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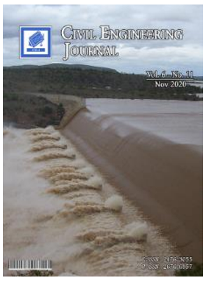

Assessment of Seismic Site Response and Liquefaction Potential for Some Sites using Borelog Data

Manish Bhutani [a*], Sanjeev Naval [b]

[a] *Research Scholar of IK Gujral Punjab Technical University, Kapurthala, India.*

[b] *Associate Professor, Department of Civil Engineering, DAV Institute of Engineering & Technology, Jalandhar, Punjab 144008, India.*

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Abstract

Assessment of Liquefaction susceptibility of soil is very important aspect of disaster risk reduction for a particular region. The present research is an investigation to find out the liquefaction capability for the sites of Jalandhar and its surrounding region, Punjab (India) using semi empirical approach of Idris and Boulanger. Initially, the response of Ground has been analyzed with the help of DEEPSOIL software for evaluating the maximum ground acceleration values (PGA_{SUR}) at surface using five earthquake motions of magnitude, M = 6.0, 6.8 and 7.3 selected from worldwide recorded database based on seismicity of the region. The investigated PGA values ranges from 0.196 g to 0.292 g for the sites under investigation. Soil's potential against liquefaction for 45 locations has been carried out using PGA_{SUR} results so obtained. It has been observed that eighteen sites out of forty-five are found to be susceptible to liquefaction. In order to help structural designers and geotechnical engineers for the preparation of realistic plan towards disaster risk reduction for the region, PGA_{SUR} contour map of obtained results and liquefaction hazard maps for earthquake of magnitude 6.0 and 7.0 has been prepared on geographical information system (GIS) platform using QGIS software.

Keywords: Ground Response Analysis; Surface Peak Ground Acceleration (PGASUR); Liquefaction Potential; QGIS.

1. Introduction

Seismic tremors have been happening in the subcontinental region of India since historical times. Seismic framework of this region overlaying a territory of around 32,00,000 km^2 is varied. The vast majority of the exercises, including numerous incredible seismic tremors have happened in the northern part of Indian subcontinent and within the region of Andaman and Nicobar. Every year, the rate of movement of Indian tectonic plate towards north is around five centimeters and in doing so, crashes into stable Eurasian tectonic plate. This rapid movement of Indian tectonic plate in the north east direction of Himalayas together with lower thickness of plate is probably the reason for a growth in increase in the seismic activities in the Indian region [1]. As indicated by the Geological information, almost 60 percent Indian land is inclined to various degrees of seismic danger which is sufficiently revealed by the detail that in more than 600 quakes of strength more than 5.0 magnitudes were documented in this locale in most recent 100 years. The seismic hazard in the nation has been expanding rapidly in the recent years as stable less seismic active regions were also encountered earthquakes of large magnitude. Over the most recent couple of decades monetary misfortunes because of catastrophic events including seismic tremors have increased exponentially worldwide and little advancement has been found in reducing their pace of fatalities. This has happened essentially because of increasing population and industrial density in high hazard and areas of high vulnerability [2]. On 21st May, 2003, earthquake of

* Corresponding author: manish_0220@yahoo.com

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magnitude 6.5 occurred in the city of Mohammadia, resulted in high intensity damage in the city. Bousbia et al. (2019) [3] conducted seismic microzonation investigation for the city Mohammadia-Algier, as this region falls near to tectonic plates of Euarasia and Africa due to which the north region of Algeria observed numerous earthquakes in recent years. Initially, shear wave velocity at 30m depth is calculated and contour map showing the variation of same is prepared for Mohammadia city. The amplification of soil is calculated and further used to construct the seismic microzonation map of the Mohammadia city. The subsequent microzonation guides of site class as per NEHRP and otherworldly ground surface increasing speed will be helpful to designers to perform the structure design of structures resistant to tremors utilizing the map data.

Undoubtedly, the Himalayan region is the most powerful seismic territory as it is located very close to the boundaries of Indian tectonic plate, which is plummeting into Eurasian tectonic plate. Numerous activities related to earthquake have been occurring in this region. The places such as Northwestern & Eastern part of Kashmir, boarders of India-China & Afghanista-Russia, Pakistan and Tadzkistan are all highly seismic active regions. This region has encountered many damaging earthquakes previously and caused widespread damages such as 1905 Kangra Earthquake (Mw 8.0), 1929 Rawalpindi Earthquake (Mw 7.1), 1885 Kashmir Earthquake (Mw 7.0), 1945 Chamba Earthquake (Mw 6.5) 1974 Pattan Earthquake (Mw 5.9), 1967 Anantnag Eartquake (Mw 5.5). The study and analysis of all the major earthquakes occurred in the last century in India reveals that during ordinary occasion of earthquakes in different zones of earthquake remains same, there are seismically dynamic periods lasting on for two decades during which the event of huge or incredible quakes increases [4]. Likewise, the Interest in earthquakes of strength less than 5.0 M and their probable outcomes in the past few years has expanded essentially, generally because of some undesirable events of earthquakes causing damage, the advancement of evaluation systems of risk related to the seismic activities for present structure stock, and the acknowledgment of the possible danger of actuated seismicity [5]. This state of Punjab (India) is in a rapid phase of development regarding industrial growth, escalation of urbanization and population explosion. The three cities namely Amritsar, Ludhiana and Jalandhar have selected to be developed as smart cities.

City Jalandhar is one of the metropolitan agglomerations with about 1,000,000 people. Metropolitan agglomerations are essential to the monetary development of the nation. The high-density population and development in restricted region, rises the susceptibility of a zone and prompts huge misfortune possibilities. So as to decrease susceptibility, explicit microzonation investigations are needed to be an aspect of planning for development exercises in smart cities for structures resistant to earthquake. For the planning and designing of structures safe against earthquakes, it is important to conduct the seismic risk examination so it can help the city planners and designers in like manner [4].

Tremors happen below the earth’s surface and release tremendous quantity of seismic energy. As most recent couple of decades, India has encountered a couple of perilous seismic occasions. Due to such seismic activities, most part of the region is presented to foremost seismic hazard level and there is a requirement to lower the level of seismic risk [6]. The waves generated from the source of earthquake in the earth’s crust, travel through different deposits to the earth’s ground surface. In this process the properties of seismic waves like Peak Amplitude, Peak Velocity are greatly influenced by relatively soft soil in comparison to stiff rocks (at larger depth). It has been seen in past investigations that the site explicit conditions of soil can greatly affect the properties of travelling seismic waves due to which it becomes important to conduct the Response of Ground for Specific Site to determining exact ground motion parameters in that particular region. It is generally perceived that nearby geological circumstances have articulated effect on ground movement at a particular selected site. Each and every kind of Soil reacts in an unexpected way, when exposed to the ground movements, forced because of seismic tremor stacking. Typically the more youthful milder soil intensifies ground movement comparative with more established, more capable soils [7]. During the seismic tremor, when the earth’s surface is trembling, it encounters distortion and acceleration. The greatest pace of addition in speed estimated at a particular location is defined as maximum ground acceleration at surface (PGA_{SUR}). It is the highest estimation of acceleration at wherever when a quake happens. The reaction of any structure generally relies upon the value of PGA_{SUR} as seen by Güllü et al. (2016) [8]. It is very crucial for an emerging nation like India to determine the ideal and dependable value of conceivable tremor ground movements during a particular time span. These anticipated figures will be a contribution to evaluate the earthquake vulnerability of a region dependent on which new development and the rebuilding works of existing buildings and other structures can be completed [9].

It was likewise seen that the ground catastrophes created by liquefaction have been significant reason for harm during previous tremors and carry extensive ability for harm and damage during upcoming earthquakes. Such failures do not occur at random but are limited to certain geologic settings and levels of seismic shaking [10]. Ground failure opportunity occurs when the intensity of seismic shaking reaches a level strong enough to cause liquefaction and consequent permanent ground displacements in susceptibility materials. Ground failure vulnerability denotes the comparative ease which leads to the liquefaction of the sediments in that specific geologic setting during earthquake shaking and permanent ground displacement ensue. The reaction of the dirt because of earthquake, delivering a huge amount of soil liquefaction, which has been considered as one of the significant worries for soil engineers or design engineer doing study or work in the high intensity earthquake zones. Soil failure due to liquefaction can happen in medium to high strength seismic tremors, which can make extreme harm to the buildings.. During earthquakes, when ground shaking happens, soil losses its shear strength and it might prompt failure of ground. The ground shaking results in the rising of pore pressure in soil which diminishes the soil's effective stress and subsequently decreases the shear strength of the soil, particularly sand. The surplus water will rise to the top surface through minute cracks in the different layers in case of dry soil crust and carrying particles of sand along with it which makes soil boils, called as sand volcanoes." [11].

The wonder of liquefaction drawn consideration of numerous scientists Earthquakes of Alaska and Niigata occurred in 1964 drawn attention of numerous geologists and scientists on the soil liquefaction. Noteworthy harm to numerous buildings because of soil failure due to liquefaction was seen during tremors in recent twenty years for example 1999 – Chi Chi, Taiwan, 2001-Bhuj, India, 2011 – Fukushima, Japan and 1995- Kobe, Japan. 1. Government of Andhra Pradesh are expecting to create large scale projects in the region, therefore targets to evaluate potential of soil failure utilizing LPI for various areas in the state of Andhra Pradesh [12]. Also hazard map for the state of Andhra Pradesh has been prepared. The conclusion of the investigation is useful to recognize the regions prone to liquefaction in this district that assists engineers for taking appropriate measures to reduce the risk of Soil liquefaction. In case of loose and saturated soil conditions, numerous structures encountered traverse over the water bodies as all the affected sites are prone to soil damage due to liquefaction. Also, during the major earthquake of India i.e. Bhuj 2001 Earthquake, an enormous region of the Gujarat state was influenced due to soil failure.

Liquefaction problem became important when it started to affect human and social activities by disturbing the function of facilities and also after rapid urbanization by expanding the cities in reclaimed areas. Soil Failure or damage happed during earthquake leads to the failure of high rise structures, RCC and steel bridges, water and sewage pipelines or other structures in different ways. The behaviour of soil below the water table during earthquake relies upon the potential for critical strains or loss of shear strength that can add to surface distortion or unsteadiness during a tremor. Noteworthy huge seismic tremors all through the world clarify that the loss of shear strength related failure of ground normally results in huge damage to buildings in the urban regions. So, evaluation of liquefaction potential is significant for assessing and decreasing the danger through proper relief procedures [13]. Seismic tremor incited soil failure is by and large assessed from SPT blow checks utilizing the simplified methodology that was initially recommended by Seed et al. (1971) [14]. Afterward, that methodology has been refreshed, aligned, and approved by numerous geologists and scientists. The method is applied to assess the factor of safety (FOS_{LF}) for liquefaction, where FOS_{LF} is greater than 1 assigns that soil strata will not be undergo liquefaction and FOS_{LF} less than 1 shows that the soil strata will liquefy due to earthquake shaking and presented liquefaction potential index, where FOS_{LF} is a component of the height of soil layer undergoing liquefaction and profundity of the layer starting from the top surface. In spite of the fact that this district has high possibility to cause tremor incited liquefaction, no examination has been examined at this point to survey the seismic soil liquefaction peril for this area. Subsequently, the development of the area is being built without considering earthquake hazard. To prevent the damage to structures and loss of lives in the Downtown region of Yangon, Myanmar, prepared soil distribution and liquefaction severity map for Geotech Engineers and Structural Designers [15].

For the purpose of preparing maps of the study region in the city of Yangon, ArcGIS program is used. Geotechnical data for the different locations of Yangon city has been gathered to get the subsurface details such as ground WT, Dry and wet density, SPT Number, Specific Gravity etc. At last, liquefaction's safety factor is calculated and maps corresponding to 1, 2 and 10% of yearly probability are created. In the present research, ground response examination for the specific locations has been examined by various earthquake inputs and liquefaction potential is find out using simplified procedure given by Seed et al. (1971) [14] for the forty five sites of the Jalandhar region, Punjab (India). These data points spread throughout in and around Jalandhar region covering almost the entire region to study the sub soil heterogeneity. Seismic soil classification based on Average shear wave velocity for all the selected sites of entire region has been made in accordance with the program related to decrease the risk of people life and destruction of infrastructure from the future tremors i.e. Earthquake reduction program of nation (NEHRP) [16] and map for the same has been prepared. After carrying out 1-D Nonlinear ground response analysis, PGA_{SUR} has been assessed with the help of computer software i.e. DEEPSOILv6.1 software. The obtained values of PGA_{SUR} required to access the soil liquefaction, varies between 0.128 to 0.292g and used as an input to calculated FOS_{LF} for the sites of Jalandhar and its surrounding regions. It has been observed that around 40% of the region is found to susceptible to liquefaction. The liquefaction hazard maps for earthquake of magnitude, M = 6.0 & 7.0 have been prepared for the region on geographical information system (GIS) platform using QGIS software, which has been considered as an incredible software in the field of engineering. The flow chart related to the step by step process for the assessment of seismic site response and liquefaction potential for the research area, is shown in flowchart below (Figure 1).

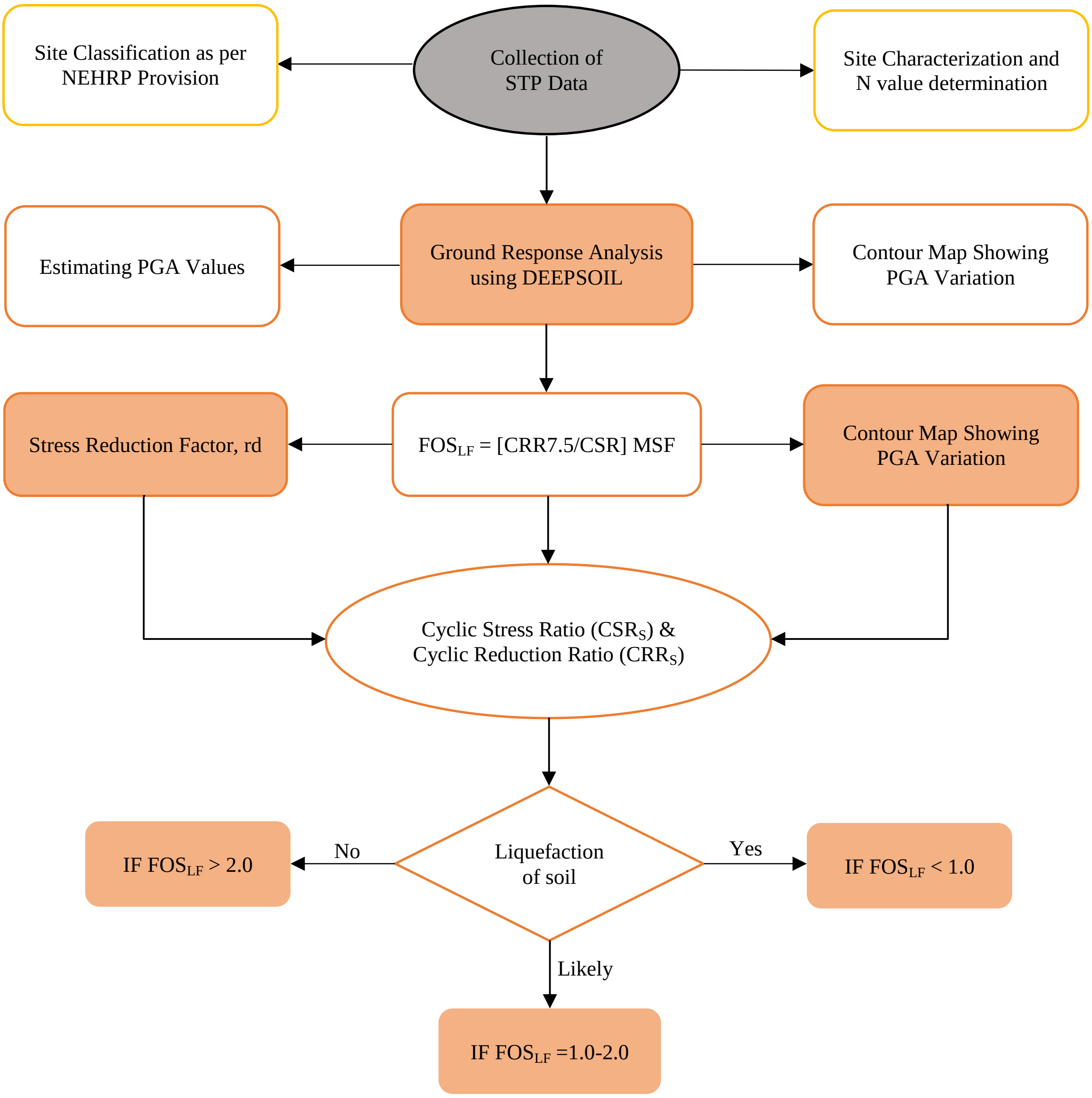

Figure 1. Methodology for evaluation of Seismic Soil Liquefaction

2. Description of Study Area

Jalandhar, city of Doaba portion in the state of Punjab in India, formerly known as Jullundur in India during British Period. Jalandhar is the most significant city in the Indian province of Punjab lies close by the GT Road and is a very well connected to other modes of transportation such as roadways and railways. It is surrounded by Punjab's largest city, Ludhiana in East, Kapurthala, one of the least populated cities of India in West, Ferozepur, city on the banks of the Sutlej river in south and oldest district of Punjab i.e. Hoshiarpur in North and 380 km of New Delhi, capital of India. Jalandhar lies in between coordinates 31.3260º N and 75.5762º E, which is portrayed as the dry climate region and is appropriate for growing crops such as sugar cane, wheat, etc. Figure 2.

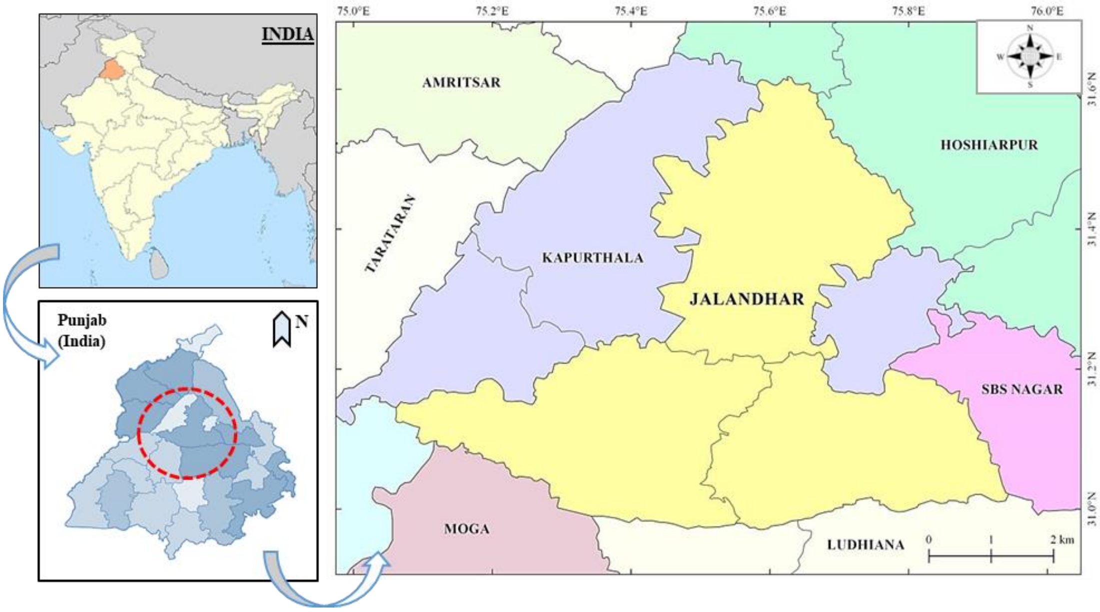

Figure 2. Map showing the location of the study area (Jalandhar and its surrounding regions)

A significant business center of Punjab, city has gone through fast urbanization and has formed into exceptionally industrialized focus of trade. City Jalandhar has also been chosen in the 2nd stage of the smart city project. Covering an enormous region of 3,401 sq. km, Jalandhar lies between the rich farming place where there is River Sutlej and Beas with population nearly 21 million. This gives Jalandhar, a ranking of 209th in India having a population density near to 800 occupants for each km^2 i.e. 2150 /mi^2) with development pace of 11.16 percent over the period of 2001-2011 [17].

2.1. Topography and Geology of the Region

The geography of the area is average delegate of an Alluvial plain; it owes its beginning to the geological work of the river Sutlej. The loose unconsolidated soil transported by the waterway has been worked over by the wind results in the formation of Sand dunes and other resulting features. The majority of these sand dunes have been flattened by the farmers of the region [18]. Region of Jalandhar is formed by brown colour tropical dry soil in significant areas whereas south west part occupied by arid soil, brown in colour. According to the report of CGWB 2007, the topography of the region varies from steep gradient in the North Eastern to as good as level surface in the middle and South Eastern with constant bed of clay of thickness up to 15 meter at different profundities. The topmost bed of clay with small composition of kankar and brown in colour occurs at the depth of 10-30 m whereas second prominent layer lies between 25 to 65 m beneath earth. The 2nd & 3rd layer (found at 65 to 120 m below GL) separated by thin layer of sand are found to be very thick. The clay layer in this zone is found to be having some proportion of sand having size less than 75 micron mixed with coarse aggregates

2.2. Seismicity of the Region

In light of previous tremors and movement of Indian & Eurasian tectonic plates, an earthquake hazard map of India has been created set up by a board of trustees of specialists under the sponsorship of Bureau of Indian Standard (BIS Code: IS: 1893: Part I 2002), showing different earthquake zones. In this map, the vast majority of Punjab State's region lies in III and IV earthquake zone. In any case, northern limit of Punjab State with Himachal Pradesh is in nearness to V earthquake zone [19]. The acceleration of earth's surface and intensity of earthquake at particular location relies on the location of focus, earthquake's duration & strength, properties of soil and other dynamic characteristics. Usually, the harm to the structures established on soil with major proportion of sand will be more as compared to the structures resting on rock. Likewise, the harm will be higher for earthquake of high strength and long period of seismic tremors, smaller distance of epicentre, loose soil and soils having high potential of liquefaction. 650 mm and radius 17.5 mm (internal) and 25 mm (external) known as split spoon sampler is penetrated in the ground with free falling hammer (63.5 kg wt.) from height of 760 mm. The sampler is headed to enter to a profundity of 450 mm. The no. of hammer blows needed to drive split spoon sampler to a depth of 30 cm will be referred as SPT N value. The selected locations of the 45 sites for the present study are shown in Figure 4.

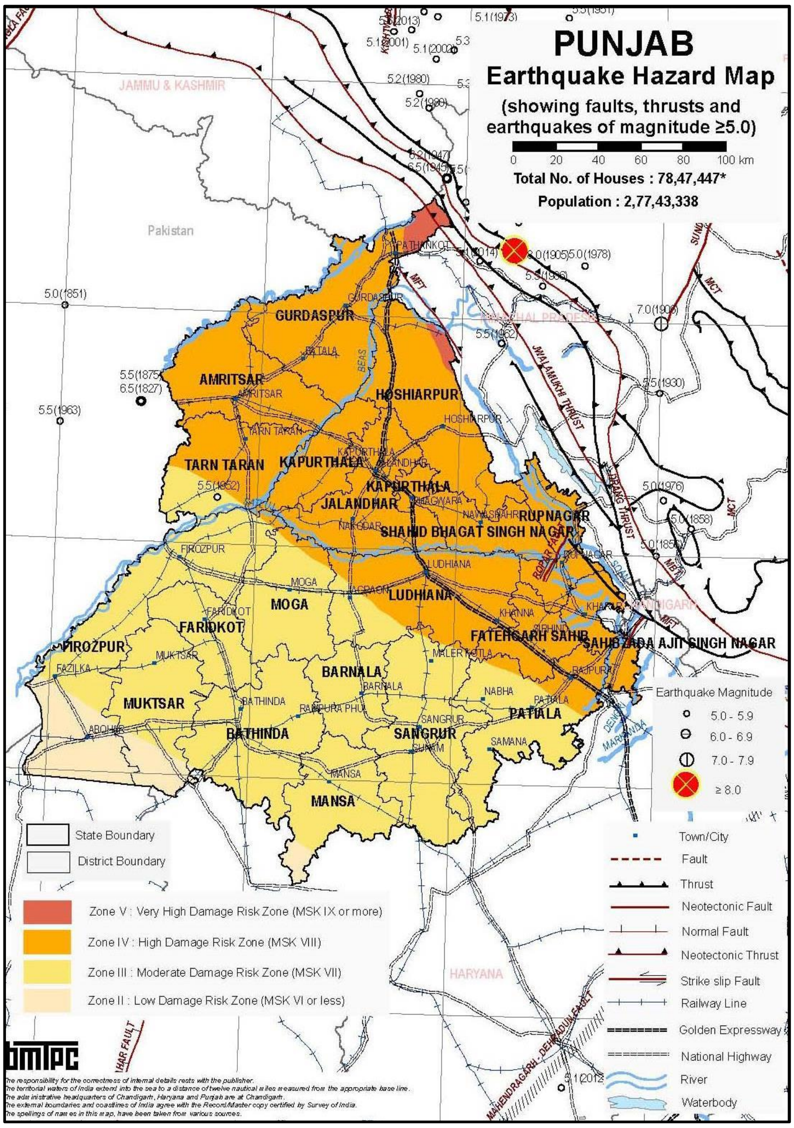

Figure 3. Earthquake Hazard Map of Punjab

From the map given in Figure 3, it has been perceived that around half of the region in state comprising of Jalandhar, Gurdaspur, Patiala, Ropar, Ludhiana, Amritsar, Hoshiarpur, Kapurthala and Hoshiarpur regions are liable to high intensity of VIII and remaining regions to VII earthquake intensity. In 1952, an earthquake of magnitude 5.5 took place in the region of Kapurthala and a lot of bigger seismic tremors of strength more than 7.0 magnitude took place in HP at around 50 km from the boundary of state, which might be a reason for high damage in the areas of Hoshiarpur, Gurdaspur and Amritsar. So, as per the BIS map 2002, the territory of Punjab lies in the medium to high earthquake threat. Factually, this portion of state encountered earthquake of magnitude 4 to 5. The conspicuous among them influenced the various districts of Punjab are: 8.0 M magnitude Kangra Earthquake – 1905 affected around 28 thousand people in the Kangra-Dharamsala area of HP and likewise damage happened in nearby regions of Punjab (Lahore, Ludhiana, Jalandhar, Sialkot and Amritsar), Dharamshala Earthquake – 1986,; 6.8 M Uttarkashi Earthquake – 1991 and and 6.5 M Chamoli Earthquake - 1999 felt very powerfully in the areas of UP, Punjab, Haryana, Chandigarh and affected around 2000 people; 7.6 M Pakistan Earthquake -2005 was one of the major earthquake stuck at the boarder of India – Pakistan and felt strongly in Pakistan, Northern India and Eastern Afghanistan. Other than the above vital seismic tremors, numerous other noteworthy seismic activities from IMD inventory happened in the district of Punjab and its surrounding regions. Few of those might have been felt in the Punjab and its surrounding region.

2.3. Site Characterization

In this study, Standard Penetration Test (SPT) information was gathered from45 location of study region. This test is extensively utilized at site to assess the general and engineering properties of soil.

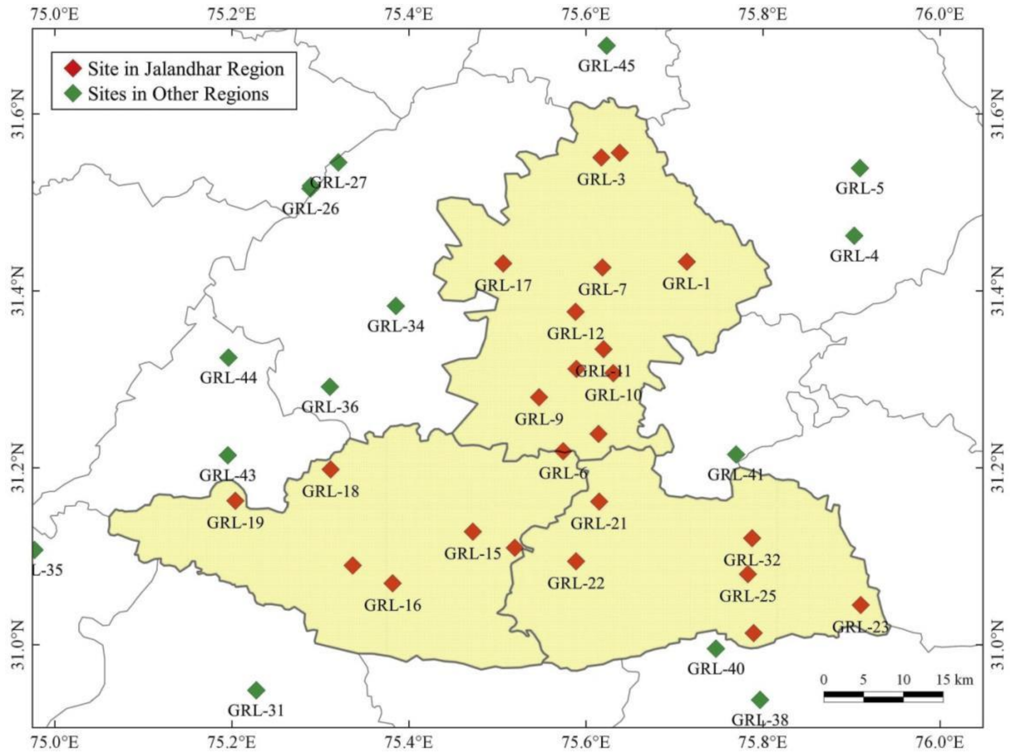

Figure 4. Location of Selected Sites for study

Out of 45 sites, 26 sites are located with the boundary of Jalandhar district and 19 sites are in the other regions surrounding Jalandhar. The location detail of each site along with the region, Avg. N- value and Avg. (V_{S30}) shear wave velocity is given in Table 1.

Table 1. Detail of selected sites considered for the study

Site No.	LATITUDE	LONGITUDE	Avg. SPT N-Value	Study Region	Avg. Shear Wave Velocity (V_{S30}) (m/s)	Site Class (as per NEHRP)
GRL-01	31.432949	75.713901	17.39	Jalandhar	258.04	D
GRL-02	31.556119	75.638266	11.57	Jalandhar	209.64	D
GRL-03	31.550755	75.61739	20.71	Jalandhar	278.77	D
GRL-04	31.462282	75.903134	17.04	Hoshiarpur	275.14	D
GRL-05	31.53874	75.909487	25.07	Hoshiarpur	303.75	D
GRL-06	31.218722	75.574247	20.74	Jalandhar	280.20	D
GRL-07	31.426417	75.618644	12.56	Jalandhar	218.91	D
GRL-08	31.238274	75.61425	17.58	Jalandhar	256.92	D
GRL-09	31.279701	75.54703	17.66	Jalandhar	260.36	D
GRL-10	31.30695	75.63085	35.93	Jalandhar	383.00	C
GRL-11	31.33412	75.61986	41.58	Jalandhar	420.67	C
GRL-12	31.37636	75.58831	45.11	Jalandhar	440.14	C
GRL-13	31.31176	75.58923	19.87	Jalandhar	289.08	D
GRL-14	31.089503	75.336481	16.83	Jalandhar	249.87	D
GRL-15	31.127789	75.472192	20.97	Kapurthala	287.53	D
GRL-16	31.069337	75.38156	17.45	Kapurthala	256.43	D
GRL-17	31.430951	75.506509	20.44	Jalandhar	286.67	D
GRL-18	31.198099	75.311546	22.18	Jalandhar	296.04	D
GRL-19	31.162664	75.203898	20.00	Jalandhar	273.82	D
GRL-20	31.10949	75.519669	26.93	Jalandhar	334.94	D
GRL-21	31.161781	75.614954	13.38	Jalandhar	225.03	D
GRL-22	31.094262	75.588799	22.80	Jalandhar	294.29	D

GRL-23	31.044798	75.910421	20.95	Jalandhar	305.07	D
GRL-24	31.013066	75.789472	18.05	Jalandhar	262.20	D
GRL-25	31.07973	75.78295	14.25	Jalandhar	234.82	D
GRL-26	31.515717	75.288737	20.07	Kapurthala	275.89	D
GRL-27	31.545256	75.320269	22.73	Kapurthala	294.10	D
GRL-28	31.518774	75.289315	12.56	Kapurthala	217.09	D
GRL-29	31.724413	75.584433	25.92	Hoshiarpur	322.18	D
GRL-30	31.819245	75.659493	17.84	Hoshiarpur	262.66	D
GRL-31	30.948419	75.227567	28.50	Hoshiarpur	334.15	D
GRL-32	31.120391	75.787707	24.23	Jalandhar	298.11	D
GRL-33	31.124275	76.115594	14.15	Jalandhar	251.39	D
GRL-34	31.38292	75.38525	15.59	Kapurthala	269.08	D
GRL-35	31.107119	74.976942	15.75	Kapurthala	268.22	D
GRL-36	31.291541	75.310745	7.12	Kapurthala	176.59	C
GRL-37	30.902062	75.807709	8.88	Ludhiana	184.78	D
GRL-38	30.93757	75.796696	8.85	Ludhiana	183.99	D
GRL-39	30.903216	75.854086	6.80	Ludhiana	162.84	E
GRL-40	30.995502	75.746867	6.09	Ludhiana	154.51	E
GRL-41	31.215004	75.769637	27.51	Kapurthala	318.17	D
GRL-42	31.052128	76.117499	26.66	SBS Nagar	327.33	D
GRL-43	31.214128	75.195393	21.12	Kapurthala	288.08	D
GRL-44	31.324551	75.196163	GRL-44	Kapurthala	230.38	D
GRL-45	31.67719	75.623374	GRL-45	Hoshiarpur	216.37	D

Considerable techniques dependent on amplification properties are available for grouping different types of soils and aggregates. Shear wave velocity (*Vs)* is a dynamic property of soil that determines the shear strength and stiffness of soil at site with the help of Cone Penetration Test, Cross Hole Test and Surface wave test (Spectral and Multichannel). The technique for calculating *Vs* using surface wave test has been generally utilized for the classification & response studies of site. As in most of the cases *Vs* data is not available for deeper depth so in such cases, actual data of *Vs* is extrapolated to assess seismic site class. The assessment of the *Vs* encourages classification of site as there lot of studies supporting the extrapolation of *Vs* profiles from the available depth. So in this study, *Vs* for entire 45 sites of the study region is calculated by using already developed the relationship N value (SPT) and V_S suggested by Anbazhagan and Bajaj (2017) [20] for Punjab Haryana Region.

$$V_S = 64.23 \times N^{0.48} \tag{1}$$

For the development of Equation 1 amongst N-value (SPT) and *Vs*, Gupta and Anbzahagan 2019 carried out surface wave survey at 276 locations in the North Indian plain. To study the spatial variability of *Vs*, the entire plain separated in the region of Punjab & Haryana, Bihar and U.P. initially, a relationship for all three regions amongst N value (SPT) and *Vs*, utilizing the least square method has developed, The Equation 1 has been derived using both of the regression methods i.e., least square and orthogonal and can be used for the calculation of V_s in Punjab Haryana Region. Shukla and Solanki also proposed correlation between shear wave velocity (SWVs) and SPT-N number for all types of soil using regression analysis. For this region, 40 correlations have been composed and utilized for determining the correlation of Shear Wave Velocity (SWVs). The produced relationship is then utilized for the calculation of SWVs for the analysis of ID ground response using DEEPSOIL v6.1 program at two distinctive points in the district of Indore.

Seismic classification for sites based on the V_{S30} of the upper 30m strata of soil, is general exercise required for seismic microzonation, as per NEHRP and IBC. For classification of sites of Jalandhar and its surrounding region, V_{S30}determined from the following equation:

$$V_{S30} = \frac{\sum_{i=1}^{n} di}{\sum_{i=1}^{n} \frac{di}{Vi}} \tag{2}$$

Where, V_{S30} is the avg. shear wave velocity of soil for 30m depth. Soil Column depth, V_i is the shear wave velocity of particular soil strata and *di* is the depth of particular soil strata. For the classification of sites, the values of V_{S30} and N value (SPT), suggested by NEHRP (BSSC, 2003) were taken: for seismic site class A (V_{S30}greater than 1.5 km per sec), class B (0.76 km/s V_{S30} ranges from 0.76 to 1.5 km per sec), class C (V_{S30} ranges from 0.36 to 0.76 km per sec or N-value30), class D (V_{S30} ranges from 0.18 to 0.36 km per sec or N Value 15-30), and class E (V_{S30} less than 0.18 km per sec or N value less than 15). Since some of the sites had data available for lower depth (<30 m), the shear wave velocity of the lowermost layer was assumed for the rest of the depth. Calculated V_{S30} from Equation 2 varies from 160 to 440 m/s, and accordingly the values were grouped. Figure 5 shows the V_{S30} distribution for the study region.

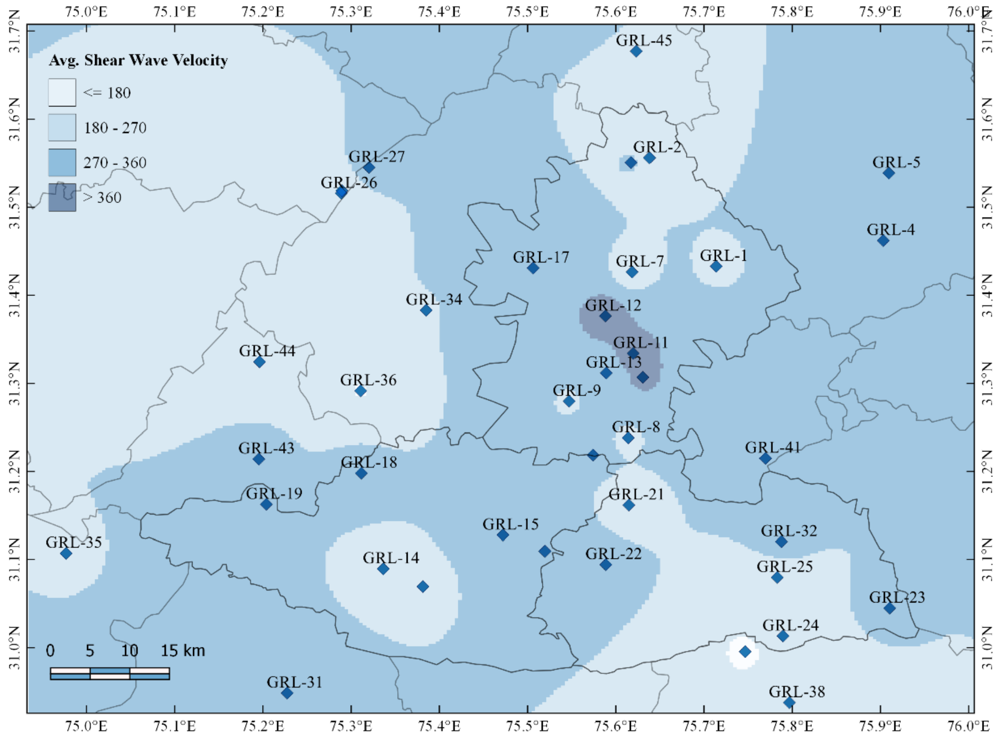

Figure 5. V_{S30} Distribution Map for the Study Region

It tends to be seen that the whole region goes under "D" seismic site class, with small regions falling under "C" & "E" seismic site class. As per the recommendation of NEHRP, soils with lower values of V_{S30} will encounter more ground shaking due to earthquake as compared to bedrocks because of the wave-intensifying properties of the soil strata. This implies most some portion of study will pretty much experience amplification of soil due to earthquake [21].

3. Response of Ground for Study of Particular Location

Response of the Ground is investigated to evaluate the reaction of delineated soil considering spectral acceleration, stress and strain histories, variation of Ultimate acceleration of Ground Acceleration with depth & response spectra of a soil withstand to input earthquake motion. There are three methods normally used to carry out investigation are Direct, Non-Linear & Equivalent Linear [22]. Linear method of ground response depends on the presumption that the parameters of soil other than static i.e., shear modulus of soil (G_s) & soil's damping ratio (D_s) are strain free & steady for every layer of soil column. On the other hand, equivalent linear ground response method was created to investigate the nonlinear reaction of soil using the analysis based on frequency domain with the help of linear transfer function. This study is an estimate technique wherein the non-linear conduct of the soil layer is demonstrated in terms of equivalent linear properties relating to effective shear strain utilizing iterative method [22]. The iterative method is administered by the objective of finding a compatible value G_s & D_s for a specific viable shear strain. For the most part, the successful shear strain is viewed as sixty five percent of the greatest shear strain created in the soil layer [22]. However, this strategy is computationally advantageous and gives sensible outcomes; it is unfit to speak to the adjustment in soil firmness that really happens during the seismic tremor [22]. In nonlinear technique of analysis, the unpredictable however reasonable stress strain conduct of soil is displayed for more realistic estimation of soil behaviour in time domain utilizing direct numerical integration Soil's G_s and D_s proportion have been fused by pressure subordinate hyperbolic model. This requires reference strain, stress-strain bend parameter (β), stress-strain bend parameter (s), pressure subordinate (reference strain) parameter (b), reference pressure, pressure subordinate (damping bend) parameter (d) to be characterized for each layer of the soil.

The current investigation, ground response analysis is done with non-linear method of analysis using the DEEPSOIL software, created to conduct 1D analysis. This program has been created to perform one dimensional (1-

D) ground reaction investigations [23]. Linear and Equivalent Linear analysis in DEEPSOIL is done in the frequency domain whereas linear and nonlinear investigations is done in the time domain to examine the reaction of soil under seismic loading and make a near investigation of the result from the above said technique. Soil Column is discretized in different layers in case of Non-Linear model utilizing multi degree of freedom lumped parameter. Non-linear parameters of soil are dictated by linear mathematical incorporation technique [24]. Firstly the parameters have been given the values that compare to non-linear Darendeli modulus reduction and damping bends. A reference bend is then characterized for a soil layer dependent on its sort and related soil properties like Plastic Limit, Liquid Limit and so on. The reduction curves of G_s along with soil's D_s for sand, silt, clay dependent on Atterberg limits suggested by Darendeli have been allocated as reference bends in the current analysis [25]. At last for each and every layer, a bend fitting method is adopted to locate the above parameters that give a best fit to reduction curves of G_s along with soil's D_s. The thickness of soil strata is changed in accordance with the point that the most extreme frequency that the layer can proliferate falls between 25 Hertz to 50 Hertz. In this analysis, elastic half space bedrock with damping of 2 percent is considered.

3.1. Dynamic Properties of Soil

One of the most significant input parameters i.e., Shear Modulus (G_s) represent the stiffness of the soil layers. It likewise assumes a fundamental job in earthquake ground response analysis. At the surface, earth's motion parameters are normally acquired while performing one dimensional response analysis considering just the upward proliferation of shear wave. As shear modulus for study area isn't available so it has been determined utilizing available relationships SPT – N value and shear modulus (G_s) for various soil types. Connections can be chosen dependent on the type of soil and estimation of relationship coefficient (R). In the current investigation, correlations given in Table 2 have been selected as per the recommendations of Anbazhagan et al. (2012) study [26].

Table 2. Correlations for Calculation of Shear Modulus

Correlations	Soil Type	Author(s) Name
$G_s=24.28\times N^{0.55}$	Silty Sand with Less Percentage of Clay	Anbazhagan and Sitharam

3.2. Input Ground Motion

Earthquake Ground response investigation includes the selection of appropriate input earthquake ground motion based on PGA_{SUR}, earthquake's strength, earthquake's origin distance to area under consideration along with seismic site class, which is compatible with the maximum dynamic loading expected at the site of interest [27]. It is commonly perceived that while choosing suitable earthquake motion as an input, is considered as a significant function which influence response investigation of particular location. In India, although studies related to site response have been done in different areas, yet majority of those lacks demonstrative input motion of ground. The selection of time histories includes records that intently coordinate the characteristics of tectonic plates of particular site, strength of controlling earthquake and its location, characteristics of nearby site & response spectra and, trembling period of ground [28]. The Worldwide Standard Seismograph Network (WWSSN) in 1961, Global Digital Seismometer Network (GDSN) and Global Seismographic Network (GSN) in 1980 have significantly improved the comprehension of seismic tremor and tectonic process. Territorial varieties of instruments for recording the strength of earthquake in the nations having high chances of seismic activities [22]. For present analysis, PGA values for rock sites given in IS: 1893-2016 are used for the selection of acceleration time histories. Total 5 seismic motions are carefully chosen covering seismic hazard values for the study area. Table 3 illustrates five earthquake records and their characteristics such as date of occurrence, recording station, Location, Magnitude and Maximum horizontal acceleration. Suitable documented seismic data of Sikkim tremor (2011), India-Mayanmar earthquake (1997) and India-Burma earthquake (1988) recorded at bedrock location have been chosen for doing response study of ground.

Table 3. Characteristics of Seismic Motion

Strong Motion Parameter	Earthquake Input Ground Motion Considered				
	India Mayanmar Earthquake	India Burma Earthquake	India Burma Earthquake	India Burma Earthquake	Sikkim Earthquake
Year of Occurrence	1997	1988	1988	1988	2011
Magnitude, Mw	6.0	7.3	7.3	7.3	6.8
Location of Epicentre	24.894 N 92.250 E	26.020 N 93.770 E	26.000 N 92.860 E	25.980 N 91.480 E	27.723 N 88.064 E
Recording Station	Jellapur	Bokajan	Hojai	Nongston	Gangotak
PGA (g)	0.118	0.150	0.113	0.145	0.152
Designation	**IEM-01**	**IEM-02**	**IEM-03**	**IEM-04**	**IEM-05**

3.3. Surface Peak Ground Acceleration (PGASUR) of Study Region

The study of Non-linear response of ground is carried out to analyse situation for the sites of Jalandhar region with the help of computer program i.e. DEEPSOILv6.1 [29]. For this purpose, SPT-N profiles of 16 out of 45 boreholes were used for this study. Knowing the substrata details, one dimensional soil column is being generated in DEEPSOIL up to 30 m for all 16 boreholes of Jalandhar region. Using 30 m available data, input ground motions of Sikkim earthquake (2011), India-Mayanmar earthquake (1997) and India-Burma earthquake (1988) were used & motion of surface for particular location is obtained using DEEPSOIL Software. The PGA_{SUR} values were identified to be in the range of 0.196 – 0.292 g and Site amplification factor is found to be in the range of 1.08–2.01. PGA_{SUR} results were utilized to recognise various zones in the region with different degree of risk. PGA_{SUR} (Figure 6) for Jalandhar and its surrounding region is built.

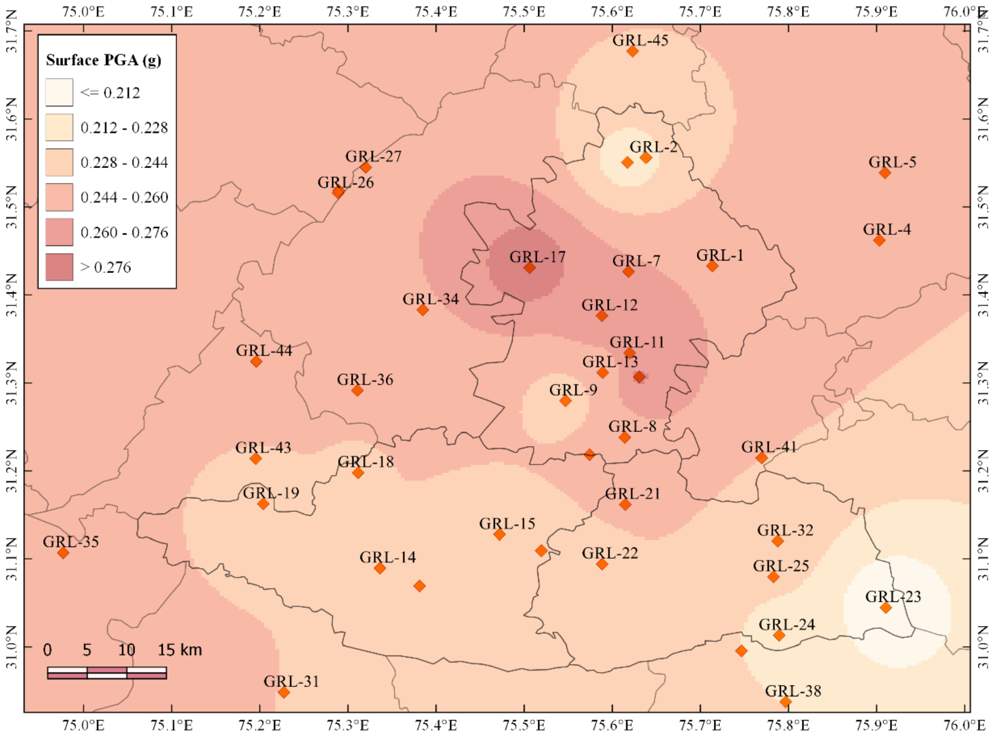

Figure 6. Surface PGA Map of the Study Region

4. Results and Discussion

The result of PGA_{SUR} obtained from the current examination is found to be in acceptable range with the previous investigations led in Jalandhar and its surrounding region. Naval and Sharma (2017) [4] carried out PSHA for Jalandhar & its surrounding region with the help of available seismic data for depth of 300 kilometer. Seven seismogenic sources has been considered for the carrying out PSHA of proposed smart city i.e., Jalandhar using Ground Motion Prediction Formula (GMPE) generated by National Disaster Management Authority of India. From the results, it has been found that PGA of the region varies from 0.16 to 0.30 g. Similarly, Deep et al. also conducted DSHA study for this zone considering seismic data of 509 years. Seismic hazard map has been developed for $0.025^{o}\times0.025^{o}$ size grid and it has been observed that PGA_{SUR} values lies between 0.140 to 0.280 g. It has also been observed that higher PGA values for the region lies in proximity to Lineament 2. For better estimation of seismic hazard in the NW Himalaya region [30], also conducted the studies related to PGA estimation in the region using stochastic approach and calculated values of PGA at 2346 locations covering an area of about 1000000 km^2 of NW Himalaya and provided a PGA map of the study area with extreme resolution of 0.2 degree for better estimate of seismic danger in the region. Higher surface PGA_{SUR} values (> 0.27 g) have been found for the middle portion of the study area including sites GRL-10, 11, 12 and 17 along with higher depth of GWT. These locations are found in the region of Site Class – D with higher SPT- N value. These locations indicate the presence of stiff sandy soil at shallow depth, which changes to dense soil at deeper depths. For the regions with shallow GWT, relatively lower response is found for those sites i.e. GRL-03, 09, 24 and 38. In this region, blend of fine aggregates such as clay, silt and fine to medium sand are the dominant soils. The obtained results of PGA_{SUR} are helpful in carrying out liquefaction studies of Jalandhar and its surrounding region.

4.1. Calculation of Soil's ability against Liquefaction

High magnitude seismic tremors that occurred in different countries reveal that, the damage of foundation soil because of liquefaction normally results into extreme damage to property and harm to people in metropolitan cities. Thus, depicting the areas inclined to failure of foundation soil, is important for assessment and decrease of seismic danger through proper technique. Initially, two geologists i.e. Seed et al. (1971) suggested simplified technique for evaluation soil's failure due to liquefaction. Further, a few techniques have been presented by different geologists. The failure of soil due to liquefaction is determined with the help of Stress based strategy suggested by Idris and Boulanger (2006) [31] along with IDRISS and another technique based on energy. The value of cyclic stress ratio (CSRS) and the cyclic resistance ratio (CRRS) is calculated on the basis of simplified technique proposed in 1971 by Seed et al. along with ensuing modifications of this technique by different geologists such as Seed et al. (1971); Youd et al. (1978); Idris and Boulanger (2006), is broadly used to assess the value of CSR_S and CRR_S. Based on the above factors, Safety factor for liquefaction (FOS_{LF}) is calculated considering Magnitude Scaling Factor (MSF) based on the following relation:

$$\text{Factor of Safety against Liquefaction}, FOS_{LF} = \left(\frac{CRR_{7.5}}{CSR}\right) \times MSF \tag{3}$$

Where, MSF = Magnitude Scaling Factor

If the CSR_S brought about by a quake is more noteworthy as compared to CRR_S then $FOS_{LF} < 1$ results in the failure of soil due to liquefaction. $FOS_{LF} > 1$ demonstrate that the resistance of soil against liquefaction exceeds the loading produced during earthquake, and therefore soil failure will not be expected. The greater FOS_{LF} in this way, implies soil is, is having extra resistance to failure.

4.2. Computation of Soil's Cyclic Stress Ratio (CSRS)

The excess pore pressure generation to start liquefaction relies upon the earthquake's amplitude and the duration of the earthquake induced cyclic loading. In the cyclic stress approach, the pore pressure generation is related to the cyclic shear stresses, hence the earthquake loading is represented in terms of cyclic shear stresses. The earthquake loading in terms of uniform cyclic shear stress amplitude has been evaluated by using Seed et al. (1971) simplified approach and subsequent revisions of the simplified procedures, based on the use of empirical correlations with standard penetration tests (SPT) given below:

$$\text{Cyclic Stress Ratio}, (CSR) = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma_{vo}'}\right) \times r_d \tag{4}$$

In this equation, parameter a_{max} represents peak ground acceleration at top surface produced by a quake; g = acc. because of earth's gravity; σ_{vo} and σ_{vo}' are the vertical overburden stresses (total and effective) at z depth & r_d = reduction coefficient of shear stress. Also, 0.65 is the factor considered for the change of irregular Earthquake loading into comparable uniform stress cycle Youd et al. (1978). The reduction factor, r_d, varies with depth and it equals to one at the ground surface. The following equation reported by Youd et al. (1978), are recommended to determine the average values of r_d:

$$r_d = \left(\frac{1.000 - 0.4113z^{0.5} + 0.04052z + 0.001753z^{1.5}}{1.000 - 0.4177z^{0.5} + 0.05729z + 0.006205z^{1.5} + 0.0012105z^2}\right) \tag{5}$$

4.3. Computation of Soil's Cyclic Resistance Ratio (CRRS)

CRR_S is an amount of the soil resistance against its failure due to liquefaction. The CRR_S of the soil at site is principally founded on relationship to these tests. These equations have been created from information based on liquefied and non-liquefied soils documented in past seismic tremors. The CRR_S arc for fines less than 5 percent is the general criterion of penetration for the simplified technique and is stated as the "SPT clean sand base curve." To determine CRR_S, fine content (FC_S) of the soil is required in order to revise SPT blow count $(N_1)_{60}$ to an corresponding clean sand SPT resistance value $(N_1)_{60cs}$. Idris and Boulanger (2006) proposed an Equation 6 for evaluation of CRR_S value for soil having zero cohesion and little any fines [31].

$$CRR_{7.5} = \left(\frac{1}{14.1 - (N_1)_{60cs}} + \left(\frac{(N_1)_{60cs}}{135}\right)^2 - \frac{(N_1)_{60cs}}{[45 + 10(N_1)_{60cs}]^2} - \frac{1}{200}\right) \tag{6}$$

The CRR_S depends on the $(N_1)_{60}$ and percentage of fines in soil. In 1971, Seed et al., prepared the data representing the difference of CRR with $(N_1)_{60}$ against fine content of 5, 15 and 35 percent. Later on, in 1978, Youd et al. suggested fewmodification and prepared improved curves. Youd et al. (1978) also presented relationships resembling these curves and considered in this study. Equation 5 can be used to compute the results of CRR_S with earthquake of strength 7.5 M for 5 percent fine contents. For higher fine contents (FC in percentage), the value of $(N_1)_{60}$ is modified using Equation 7 before using Equation 6.

$$(N_1)_{60cs} = \alpha + \beta\ (N_1)_{60} \tag{7}$$

Where; $(N_1)_{60cs} = N\ values\ with\ fines\ correction$ and α & β are the constants determined from the following equations:

$$\alpha = 0;\ \beta = 1.0, \text{for FC} \leq 5\ \% \quad (8a)$$

$$\alpha = \exp\left[1.76 - \left(\frac{190}{FC^2}\right)\right];\ \beta = 0.99 + \left(\frac{FC^2}{1000}\right) \text{ for } 5\% < \text{FC } 35\% \quad (8b)$$

$$\alpha = 5.0;\ \beta = 1.2, \text{for FC} > 35\ \% \quad (8c)$$

Equation 6 provides the value of CRR for 7.5 magnitude earthquake. Despite the fact that the earthquake utilized for the current analysis isn't of M = 7.5, the scaling factor of earthquake magnitude (MSF) is taken to find out the equivalent cyclic stress ratio for 7.5 magnitude earthquake. In 1971, Seed et al. introduced MSF to alter the value of CRR_S for earthquake of strength other than 7.5. Accordingly, values of CRR for other magnitude earthquake are as follows:

$$CRR = CRR_{7.5} + MSF \quad (9)$$

Where, MSF i.e., Magnitude Scaling Factor is defined by the following equation:

$$\text{MSF} = \frac{10^{2.24}}{M^{2.56}} \quad (10)$$

Where, M = Moment magnitude.

4.4. Evaluation of Factor of Safety against Liquefaction (FOSLF)

Liquefaction's safety factor for soil (FOS_{LF}) is normally utilized to determine the possibility of liquefaction. As mentioned, CSR and CRR are the two factors used to determine the safety factor using the following equation considering scaling factor of expected earthquake's magnitude in the study zone.

$$\text{Liquefaction's safety factor}, FOS_{LF} = \left(\frac{CRR_{7.5}}{CSR}\right) \times MSF$$

In the event that the Cyclic Stress Ratio brought about by the seismic tremor is more than the Cyclic Resistance Ratio of soil, at that point FOS_{LF} will be less than 1 and liquefaction might happen during a quake. Liquefaction will not happen if FOS_{LF} is higher than 1 and also the resistance to liquefaction excel the seismic loading. So, soil's resistance to liquefaction will increase with the increase in safety factor.

4.5. Liquefaction Potential Mapping of the Study Region

For the present study, data from 45 locations of Jalandhar and its surrounding regions were considered for the evaluation of Liquefaction. The map showing the borehole locations of the study region are shown in Figure 2. Susceptibility to soil liquefaction is defined as resistance of soil to liquefaction and it is calculated on the basis of different parameter such as the presence of cohesionless soil at depth < 20 meters, shallow GWT (< 10 meters) and SPT number under 20 [32]. Figure 7 represents the Soil Liquefaction susceptible plan for the Jalandhar and its surrounding region.

The liquefaction's safety factor (FOS_{LF}) for Jalandhar and its surrounding locations were computed by method suggested by Seed et al. (1971). The factor of safety (FOS_{LF}) values were evaluated with different PGA values (estimated from GRA using DEEPSOIL Software) varies from 0.128 – 0.292 g (Figure 3) assuming tremor of magnitude = 6.0 and 7.0, that can be considered in the research area. The least safety factor has been selected from the calculated values to express the liquefaction's safety factor, which can be further utilized for preparing maps on GIS (Geographic Information System) platform using QGIS 2.18.2 software to show the contour map for safety factor of the study area. FOS_{LF} for 6.0 magnitude earthquake of Jalandhar and its surrounding region is presented in Figure 4. Out of 45 sites, FOS_{LF} for 16 sites is lower than one and found to be susceptible to liquefaction. From the figure, it has been observed that the soils of region Kapurthala, Beas, Ladowal, Sultanpur Lodhi and Tanda are found to be affected by liquefaction with $FOS_{LF} < 1$. This might be because of existence of filled up soil at shallow depth followed by bed of fine to medium sand with the presence of silt Here also the water below the ground is located at shallow depth for the sites of Beas, Kapurthala and Sultanpurlodhi. $FOS_{LF}>1$ has been identified at sites located in the region of Jalandhar, Phillour, Nawansher, Bhogpur, Lohian and Phagwara. These areas witness the level of water below the ground higher extent. Major part of these regions shows FOS_{LF} more than two because of the existence of clayey and silty particles in sand having SPT-N values of 30 and above.

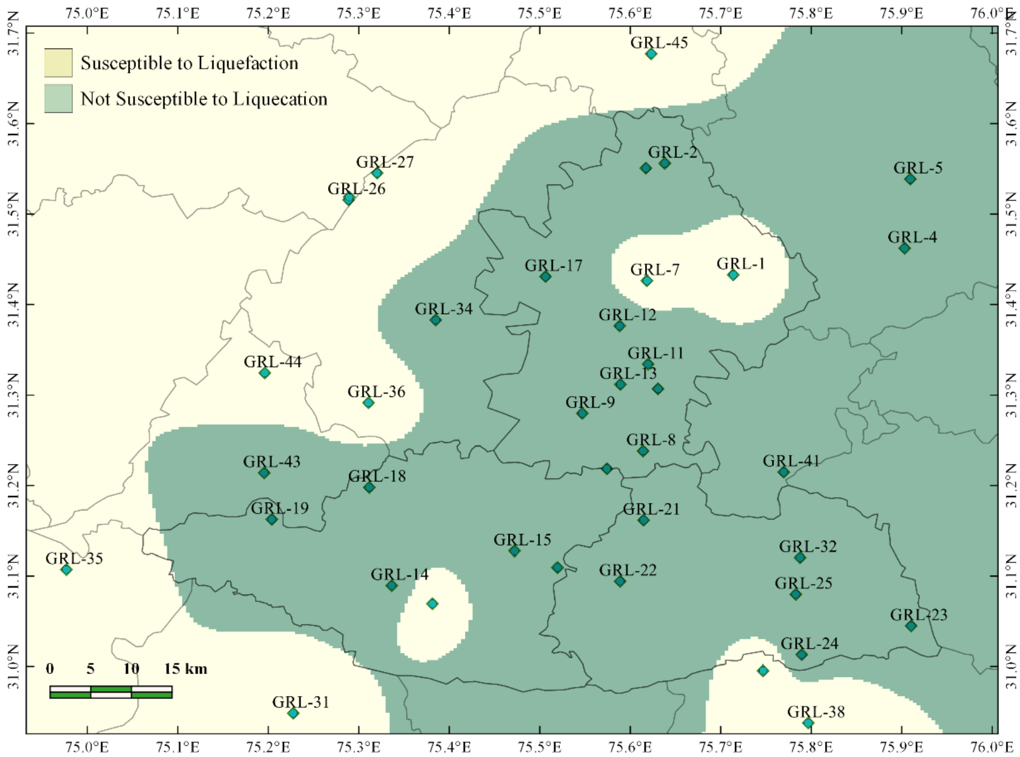

Figure 7. Liquefaction Susceptibility Map for Jalandhar and its surrounding region.

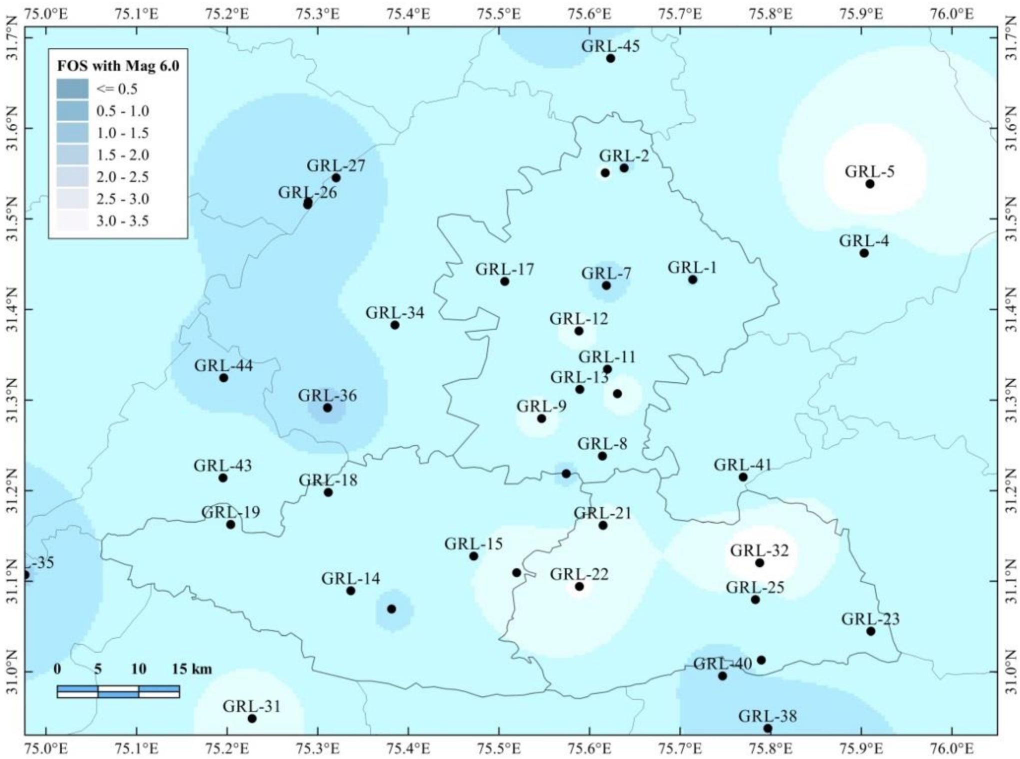

Figure 8. FOS_{LF} for 6.0 Magnitude Earthquakes

Similarly, FOS_{LF} for 7.0 M magnitude earthquake is calculated and hazard map for the same is presented in Figure 9. Of the 45 sites of Jalandhar and its surrounding regions, FOS_{LF} considering the above-mentioned magnitude, is found less than 1 for the 18 sites and found susceptible to liquefaction. The map shows that increase in the magnitude increases the CSR values and thus increasing the possibility of liquefaction susceptibility. From the risk map produced, it has also noticed that sites GRL-04, 05, 25, 32 located in the NE region, sites GRL-08, 09, 10, 11, 12, 13 located in the central region and few sites GRL-18, 19, 43 located in SW region are found safe against liquefaction. Figure 9 shows the contour map represents the dispersion of safety factor for soils of Jalandhar and its surrounding areas for 7.0 magnitude earthquake.

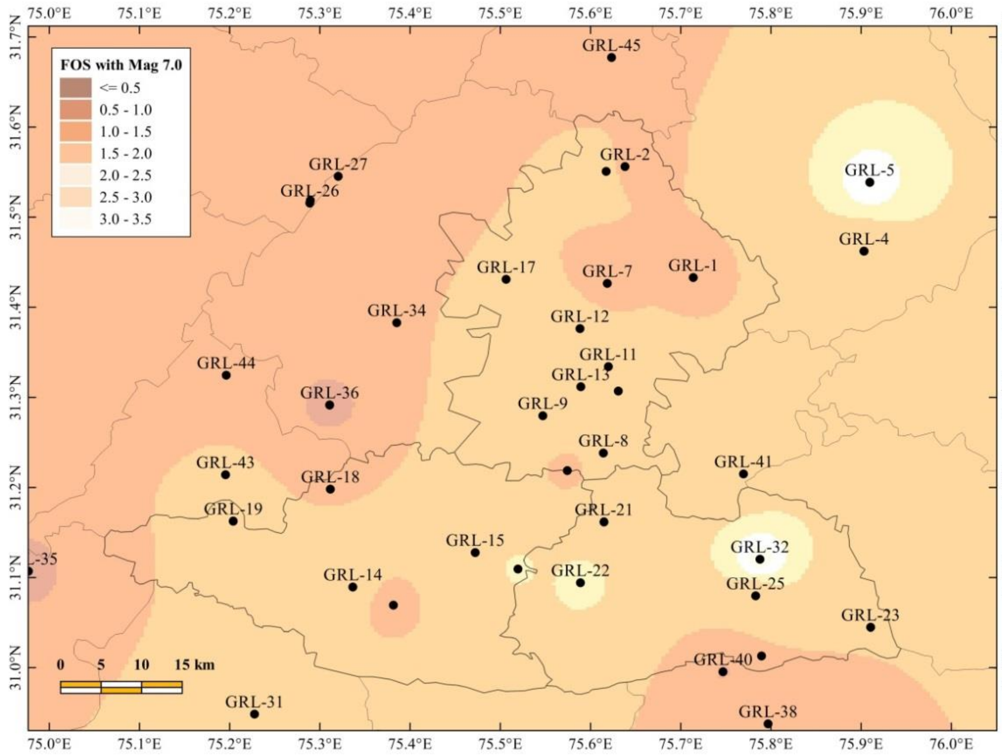

Figure 9. FOS_{LF} for 7.0 Magnitude Earthquakes

5. Conclusions

This paper presents a detailed work of seismic site response investigation along with assessment of Soil liquefaction for Jalandhar and its surrounding region using SPT bore log data. Liquefaction susceptibility of the region has been evaluated on the basis of the existence of sandy strata up to the depth of 20 meters, GWT at shallow level (less than 10m) along with lower N-value (< 20). The outcomes are obtained in terms of soil's safety factor in terms of liquefaction (FOS_{LS}) and seismic hazard maps, depicting the vulnerable zones in the study region. On the basis of the results obtained, it may be concluded under:

- Average shear wave velocity (V_{S30}) upto 30 m depth varies from 154 to 440 m/s for GRL-40 & GRL-12. Soils with lower V_{S30} values will experience more amplification as compared to the soils having higher V_{S30} values. The majority of sites falls under the seismic class "D" however couple of locations have a place with seismic site class "C" and a not many to "E"
- The PGA value at top surface varies from 0.128 to 0.292 g for GRL-23 & GRL-17. Higher surface PGA (more than 0.24 g) has been observed at sites GRL-04, 05, 06, 10, 11, 12, 14, 17, 19, 18, 22, 31, 34 & 43 due to higher number of SPT & deeper depth of ground WT.
- The liquefaction susceptibility map of the study region is prepared and it has been found that 17 sites Viz at Adampur (01), Bhogpur (01), Kapurthala (03), Beas (03), Dasuya (02), Ladowal (04), Tanda (01), Sultanpur Lodhi (01) and Jalandhar (01) are likely to be liquefied.
- The FOS_{LF} for 45 sites is determined considering earthquakes of Magnitude M = 6.0 & 7.0. It has been found that out of 45 sites, 16 sites are found susceptible to liquefaction for earthquake of magnitude M = 6.0 & 18 sites for M = 7.0. This infers the importance of seismic tremor strength for the evaluation of Soil's liquefaction, regardless of its type and depth of ground WT of the location. The results so obtained has been represented as a safety factor against soil failure in terms of liquefaction & prepared risk maps for the region. Liquefaction potential maps are prepared using interpolation technique in QGIS software for earthquake of magnitude M = 6.0, & 7.0. These maps are very useful to identify locations with possible risk of liquefaction and mitigation measures can be suggested accordingly. Therefore, the risk maps prepared from the current study will help the professionals during designing and planning of structures in future.

6. Conflicts of Interest

The authors declare no conflict of interest.

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