An Earthquake Risk Assessment and the Imperative of Conserving Archaeological Sites in Gujarat, India

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Abstract
The proximity to the convergent boundary of the Indian and Eurasian tectonic plates makes Gujarat a seismically active region in India. It is divided into four earthquake zones: II, III, IV, and V, with V being the most active. Though earthquakes are highly devastating to archaeological sites, among the numerous measures implemented to minimize the impact of earthquakes, they are often overlooked. Earthquakes collapse and displace the fragile structures and stratigraphy of subsurface sites. Therefore, for effective heritage management, assessing the risk of earthquakes before a disaster is crucial. In this study, a risk assessment was carried out for 508 archaeological sites in Gujarat, associated with the Indus civilization and regional Chalcolithic cultures, using hazard, value, and vulnerability parameters. Hazard is the source of harm; value is the significance; and vulnerability is the internal weakness. The earthquake potential was measured using the magnitude and intensity of earthquakes in the last 70 years. The value of archaeological sites was estimated based on their physical structure and tourism potential. The vulnerability was assessed using the three climate change indicators: exposure, sensitivity, and adaptive capacity. The earthquake zones, the state of preservation of sites, and the protected status of the sites served as the parameters for the vulnerability indicators, respectively. The results show that 41 sites are at high risk from earthquakes. Prominent sites include the Dholavira World Heritage Site, Kanmer, Bagasra, and Kuntasi. With this study, an attempt has been made to provide a framework for the risk assessment of archaeological sites.

Keywords: Earthquake Risk, Indus/Harappan Civilization, Dholavira

Introduction

Gujarat, a state in western India, is situated near the convergence of the Indian and Eurasian tectonic plates. The Indian plate moves northward and collides with the Eurasian plate, resulting in active faults. This makes Gujarat an active seismic zone. It is divided into four zones: II, III, IV, and V, with zone V being the most active.

The impact of earthquakes on archaeological sites can vary from displacement of delicate stratigraphy to minor surface disturbances to complete structural collapses. Often, this damage is irreversible. Hence, it is crucial to evaluate which sites are vulnerable before a potential disaster.

Materials

In this study, 508 archaeological sites in Gujarat, India, belonging to Indus/Harappan civilization and regional Chalcolithic cultures are considered. The list of sites has been compiled from previous works (Ajithprasad and Sonawane, 2011; Rajesh, 2011) and ground truthing.

Methods

Here, a geospatial approach (using ArcGIS Pro) was used to evaluate the quantitative risk of archaeological sites by applying the formula.

$$Risk = Hazard \times Value \times Vulnerability \quad \text{(i)}$$

Hazard: Earthquakes with magnitude 5 and above have the potential to cause destruction to any built heritage. Hence, first, a list of earthquakes (Mag≥5) from 1950 was obtained from United States Geological Survey (USGS: https://www.usgs.gov/programs/earthquake-hazards/earthquakes). The hazard was determined by measuring the proximity of archaeological sites to the epicenter and scored from 1 to 3, with 3 being very close (≤30 km) and 1 being very far (≥60 km).

Value: Value was measured using two parameters: physical structure and tourism potential. Sites were categorized into subsurface sites (V=1), sites with structures above the ground (V=2), and sites with structures above the ground that are also tourist places (V=3; high value sites).

Vulnerability: Vulnerability was assessed using the Intergovernmental Panel on Climate Change (IPCC) method. It defines vulnerability as a function of exposure, sensitivity, and adaptive capacity (Parry, 2007).

$$Vulnerability = Exposure\ (E) \times Sensitivity\ (S) \times Adaptive\ capacity\ (AC) \quad \text{(ii)}$$

Exposure refers to the "presence… at a location where harm is experienced if a hazard occurs" (Sharma and Ravindranath, 2019). Sensitivity refers to the "degree to which a system is affected" and adaptive capacity is the "ability to adjust to the change" (Parry, 2007). Over the years, these parameters have been modified and adapted for cultural heritage sites. Exposure has been defined as the presence of conditions that affect negatively such as physical location or the surroundings of the cultural heritage site. Sensitivity is the inherent

susceptibility of a cultural heritage site arising from its physical features. Adaptive capacity is its ability to cope which comes from management, availability of resources, etc. (Paupério et al., 2012; Yıldırım Esen ans Bilgin Altınöz, 2018; Sesana et al., 2020).

In this study, considering the above–mentioned approaches, exposure, sensitivity and adaptive capacity are taken as the earthquake zones of Gujarat, physical typology of the sites, and the management categories of the sites (Table 1).

Score	Exposure	Sensitivity	Adaptive Capacity
Value = 1	Zone III	Subsurface sites, mounds	Unprotected sites
Value = 2	Zone IV	Sites exposed to the environment	Excavated sites
Value = 3	Zone V	Sites damaged in the past or located in Croplands	World heritage site, Protected sites

Table 1: The vulnerability assessment

Risk: The final risk was assessed using formula (i).

Results

Earthquakes: Since 1950, there have been 20 earthquakes with a magnitude of 5 or greater. Most of these earthquakes occurred in the Kachchh region. However, two occurred in the Gir National Park in Junagadh and one in Ankleshwar near Bharuch (Figure 1).

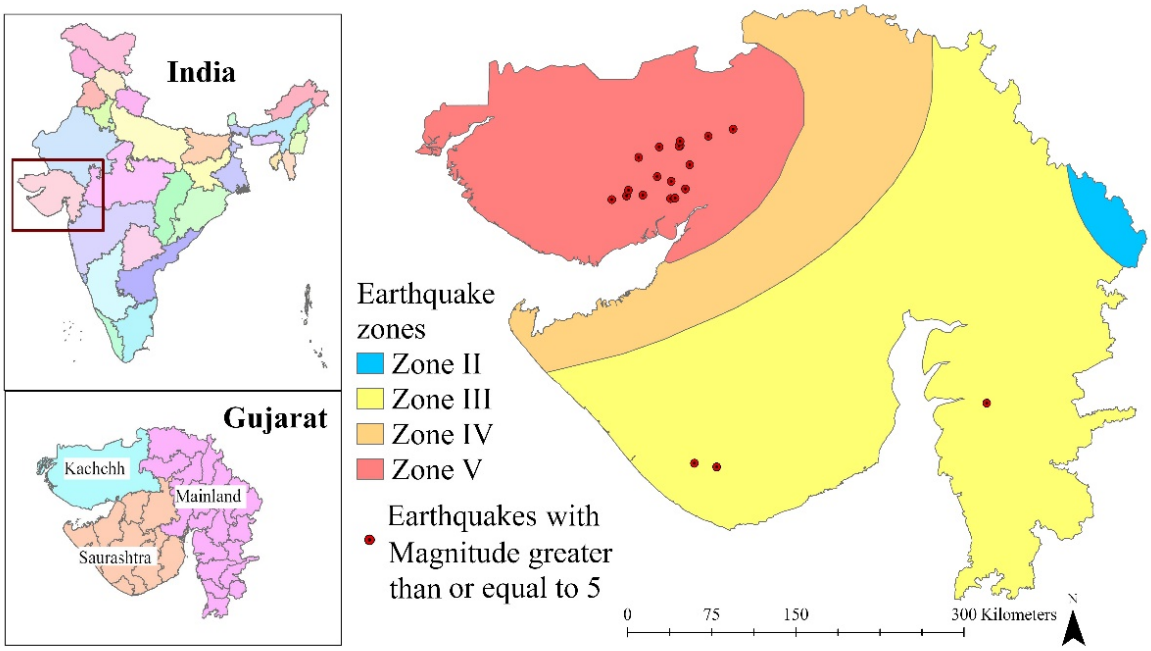

Figure 1: Map showing – Left: The study area – Gujarat; Right: The earthquake zones of Gujarat and earthquakes with magnitude ≥5 since 1950.

Hazard: 51 sites are in high proximity to earthquakes with a magnitude greater than 5, 68 are in medium proximity, and 389 are in low proximity (Figure 2).

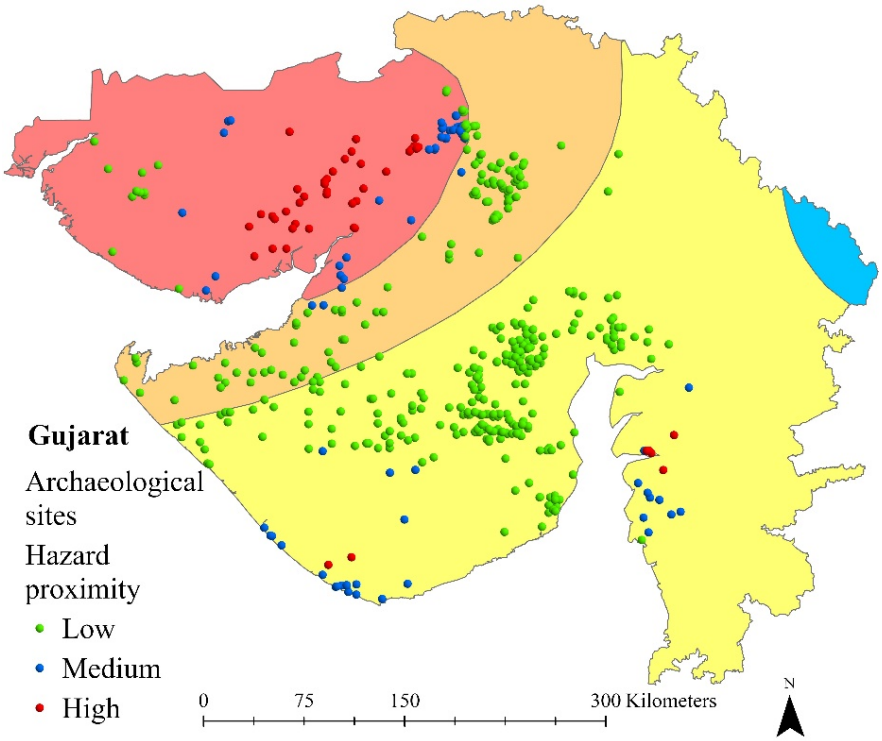

Figure 2: Map showing the earthquake (hazard) proximity of archaeological sites in Gujarat.

Value: Dholavira and Lothal are the most prominent tourist destinations, but there are also 10 more sites with significant archaeological features or visible structures. These sites include Kanmer, Khirsara, Navinal, Juni Kuran, Datrana-I, Bagasara, Kuntasi, Rojdi, Surkotada, and Aai no Dhora. The remaining sites are subsurface (Figure 3).

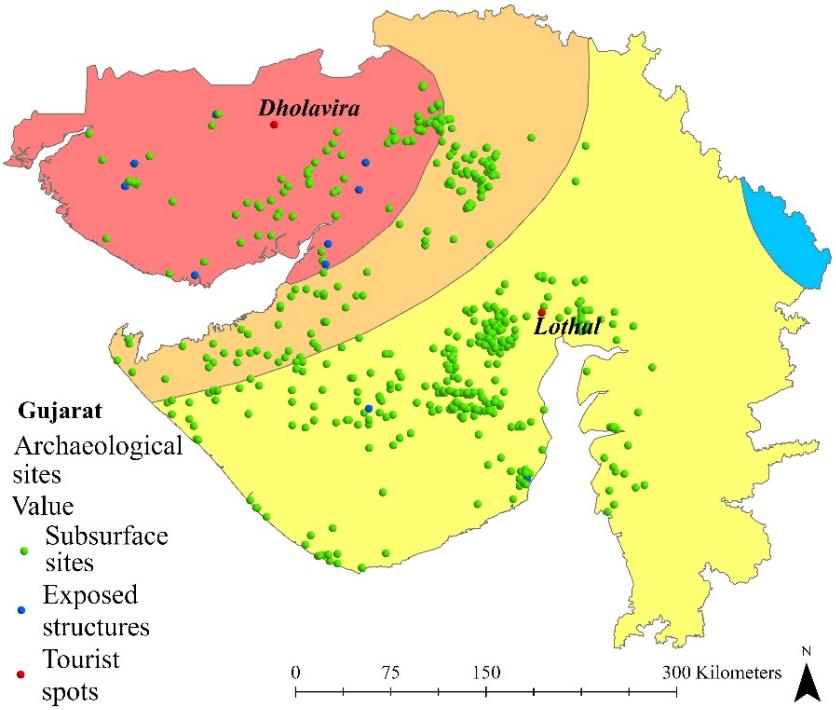

Figure 3: Map showing the division (value) of archaeological sites in Gujarat into subsurface, exposed and tourist spots.

Exposure: 52 are in Zone V, 110 are in Zone IV, and the remaining 346 are in Zone III (Figure 4).

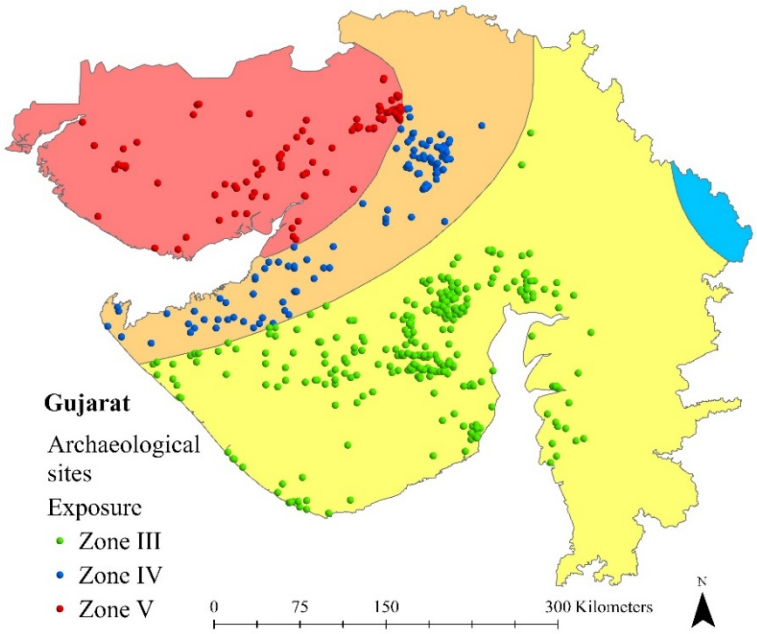

Figure 4: Map showing the location of archaeological sites as per the earthquake zones (Exposure) of Gujarat.

Adaptive Capacity: The sites were classified based on whether they protected sites, (Dholavira, Juni Kuran, Lothal, Rangpur, Surkotada, Vaniavadar, Valabhipur, Bed, Lakhabawal, Mora, Narmana, and Pabumath), excavated sites (n=56, protected sites are not included here), or unprotected sites (the rest) (Figure 5).

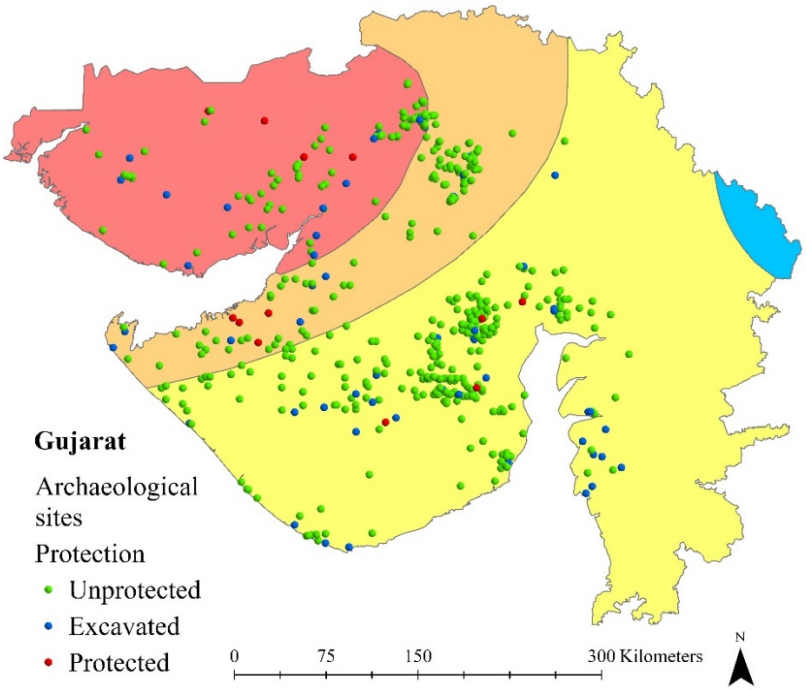

Figure 5: Map showing the management status of archaeological sites in Gujarat (Adaptive capacity).

Risk: 41 of the 508 sites studied are at high risk of destruction from earthquakes. Prominent sites include the Dholavira World Heritage Site, Kanmer, Bagasra, and Kuntasi (Figure 6).

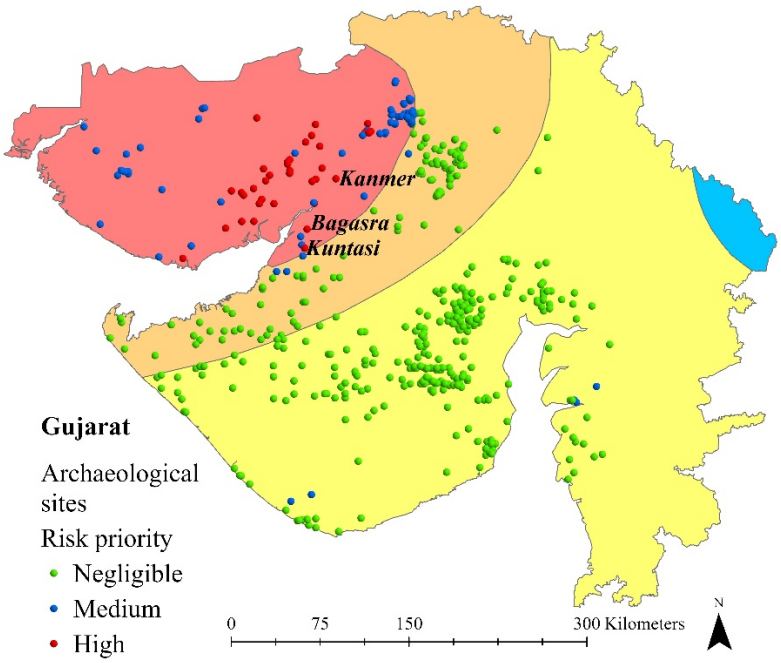

Figure 6: Map showing the earthquake risk priority of archaeological sites in Gujarat.

Discussion

Liquefaction and ground motion are two primary factors of destruction stemming from earthquakes. Ground motion is devastating to fragile archaeological structures. In addition to that, intense ground shaking changes the water-saturated soil to liquid. This change in the state of soil to liquid is called liquefaction which destroys the fragile archaeological stratigraphy.

The archaeological sites at high risk are located in areas with a shallow water table, typically 5 to 40 meters deep, making them susceptible to soil liquefaction. The soils in these areas are predominantly sandy, alluvial, or loamy, which are particularly prone to liquefaction when saturated. These regions also experience high peak ground acceleration (PGA) (Chopra et al. 2013), indicating intense ground shaking that further increases the risk.

Sites	Dholavira	Kanmer	Bagasra	Kuntasi	The rest
PGA (cm/s^2)	800	600	400	300	300–800
Ground water depth (m)	< 10	10 – 40	10 – 40	10 – 40	5 – 40

Table 2: Peak ground acceleration (PGA) and ground water depth of archaeological sites at high risk

Conclusion

In this study, an earthquake risk assessment was done for 508 archaeological sites in Gujarat. Using ArcGIS Pro, the geospatial approach was integrated with the quantitative risk assessment. Risk was taken was the function of hazard, value and vulnerability parameters.

The final calibrations show that in Gujarat, the central part of the Kachchh region is more prone to earthquakes. 41 archaeological sites located there are highly vulnerable to damage from earthquakes. The return period of earthquakes with magnitude 5 and above in this region has been calibrated to be 20 to 29 years (Tripathi, 2006; Yadav et al., 2008). In that case, destruction of archaeological sites is inevitable.

For the Dholavira world heritage site, ground shaking seems to be a major threat. Various previous works have noted significant structural issues such as rotation and tilting of the north gate of the citadel and sinking of the east wall at Dholavira (Dumka et al., 2019). This study recommends seismic retrofitting techniques such as jacketing for these.

The rest of the sites have very few to no structural features above the surface and might not need seismic retrofitting. However, they are prone to liquefaction. Out of 41 only seven sites have been excavated (Datrana III, Datrana IV, Dholavira, Bagasra, Kanmer, Kuntasi, and Navinal). This analysis raises questions about the current existence of unexcavated sites. It is possible that other unexcavated sites have already been destroyed not only by earthquakes but also by other natural hazards such as floods, erosion or modern infrastructure development. Hence, they need to be excavated and recorded.

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