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# Hazard Risk Level Evaluation for Heritage sites in Gujarat, India

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**Abstract.** Heritage sites in India are well known for brilliant architecture, massive structures and stone carvings which symbolizes its cultural and civilizational aspects. Unfortunately, the construction of the glorious past has suffered degra- dation due to events such as earthquake, weathering, vandalism and human neg- ligence, etc. Conservation of these structures are of utmost importance with re- spect to our civilizational and economic value. In the present study, the risk level for 207 heritage sites in Gujarat falling under UNESCO and ASI monuments are evaluated based on the seismic zonation map of India, the seismic hazard and liquefaction hazard study for Gujarat region from literature. The study aims to identify the vulnerable sites by assigning a risk factor to each site with respect to the PGA values of the area based on the three aspects: earthquake zones, proba- bilistic seismic hazard and liquefaction hazard. The different weightages of these three aspects are accounted and the mean risk for each site is evaluated to prepare the hazard risk map of heritage sites in Gujarat. The future direction on how to account the structural condition assessment of the heritage structure to the eval- uated mean risk is also provided by performing condition assessment of UNESCO world heritage site Rani ki Vav.

**Keywords:** Heritage structures; Seismic hazard analysis; Liquefaction; ASI monuments; Condition assessment.

## 1 Introduction

Heritage monuments are integral part of any region's history and culture. It has shaped identity of people for long period of time from different regions to communities. These sites have displayed influence on the political, social and economic wealth of previous generation. It helps future generation to identify the values and priorities in past centu- ries. Conservation of heritage buildings benefits country and government by generating revenue by developing tourism, which directly connected to economic growth and so- cial integrity towards ideology represented by the site.

India has large number of heritage sites. As per UNESCO, there are total 40 heritage sites in India as of year 2022. In this paper, Gujarat has been selected as study region. Gujarat is located at western coastline of India and bounded by Arabian sea on its three sides. Gujarat is a state with rich heritage structures and cultural values. Many places from Gujarat were a part of Indus valley civilization, which shows the ancient values this region holds as state. It possesses ancient, medieval and modern architectures. It has 4 UNESCO heritage sites and 203 heritage sites of national importance. Gujarat having variety of factors like architectures of different era, diverse soil properties and several seismic zonation, these collective factors make Gujarat a proper study region for research. The heritage structure exists for many centuries thus geotechnical proper- ties like seismicity, liquefaction of soil, local site effect, basin effect, etc. are major factors to be consider in the conservation of heritage sites, along with this properties, heritage site's structural condition assessment helps in measuring seismic vulnerability of structure including fabric resistance to climate change, diaphragm flexibility, irreg- ularity in masonry, wrong retrofit interventions, etc. (Sheth et al. 2004). Condition as- sessment could be done by visual inspection or using modern non-destructive tests like rebound hammer method and ultrasonic pulse velocity method (Venkatesh et al. 2017). As per BIS 1893: (2002) Gujarat region is divided in all 4 seismic zones (high to low). Therefore, it can be considered as region with active seismicity. In the study, the seis- mic vulnerability of 207 heritage sites in Gujarat is evaluated and four clusters are iden- tified to give preference to particular heritage sites.

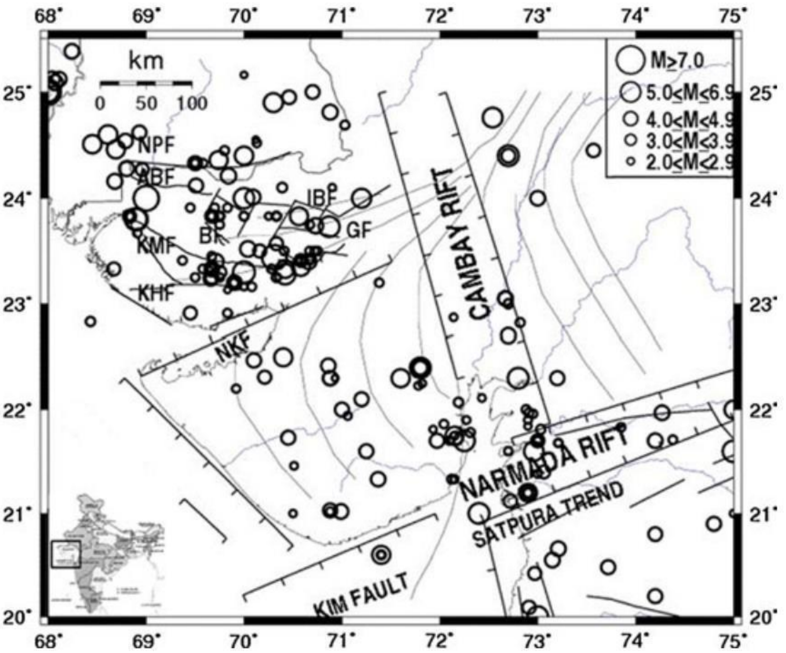


**Fig. 1** The major tectonic features of the Gujarat region (Yadav et al. 2000)

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## Development of Heritage hazard map for Gujarat

Gujarat state situated in western part of India covers approximately 1,96,000 $km^2$ of area. It is bounded by Arabian sea in west, Rann of Kutch and Rajasthan desert in the north, Satpura, Vindhya and Aravali ranges in the east and western ghats in the south. Geologically, all types of rock occur within the state ranging from 2500 million years old in the North eastern part to just few thousand years old in central and western part. State is divided physio graphically into three different units, mainland Gujarat, Saurash- tra and Kutch (Merh 1995). Fig. 1 shows the geological map of Gujarat. The geology of Gujarat comprises a Precambrian basement over which the younger rocks of Jurassic, Tertiary and Quaternary in age. About 60% of area is covered by Deccan basalt cover- ing major parts of Saurashtra, some portion in Kutch and major portion of South Gujarat with intervening Cretaceous and Tertiary rocks at many places (Chopra et al. 2012; Rastogi et al. 2013).

Mainland Gujarat generally comprises of Precambrian crystalline, sedimentary rocks of Cretaceous, Tertiary periods. The Saurashtra region is mainly covered by basalts and having sedimentary sequence as old as Upper Jurassic times. Kutch region shows the development of Mesozoic and Tertiary sequence (Merh 1995). The region is a tri-junction of three failed rifts: Kutch, Cambay and Narmada with several active faults (Biswas 1987, 2005; Talwani and Gangopahyay 2001). The state of Gujarat has seen many destructive earthquakes in the past with majority of them occurred in and around the Kutch region. Some of these are 1668 Indus delta (MM X), 1819 Kutch (Mw 7.6) and 1845 Lakhpat (MM VIII) (Rajendran and Rajendran 2001). In recent times, region have seen 1956 Anjar (Mw 6.0) and 2001 Bhuj (Mw 7.6) earthquakes. In Saurashtra region, Paliyad earthquake of 1938 with Mw of 5.7 was significant seismic activity. Moderate seismicity has been noticed in mainland Gujarat (Bashir et al. 2018, Yadav et al. 2008; Tripathi et al. 2008).

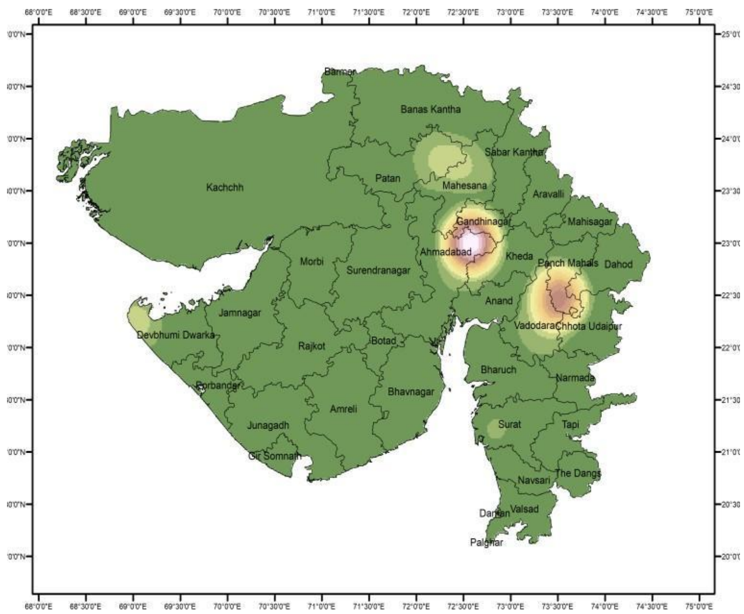


**Fig. 2** Kernel density plot for all monuments / sites in Gujarat

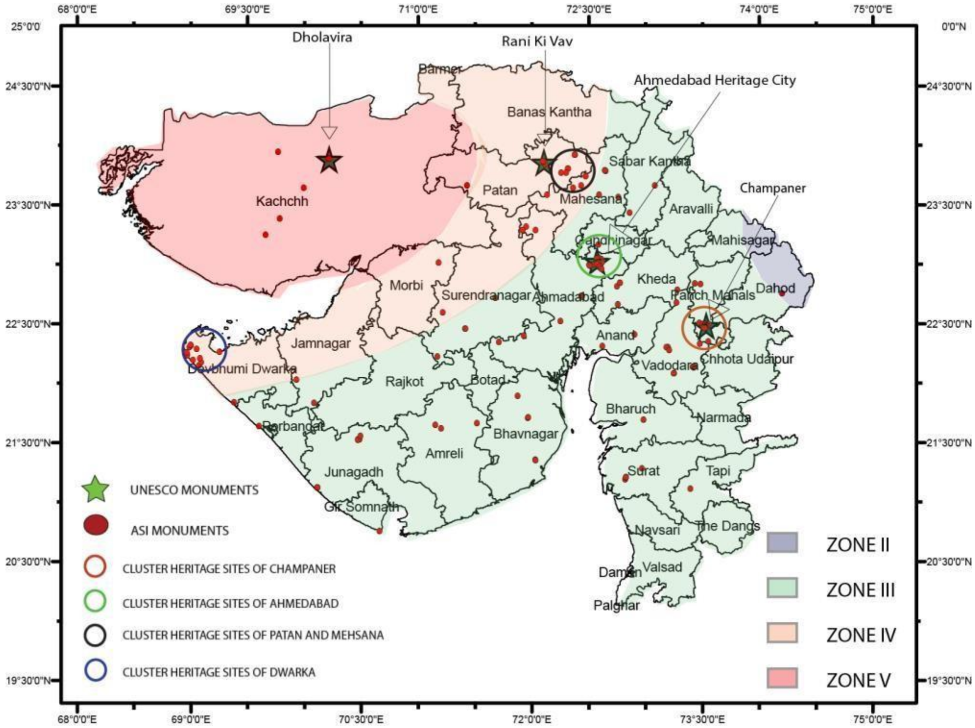


**Fig. 3** Map of Gujarat depicting the heritage sites / monuments superimposed with BIS 1893 (2002) seismic zones

### 1.1 Hazard map based on seismic zones

Bureau of Indian Standards (BIS 1893, 2002) provides a seismic zone map of India, which divides the country into four zones (II-V) with a range of peak ground acceleration (PGA) (0.16g to > 0.36g) using deterministic approach for a return period of 50 years with 10% PGA exceedance and Gujarat consists of all the 4 seismic zones. The coordinates of 203 ASI and 4 UNESCO monuments in Gujarat are marked as point on the Gujarat district boundary map and then the prepared map is superimposed on the seismic zone map of Gujarat. The map obtained (see Fig. 3) contains the information of heritage sites and in which seismic zone do they belong, also spatial analysis was done was done by plotting kernel density map (see Fig. 2) and 4 major clusters were found naming cluster of Champaner, Ahmedabad, Patan & Mehsana and Dwarka.

### 1.2 Hazard map based on seismic hazard study

Vipin et al. (2012) performed seismic hazard assessment using the probabilistic approach and a contour map was prepared to show spatial variation of PHA values for a return period of 475 years. From the hazard map, it is clearly observed that seismic Zone-V corresponds to maximum PHA values with acceleration exceeding 0.3 g (see Fig. 4). This hazard map is superimposed with the Gujarat District boundary map containing all the Heritage sites/ monuments. The obtained map helps to identify the monuments that are at greater risk due to the precise spatial variation shown in the form of contours.

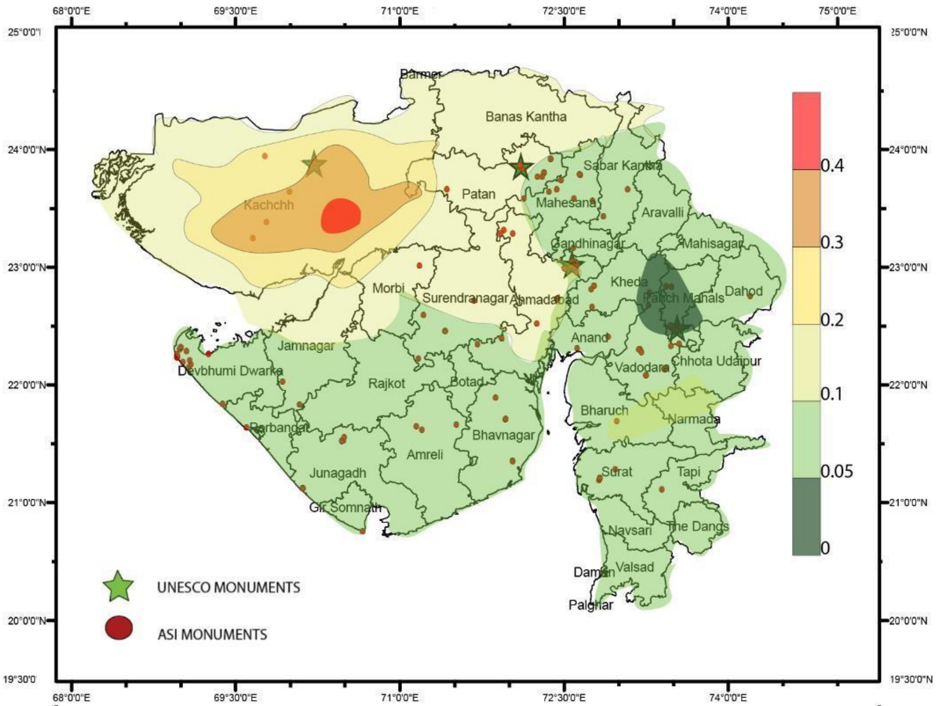


**Fig. 4** Map showing spatial variation of PHA values for a return period of 475 years as per Vipin et al. (2012), superimposed with the heritage map of Gujarat

### 1.3 Hazard map based on liquefaction study

One of the main induced effects of earthquake is the seismic soil liquefaction. Liquefaction is a phenomenon in which the strength and stiffness of a soil is reduced due to large effective stress degradation caused by earthquake shaking or other rapid loading (Marques et al. 2012). The seismic soil liquefaction during Bhuj earthquake was observed in more than 10000 km$^2$ area in the Rann of Kutch region (Pande et al. 2003) which led to ground cracking, water sprouts, lateral spreading of ground and embankment.

Based on performance-based method, the liquefaction potential of an area can be evaluated in terms of corrected SPT values required to prevent liquefaction for a given return period (Karmer and Mayfield 2007; Vipin et al. 2010). Vipin et al. (2012) characterized liquefaction resistance by SPT resistance at a given location and a particular depth considering correction for energy, overburden pressure and percentage of fines. Corrected SPT values required to prevent liquefaction for a return period of 475 years (10% probability of exceedance in 50 years) are estimated (Vipin and Sitharam 2011). Study shows the spatial variation of corrected SPT values required to prevent liquefac- tion in the Fig. 5

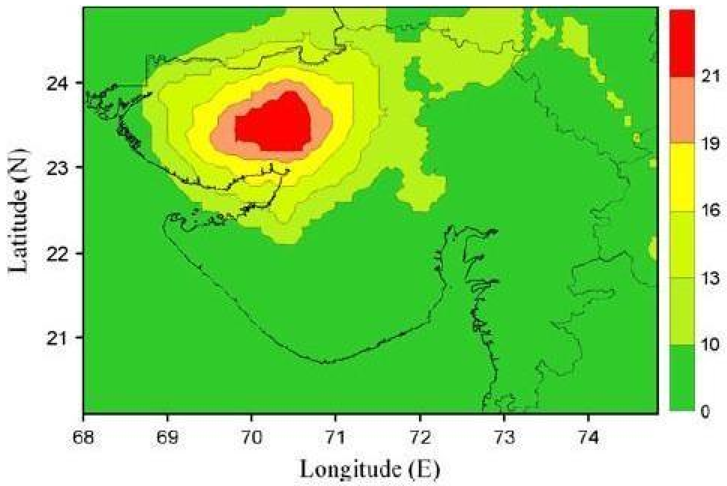


**Fig. 5** Spatial variation of $N_{1,60,cs}$ values required to prevent liquefaction for a return period of 475 years (Vipin et al., 2012)

## 2 Hazard assessment

For assessing the combined risk generated from seismicity and the liquefaction potential on the heritage sites in Gujarat, three risk factors are defined: first, seismic risk factor derived from the seismic zone map (Fig. 3); second, hazard risk factor derived from hazard map (Fig. 4) and third, Liquefaction risk factor based on SPT values (Fig. 5). With the help of these risk factors, the vulnerability of each heritage site is calculated.

### 2.1 Seismic risk factor

Based on the seismic zonation map of India prepared by the Bureau of Indian Standards (BIS-1893-2002), the zones are differentiated from zone II to V by the PGA values based on the 50 years of the return period and the intensity of shaking. Table 1 shows that these seismic zones are assigned with the seismic risk factors (2-10), linearly var- ying in nature with the seismic zones.

**Table 1**: Seismic risk factors

| Zone | I | II | III | IV | V |
|---|---|---|---|---|---|
| **Factor** | 2 | 4 | 6 | 8 | 10 |
| **PGA** | - | 0.1 | 0.16 | 0.24 | 0.36 |

### 2.2 Hazard risk factor

The hazard map (Fig. 4) of Gujarat based on 475 years return period by Vipin et al.

(2012), can be divided into six zones naming from A to F differentiated by thei rcorresponding PGA values, these zones are further allocated with the hazard risk factor (0-10) that is varying linearly. Risk factors with their zone are represented in Table 2.

## 2.3 Liquefaction risk factor

Based on the study done by Vipin et al. (2012) of liquefaction potential of different regions of Gujarat, risks are assigned based on the SPT values derived – no risk, low risk, medium risk and high risk and these risks are further allocated with their risk factors that are also linearly varying in nature. These risk factors, along with their risk type and SPT values, are shown in Table 3.

**Table 3:** Liquefaction risk factors

| **Risk Type** | **No** | **Low** | **Medium** | **High** |
|---|---|---|---|---|
| **Factor** | 1 | 3 | 5 | 7 |
| **SPT Value*** | 0-10 | 10-16 | 16-21 | >21 |

*The required SPT value to prevent liquefaction

## 2.4 Overall risk factor

After assigning the risk factors to all the heritage sites, three types of mean risk are generated by varying the percentage weightage in each risk factor. In the first mean risk ($MR_1$), all the three risk factors, seismic, hazard and liquefaction, are given equal weightage. In the second mean risk ($MR_2$), 40% weightage is given to each seismic and hazard risk and 20% to liquefaction. And in the third mean risk ($MR_3$), 50% weightage is given to seismic and 25% to hazard and liquefaction.

Out of the three mean risks obtained, the maximum value is taken into consideration to assign the absolute risk that gives the hazard level on that heritage site. The same operation is carried out for all the UNESCO and ASI sites, and a new map is prepared (Fig. 6) that designates the risk to each site in four levels: severe, high, medium and low shown in Table 4.

**Table 4**: Absolute risk levels

| **Risk Level** | **Intensity** | **Colour** |
|---|---|---|
| 7+ | Severe | Red |
| 6-7 | High | Orange |
| 5-6 | Moderate | Yellow |
| <5 | Low | Green |

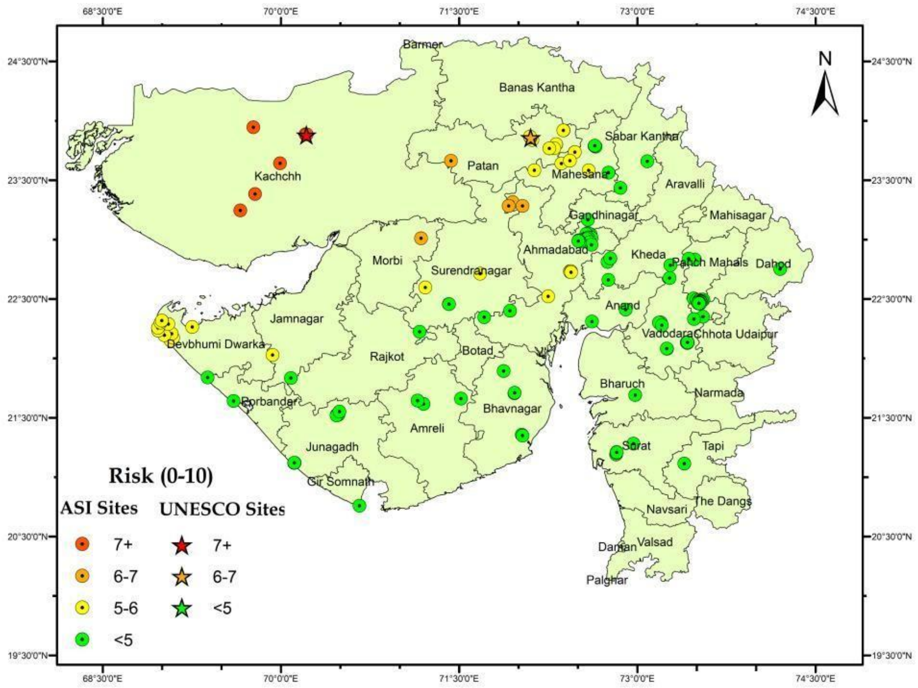


**Fig. 6** Heritage hazard map of Gujarat considering combined aspect of seismicity, hazard and liquefaction studies

## 3 Condition assessment

Having an idea of the vulnerability of a site on the basis of the hazard risk is not enough as the vulnerability of the monument also depends on its structural typology, material properties and its current state of preservation (Paul et al. 2020). Condition assessment is the way of identifying that. Based on the above parameters, each site is classified into various levels of distresses (Noor et al. 2019; Paul et al. 2020):

**Satisfactory**: The distress does not affect structure and structure components or any structural services
**Slight**: A minor distress which doesn't have any effect on structure or structural components but still should be maintained
**Moderate**: Structural members show unusual pattern but still the functionality of the structure is maintained.
**Poor**: The functionality of the structure or structural component is affected and may cause injury to the occupants
**Severe**: The distress may cause structural failure or services failure if not repaired or maintained

In the study, to show the method of evaluating the correct risk to the heritage site, a visual inspection method is used which involved taking systematic photograph

(Shown in Figs. 7 - 10), educational judgements on the defects visible, etc. Based on the visual inspection of heritage site Rani ki Vav, the site can be considered as “slight to moderate” level of distortion. This information can be used to evaluate the final risk of that site.

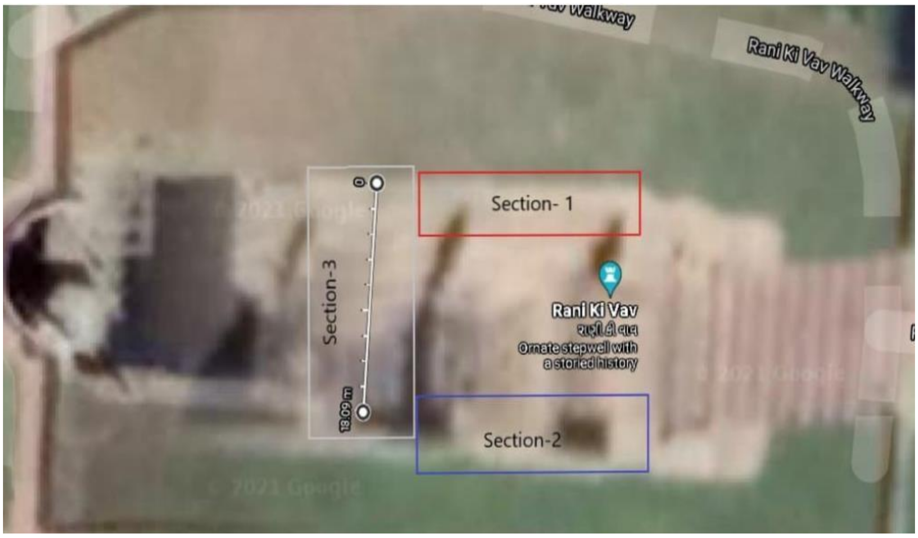


**Fig. 7** Alignment of Rani ki Vav with sections defined as 1, 2 and 3

**Fig. 8** Moderate cracks in the ceiling (Section 3)

**Fig. 9** Deterioration of the wall (Section 2)

**Fig. 10** Slight deterioration in the carvings

## 4 Conclusions

This paper assesses the vulnerability of UNESCO sites, Group of monuments and ASI structures of Gujarat with respect to seismic zonation of Gujarat according to BIS 1893 (2002) and based on seismic hazard studies conducted by the researchers on probabil- istic hazard assessment. The report takes a review on the geotechnical and structural aspects of the few identified zones. Following conclusions can be made from the study:

1. A combined assessment is made considering all the three aspects and a hazard map is developed which depicts heritage sites in Gujarat of which 154 are in zone green, 37 lies in zone yellow, 6 lies in zone orange and 6 lies in zone red. It is noted that the red colour has highest risk and green colour has the least risk. Color zonation of the heritage site help the authorities in identifying the vulnerable sites and accord- ingly suitable retrofitting, restoration and repair work can be carried out.
2. Condition assessment for the Rani ki Vav is performed, which is the next step after identification of vulnerable site from the map. Assessment showed the various dis- tresses which needs repair and maintenance. Further studies on structural health and geotechnical features of these vulnerable sites of hazard zones will help in deter- mining the level of damage these monuments have taken up. This will help in eval- uating the actual hazard risk and to determine the rehabilitation and conservational interventions required to be done.

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