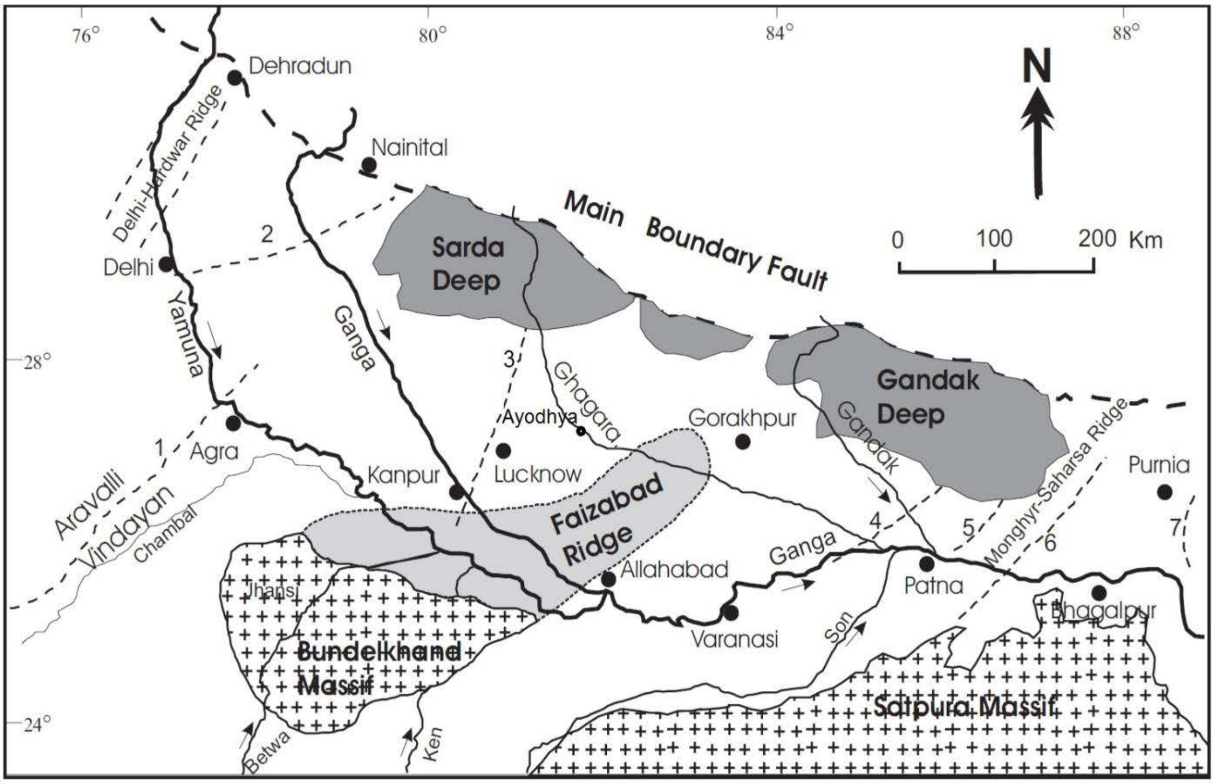

Figure 1: Subsurface geology and tectonic in and around Ayodhya. 1-Great Boundary Fault, 2-Delhi-Moradabad Fault, 3-Lucknow Fault, 4-West Patna Fault, 5-East Patna Fault, 6-Monghyr-Saharasa Ridge Fault, 7-Malda-Kishanganj Fault (Based on Sinha et al., 2005).

During the 1934 Bihar Nepal earthquake, the seismic intensity at Ayodhya was estimated as VI MM (Dunn et al., 1939). Due to the directivity effects, the seismic intensity at Ayodhya was only VMM during the 2015 Nepal earthquake. No information on local earthquakes is available as microearthquake survey was not carried out so far.

3. Structural Designs of the Tall Statues

The tall statues in China and Myanmar have been designed in seismically active regions but their details are not available.

Sardar Patel statue is located on Sadhu island in the Narmada River, 3.2 km away from the Sardar Sarover Dam. Considering the active seismicity of the region, the statue has been designed for the maximum earthquake of magnitude 6.5. Its structural design was based on the Indian Standards codes including IS: 875-1987, IS 1893-2002, IS 456-2000 IBC 2009, ASCE7 10, ACI 31808, AISC 325-05 as well as reference to British Standards (BS 7543) for durability considerations. Wind loads were calculated based on IS 875 Part 3- Code of practice for design loads for buildings and structures.

The statue of Shivaji Maharaj has been designed according to seismic zone III of the Bureau of Indian standards. Further this structure is also designed to withstand wind forces during the cyclonic storms.

In view of the significant tectonic features in the region, design features of the proposed tallest statue at Ayodhya are discussed in the following.

4. Seismotectonic Model

In order to evaluate the seismotectonic model, the following data are required:

(i) Historical and instrumental catalogue of earthquakes, isoseismal maps including maximum seismic intensity expected at the site, focal mechanism of earthquakes, peak ground acceleration, shaking duration and source directivity.

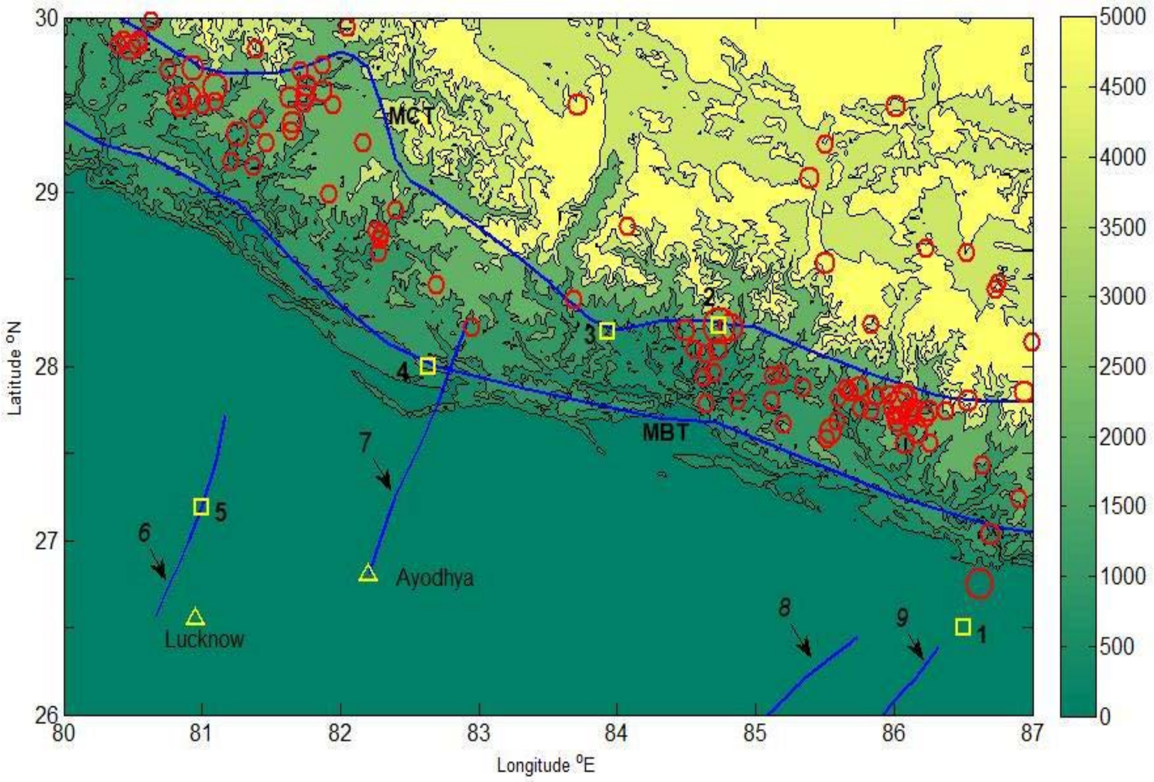

Figure 2: Significant earthquakes and topography (in m) near Ayodhya. (1) 1934 Bihar-Nepal earthquake, (2) 2015 Nepal earthquake, (3) Hypothetical earthquake on MCT, (4) Hypothetical earthquake on MBT, (5) Hypothetical earthquake in Lucknow fault, (6) Lucknow fault, (7) Ayodhya (Faizabad)–Pyuthan Lineament, (8) West Patna fault, (9) East Patna fault. The tectonic features 6 to 9 are based on Dasgupta et al. (1987). MBT, MCT are based on Balakrishnan et al. (2009). Epicentres of earthquakes of magnitude 5 and above during 1964 to 2018 from US Geological Survey are shown in red circles in three sizes: smallest size shows magnitude 5 to 5.9, middle size 6 to 6.9 and largest size 7 to 7.9.

It may be mentioned that the duration of strong ground motion is considered important for nonlinear response (Lee, 2002).

(ii) Geology regional and local site response, dynamical behaviour of soil or rock, predominant period of ground and liquefaction potential. The amplification of ground motion due to the local site condition plays an important role in the damage during earthquakes. This is supported by significantly larger values of peak ground acceleration (PGA) recorded at soft soil sites during several earthquakes. The PGA was 0.11gal at the passport office building at Ahmedabad city at a distance of about 240 km from the epicentre of 2001Bhuj earthquake and was attributed to peculiar geological structure of Ahmedabad basin.

5. Specific Considerations

5.1 Maximum magnitude

(i) The maximum magnitude of an earthquake in a region is an important parameter in earthquake hazard assessment. The usual methodology to assess the largest magnitude of an earthquake in the region is based on the seismotectonic model using the past earthquake data and the tectonics of the region. In a place like Ayodhya, we need to consider the largest earthquake expected locally as well as distant effects like site response due to a major (Mw8) earthquake originating in the Himalayan thrusts. Considering the differences in the tectonically active Himalaya region with that of island arc, past seismicity and the extent of respective locked zones, Srivastava et al. (2013c) showed that the largest magnitude of an earthquake in the Himalayan region cannot be as large as in subduction zone. Srivastava et al. (2013a) further divided the Himalayan region into two types of seismic gaps. The region where earthquakes of magnitude 8 or more have occurred in the past are categorised as seismic gaps of ~~c~~category 1, which includes Kashmir, west Himachal Pradesh (Kangra), Uttarakhand (Dharachulla), central Nepal to Bihar, Shillong, Arunachal gap extending up to Assam. On the other hand, the category 2 of seismic gap include Jammu Kishtwar block, east Himachal Pradesh, western Nepal (excluding Dharachulla) and Sikkim Bhutan. Among these gaps, the importance of the central Nepal Bihar gap assumes greatest importance for Ayodhya since it is the nearest seismic gap where 2015 Nepal (Mw7.8) and 1934 Bihar Nepal (Mw8.0) earthquakes occurred in the past. Thus for design purpose, the largest magnitude of 8 near the main boundary thrust in the Himalaya could be adopted for the statue at Ayodhya. However, as mentioned earlier, the magnitude of a local earthquake on nearby Lucknow fault extending up to Ayodhya or a fault along Faizabad ridge and adjoining alluvium may be taken as 6. Statistical method to compute the maximum magnitude taken for design purpose has been described by Srivastava et al. (2007, revised 2020) but the same cannot be used in the present case due to the limitations of data.

(ii) Singh et al. (2002) estimated the peak ground acceleration at Delhi from a hypothetical earthquake of magnitude 8 in India Nepal border as 96 and 140 gals on soft grounds. For 8.5 magnitude, the corresponding values are 174 and 218 gals. For hard sites, the values were 3 to 4 times less than the soft sites. Kumar and Khandelwal (2015) found bimodal attenuation trend based on the strong motion data of 4 April 2011 Nepal earthquake (M 5.7). Higher H/V ratio was found for the closer distances up to 100-150 km while the other trend was observed beyond 1000 km implying site effects. This observation supports the view that site response effects at Ayodhya due to a major/great Himalayan earthquake needs to be considered similar to that observed during 1803 and 1505 earthquakes.

5.2 Soil liquefaction and site response

Liquefaction of the soil due to large earthquakes arises due to transformation of granular deposit from a solid state into liquefied state by the increased pore water pressure depending on the anomalous propagation and amplification of the seismic waves at the surface. It also depends upon the site condition, grain size and density of deposits and the ground water level. The consequence of this phenomenon is the differential settlement causing tilting of buildings or total loss of foundation support. Since the proposed statue to be located at Ayodhya near Saryu river, this phenomenon needs to be examined keeping in view 1803 and 1505 earthquakes (Srivastava et al., 2013a) during which liquefaction effects were observed as far as Mathura and Agra respectively.

Laboratory and field studies have shown that the phenomenon of liquefaction depends on the earthquake magnitude, shaking duration, peak ground motion (acceleration/velocity), depth of ground water table, basin structure, site effect and susceptibility of sediments to liquefaction. Generally empirical relations between the earthquake magnitude and the epicentral distance have been worked on the basis of liquefaction observed during the past earthquakes. But in current engineering practice, the assessment of liquefaction is based on the ground penetration test. One of the key parameters in assessing soil resistance to liquefaction is given by N value which is determined by the standard penetration test at 1.5 m depth intervals through a hollow thick walled steel tube at the bottom of a bore hole. Special accelerometers and strain gauges are used to calibrate each rig. The other method to study liquefiable deposits makes use of cone penetration technology (CPT) to obtain continuous readings in vertical soundings. This method consists of electronic steel probe, pore pressure transducer and velocity geophones inside the seismic piezocone penetrometer. In this technique, a light weight truck with 20 tons capacity hydraulic system is used to push the penetrometer to a depth of 20 to 40 m.

Another useful parameter in assessing soil resistance to liquefaction is the shear wave velocity to measure stiffness of the soil by surface crosshole or downhole techniques. Two or more cased and grouted boreholes are dug to permit entry by the vertical geophones and downhole hammer source as well as slope inclinometer surveys of the boreholes for accurate path distance determination. Seismic reflection and refraction methods are used in the multichannel surveys to determine the variation of the shear wave velocity with the depth. Surface wave analysis is done by using the dispersion of short period surface waves to get shear wave velocity profiles through inversion.

Although NDMA (2010) attempted a probabilistic hazard map for the Indian region, it could not be adopted for the proposed site due to meagre data used in the analysis. The influence of smallest magnitude detected or different periods of observational data showed a high degree of variability on the return period of earthquakes (Srivastava and Dattatrayam, 1986). Also, the activity of the local faults cannot be reliably assessed due to absence of microearthquake survey. Hence, the assessment of maximum magnitude in this study could be based on tectonics only.

6. Peak Ground Acceleration (PGA) at Ayodhya

The above assessment of magnitude 6 of a local earthquake close to the proposed statue places the region close to zone IV instead of zone III as per seismic zoning map of Bureau of Indian Standards (BIS). Srivastava and Gupta (2004) also suggested that keeping in view 1967Koyna and 1993 Latur earthquakesin Maharashtra, which led to revisions in the seismic zoning map of India, it is safer to design structures corresponding to magnitude 6 earthquake in zone III as well. This is not unrealistic due to the possibility of a fault near the junction of Faizabad ridge and adjacent alluvium or extension of Lucknow fault upto Faizabad ridge (Fig.1). Integrating this with the importance of the structure, it appears safer to design the statue close to zone IV. However, the wind factors may not be considered for the Ayodhya site since the location is far away from the tropical cyclones. Only if the tornadoes strike the region, large wind force could impact it. However, such incidences at Ayodhya are extremely rare.

A large number of statistical relations to estimate peak ground acceleration (PGA) are available based on the past earthquake data of acceleration recorded in different parts of the world during the earthquakes(Douglas,2003). The usual relation connecting the epicentral distance, magnitude (M), source directivity or the source mechanism and the site conditions are given by (Joyner and Boore, 1981)

$$\log a = -1.02+0.249\ M - \log r - 00255r +0.26\ P \quad (1)$$

for $5.0 \leq M \leq 7.7$, where a is peak horizontal acceleration in gal,$r = (d^2 + 7.3^2)^{1/2}$, d is the closest distance to the surface projection of the fault rupture in km; $P = 0$ for 50% probability that the prediction will exceed the real value and $P = 1$ for 84% probability.. Bolt and Abrahamson (1982) suggested horizontal peak ground acceleration (PGA) as follows

$$a = 1.6\ [(x+8.5\ r)^2+ 1]^{-0.19} \exp\ [-0.0026(x+8.5)] \quad (2)$$

where x is the closest distance from the surface projection of the rupture. Abrahamson and Litchiser (1989) gave the following relation

$$\log a = -0.62+ 0.177\ M - 0.982 \log\ (r + e^{0.284\ M})+ 0.132F - 0.0008\ Er \quad (3)$$

where a is horizontal peak ground acceleration, r is the distance in km closest to the zone of energy release, M is the magnitude of earthquake, F is 1 for reverse or reverse oblique fault otherwise 0, and Er =1 for interplate earthquake = 0 for intraplate earthquake.

In the past, one of the limitations in the Indian region is that strong motion data are limited upto 6 or 6.5 magnitude earthquakes only. However, recently Ambazhagan et al. (2013) obtained ground motion predictive equation considering both the recorded and simulated earthquakes of moment magnitude 5.3–8.7; the equation is given as

$$\log a = c_1 + c2\ M - b \log(X + e^{c3\ M}) \quad (4)$$

where$X= (r^2 + h^2)^{1/2}$,$r$is the closest distance of the rupture,h is the focal depth, c1= -1.283, $c2$=0.544,b=1.792, $c3$=0.381.

Table 1. PGA expected at Ayodhya.

Distance (km) from Ayodhya	Magnitude	PGA (gal)	Equation used
10	6	0.224	(1) with P=0
		0.407	(1) with P=1
		0.453	(4)
20	6	0.124	(1) with P=0
		0.225	(1) with P=1
		0.218	(4)
140	8	0.0294	(1) with P=0
		0.0534	(1) with P=0
		0.130	(4)
231	8	0.0104	(1) with P=0
		0.0190	(1) with P=1
		0.0583	(4)

We have considered local earthquake of magnitude 6 to compute PGA at Ayodhya for distances of 10 km and 20 km. We have also considered a hypothetical earthquake of magnitude 8 on MBT and MCT at the nearest point from Ayodhya which are at distances 140 km and 230 km respectively. We may compute the expected acceleration at the Ayodhya site using the relations developed on global data as well as those of Ambazhagan et al. (2013). Thus we have estimated the PGA values at Ayodhya (Table 1) using the equations (1) and (4) above.If we compare these values of PGA with those obtained theoretically simulated ground motion (Singh et al., 2001), the values are within the range. However, larger intensity or acceleration in secondary meizoseismal areas of large/great earthquakes cannot be reliably estimated by these methods because site effects are ignored in the attenuation relations with the epicentral distance.

An overview of the strong motion data worldwide and the pattern of damage during strong earthquakes showed that different site conditions can induce amplifications at different periods in the response spectra derived from acceleration for different geological conditions or tectonics. Raghukanth and Iyenger (2007) showed that the response spectrum in the Seismic zoning of India (BIS, 2002) under-estimates seismic forces at high frequency for rock sites while at soft soil sites, it overestimates at low frequencies. Predominant period of 0.242 sec for horizontal components and 0.193 sec for vertical componentsand PGA ranging from 3 to 80 cm/sec^2 in the epicentral distance from 120 to 495 km with respect to the main 2015 Nepal earthquake were reported(Sharma et al., 2017). The normalized spectral amplifications were found to be within the structural limits as per BIS code. Hough et al. (2016) compared the observed and predicted ground motions from the same earthquake and found that for nearest fault distances (less than 200 km) PGA ems was consistent with the Atkinsen and Boore (2003) subduction zone ground motion prediction equation(GMPE). At greater distances (>200 km), instrumental PGA values are consistent with this GMPE. It was suggested that the later reflects duration effect whereby effects of weak shaking are enhanced by long duration and or long period ground motions from a large event at a regional distance. Hough et al. (2016) also observed that ground motions were significantly amplified in the southern Gangetic basin but were rather low in the northern basin. In the northeast India, Ansary (2014) found that H/V ratio was estimated as 9 for soil sites based on the data from 2011Sikkim earthquake as well as strong motion data from 2005 to 2013. H/V ratio of Fourier amplitude spectra indicates that soil sites show predominant site frequencies of about 0.6 to 2.5 Hz while rock sites show predominant frequencies between 3 to 5 Hz. These values need to be determined for the site at Ayodhya.

It may be mentioned that the duration of strong earthquake ground motion which determines the rate of energy input into a structure should be considered in the analysis of linear and non-linear structural response. It has also important role in the analysis of liquefaction, permanent displacements of soil and probabilistic assessment of structural response.

If we consider the height of the statue as 221 m, the predominant period of the structure may be about 7 sec. Since the depth of alluvium in region is about 5 to 6 km (Mitra et al., 2011), the period of the surface waves generated from a great earthquake (M 8) in Himalayan foot hills could cause major shaking of the structure but appears to be outside the resonance range . The spectral values of acceleration need to worked out after modelling experiments are carried out in the laboratory and field observations collected.

7. Investigations Required

(a) Fault mapping

(i) Ground penetrating radar surveys to find shallow faults in the vicinity if any and details of the geological and structural features of the subsurface.

(ii) Multichannel analysis of surface waves (MASW) is a very useful method for investigating shallow geological structures (Park et al, 1999). It provides the relative shear strength or shear modulus which is a measure of dynamic ground stiffness. The technique uses geophones at optimum distances and a hammer and plate or buffalo gun as the seismic source. The data recorded are processed to produce dispersion curves for each shot. It is then modelled to produce a depth cross section for the shear wave velocity structure of the ground. The maximum depth of investigation is 10-30 m but varies with sites and types of active sources. Flat or gentle slopes are suitable for such study because topography can be hindrance to surface wave generation. Generally 4.5 Hz vertical component geophones are used for this purpose.

(iii) Microearthquake survey for short time as well as over semi permanent stations is required.

(b) Site response

(i) Dynamic behaviour of soil in the vicinity.

(ii) Predominant period of the ground by microtremors method and earthquakes if recorded.

(iii) Soil liquefaction aspects including CPT and SPT methods in about 50 boreholes in appropriate places.

(iv) Engineering properties: Borehole downhole and crosshole seismic surveys to quantify subsurface engineering properties.

8. Conclusions

The above study has shown that the proposed statue of Sri Ram at Ayodhya may be designed for magnitude 6 earthquake. Site response and other studies need to be conducted at the site for reliable assessment of earthquake risk and liquefaction features.

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