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PRELIMINARY INVESTIGATION FOR SCREENING OF LIQUEFIABLE AREAS IN THE STATE OF HARYANA, INDIA

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ABSTRACT

Liquefaction susceptibility of state of Haryana has been analysed by using geological and geomorphological characteristics of the area. Soil resource maps, geomorphological maps, earthquake hazard maps and ground water table data have been used for assessing liquefaction potential. A liquefaction susceptibility map has been prepared which can be used as initial rough screening guide for subsequent detailed assessment of liquefaction vulnerability of the state. The state has been classified into three zones in terms of liquefaction susceptibility value (L_s) for its proneness to liquefaction; high ($L_s \geq 0.8$), moderate ($0.5 < L_s < 0.8$) and low ($L_s \leq 0.5$). It has been observed that the high susceptible areas lie mainly in National Capital Region (NCR) and extend along the National Highway-1 (NH-1). The results have also been validated using semi-empirical procedure based on geotechnical criteria.

KEYWORDS: Earthquake, Geology, Geomorphology, Liquefaction susceptibility

LIST OF SYMBOLS

L_s-Liquefaction Susceptibility Value

PGA (g)-Peak Ground Acceleration

V_s-Shear Wave Velocity

SPT-Standard Penetration Test

INTRODUCTION

Liquefaction and related phenomena have been responsible for heavy damages in past earthquakes round the world particularly in urban areas. Liquefaction related issues evolved in India in wake of Bihar (1934) and Bhuj (2001) earthquakes. Different liquefaction features of sand boils, craters, lateral spreading etc. were observed during these earthquakes (Rajendran et al., 2001). Soil liquefaction has been a major cause of damage to life and property in these earthquakes and it clearly poses a significant threat to life and property in other states too during future earthquakes.

Based on the type of data available, liquefaction hazard mapping can be carried out by different methods, e.g. deterministic approach, probabilistic approach and susceptibility mapping based on geological and geomorphological characteristics. Iwasaki et al. (1982) and Wakamatsu (1992) have correlated liquefaction susceptibility to geomorphological and geological characteristics. Similar methodology was suggested for Shonai Plain, Japan (Kotodaet al., 1988).During the assessment of liquefaction susceptibility, the age of deposit and depth of water table are also considered important factors (Obermeier, 1996). Manmade fills and young Holocene sediments in particular are susceptible to liquefaction (Youd and Perkins, 1978). Similar studies have been conducted for Chennai City, India (Ganapathy and Rajawat, 2012), Laoag City, Northern Philippines (Beroya and Aydin, 2007) and Delhi, India (Mohanty et al., 2007).

In the present study, liquefaction susceptibility of state of Haryana has been analysed by using geological and geomorphological characteristics of the area. The Grade-Ihazard map (TCEGE, 1999) developed in the present study would serve as a rough guide for identifying zones where earthquake induced liquefaction is anticipated and hence a detailed investigation may be required.

DESCRIPTION OF THE STUDY REGION

Haryana is the Northern State of India, sprawling over an area of 44212 km^2. It ranks 19^{th} in terms of area in the country. It is surrounded by the states of Uttarakhand, Himachal Pradesh and Shiwalik hills on the North, Uttar Pradesh on the East, Punjab on the West and Delhi, Rajasthan and Aravali hills on the South. It is positioned between 27^o 37'- 37^o 35' latitude and between 74^o 28'- 77^o 36' longitude. Its altitude ranges from 700 to 900 ft above mean sea level. Haryana has a population of 25.353 million as per census of 2011 (Govt. of Haryana, 2016).

1. Geological-cum-Geomorphological Setting

The state of Haryana and the adjoining areas are covered to a large extent by Quaternary sediments of alluvial/aeolian origin. The geological set-up of the area comprises the sub-Himalayan system of rocks, mostly belonging to Siwalik Group which is exposed in the north-eastern extremity and adjoining parts. In the south and south-western corner of Haryana bordering the state of Rajasthan, older rocks belonging to Delhi Supergroup are exposed. In between lays the vast stretch of Quaternary sediments of alluvial/aeolian origin. The different geomorphic units recognised include:(1) High structural hills, (2) Moderate structural cum denudational hills, (3) Low structural-cum-denudational hills, (4) Older and younger piedmont zones, (5) Flood plain, (6) Older Alluvial surface, (7)Aeolian zone, (8) Transitional zone and(9) Upland tract.

Except the river Yamuna flowing along the eastern boundary of the state, the only other stream is the Ghagghar. This river appears to be structure controlled and flows along well-defined tectonic lines. The southerly to south-easterly direction of flow of the river Yamuna indicates a basement high. The topographical low passing through Delhi-Rohtak-Hisar and Sirsa appears to coincide with basement high and the gradual shift in the drainage system indicates some neotectonic activity in the region (GSI, 2012).

According to assessment of Ministry of Water Resources, flood prone area in Haryana is about 23500 km^2. In recent history, devastating floods hit Haryana in 1977, 1978, 1980, 1983, 1988, 1993, 1995 and 2010. The floods in Haryana occur frequently because of its physiographic situation. In Haryana, a depression saucer shape zone exists around Delhi-Rohtak-Hisar-Sirsa axis and it has a poor drainage system and sometimes heavy precipitation becomes a major contributing factor in causing floods as it was during Rohtak flood (August, 1995). The flood in these areas occurs mainly due to heavy runoff from the hilly terrain and overflow of river Yamuna in the plain areas during Monsoons (DTCP, 2010). A map prepared by Bureau of Material and Technology Promotion Council (BMTPC, 2007) and printed in Vulnerability Atlas of India (First Revision) is shown in Figure 1 highlighting the flood prone areas in Haryana.

2. Tectonic Setting

The State of Haryana falls in three Seismic Zones viz. II, III and IV, creating low to moderate damage risk from earthquakes. Ambala, Sonipat, Rohtak, Karnal, Gurgaon, Faridabad, Panipat, Rewari and Yamunanagar districts lie in Zone IV. The districts of Kurukshetra, Jind, Hisar, Bhiwani, Mahendragarh and Kaithal lie in Zone III, while only Sirsa District lies in Zone II (BIS, 2002). An earthquake hazard map for Haryana state is prepared by Bureau of Material and Technology Promotion Council (BMTPC, 2007) and printed in Vulnerability Atlas of India (First Revision) is shown in Figure 2. The region remains susceptible to earthquakes due to the following faults (Puri and Jain, 2015):

a) Aravali-Delhi Fold Belt: It includes Mahendragarh Dehradun Subsurface Fault, Mathura Fault and several major and minor lineaments.

b) Himalayan Thrust System: It includes mainly Main Boundary Thrust, Main Crustal Thrust and Jwala Mukhi Thrust along various other tectonic features.

c) Moradabad Fault.

d) Sardar Shahar Fault.

In the recent past, no major earthquakes have hit Haryana but shocks are felt whenever an earthquake occurs in areas of Himalayan Thrust System.

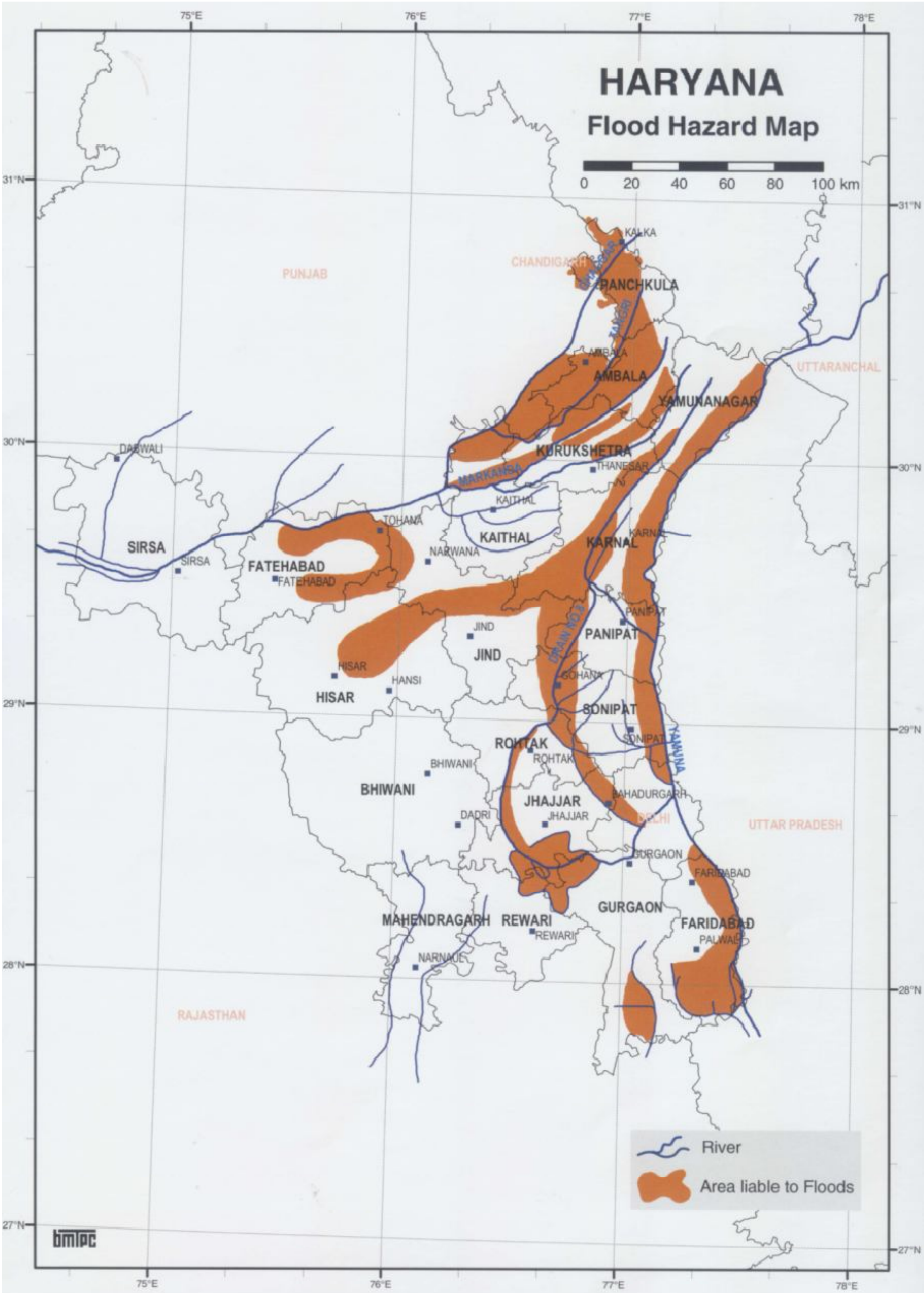

Fig. 1 Flood Hazard Map (BMTPC, 2007)

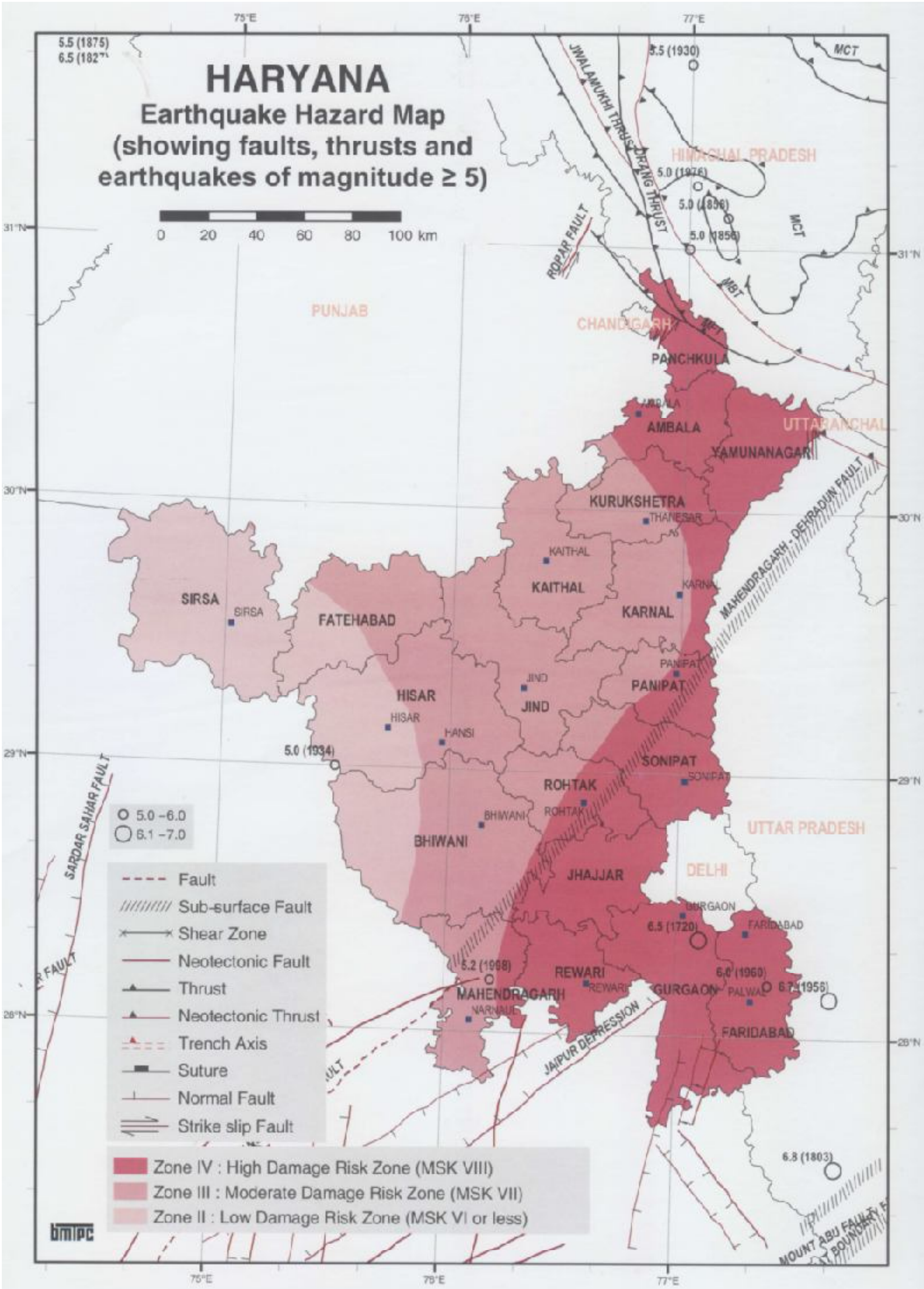

Fig. 2 Earthquake Hazard Map (BMTPC, 2007)

METHODOLOGY

Regional study based on geological and geomorphological data has been conducted to delineate areas where liquefaction could be triggered by a sufficiently large earthquake. Soil resource maps, geomorphological maps, earthquake hazard maps and ground water table data have been used for assessing liquefaction potential. A liquefaction susceptibility map has been prepared which can be used as initial rough screening guide for subsequent detailed assessment of liquefaction vulnerability of the state. The results have also been validated using semi-empirical procedure based on geotechnical criteria (Idriss and Boulanger, 2006).

Several investigators have successfully correlated geological and geomorphological characteristics with assessment of liquefaction susceptibility. The classifications proposed by Youd and Perkins (1978), Iwasaki et al. (1982), Wakamatsu (1992) and Obermeier (1996)are reported in Tables 1 to 4.

Table 1: Liquefaction Susceptibility of Geomorphological Units (Youd and Perkins, 1978)

Type of deposits	General distribution of deposits	Likelihood that cohesionless sediments, when saturated, would be susceptible to liquefaction (by the age of deposits)			
		<500 years	Holocene	Pleistocene	Pre-Pleistocene
River channel	Locally variable	Very High	High	Low	Very low
Flood plain	Locally variable	High	Moderate	Low	Very low
Alluvial fan and plain	Widespread	-	Low	Very low	Very low
Marine terrace and plain	Widespread	Moderate	Low	Low	Very low
Delta and fan-delta	Widespread	High	Moderate	Low	Very low
Lacustrine and playa	Variable	High	Moderate	Low	Very low
Colluvium	Variable	High	Moderate	Low	Very low
Talus	Widespread	Low	Low	Very low	Very low
Dunes	Widespread	High	Moderate	Low	Very low
Loess	Variable	High	High	High	Very low
Glacial till	Variable	Low	Low	Very low	Very low
Tuff	Rare	Low	Low	Very low	Very low
Tephra	Widespread	High	High	-	-
Residual soils	Rare	Low	Low	Very low	Very low
Sebkha	Locally variable	High	Moderate	Low	Very low
Delta	Widespread	Very High	High	Low	Very low
Estuarine	Locally variable	High	Moderate	Low	Very low
Beach- High wave energy	Widespread	Moderate	Low	Very low	Very low
Beach -Low wave energy	Widespread	High	Moderate	Low	Very low
Lagoonal	Locally variable	High	Moderate	Low	Very low
Fore shore	Locally variable	High	Moderate	Low	Very low
Loose fill	Variable	Very High	-	-	-
Compacted fill	Variable	Low	-	-	-

Table 2: Liquefaction Susceptibility of Various Geomorphological Units (Iwasaki et al., 1982)

Rank	Geomorphological units	Liquefaction potential
A	Present river bed, old river bed, swamp, reclaimed land and inter-dune low	Liquefaction likely
B	Fan, natural levee, sand dune, flood plain, beach and other plains	Liquefaction possible
C	Terrace, hill and mountain	Liquefaction not likely

Table 3: Liquefaction Susceptibility of Various Geomorphological Units at Ground Motion of the MMS VIII (Wakamatsu, 1992)

Classification	Specific conditions	Liquefaction potential
Valley plain	Consisting of gravel or cobble	Not likely
	Consisting of sandy soil	Possible
Alluvial fan	Vertical gradient>0.5%	Not likely
	Vertical gradient<0.5%	Possible
Natural levee	Top of natural levee	Possible
	Edge of natural levee	Likely
Back marsh		Possible
Abandoned river channel		Likely
Former pond		Likely
March and swamp		Possible
Dry river bed	Consisting of gravel	Not likely
	Consisting of sandy soil	Likely
Delta		Possible
Bar	Sand bar	Possible
	Gravel bar	Not likely
Sand dune	Top of dune	Not likely
	Lower slope of dune	Likely
Beach	Beach	Not Likely
	Artificial beach	Likely
Inter-levee lowland		Likely
Reclaimed land by drainage		Possible
Reclaimed land		Likely
Spring		Likely
Fill	Fill on boundary zone between sand and low land	Likely
	Fill adjoining cliff	Likely
	Fill on marsh or swamp	Likely
	Fill on reclaimed land by drainage	Likely
	Other type of fill	Possible

Table 4: Liquefaction Susceptibility of Various Geomorphological Units (Obermeier, 1996)

Age of Deposit	Depth of Water Table		
	0-3 m	3-10 m	10 m
Latest Holocene	High	Low	Nil
Earlier Holocene	Moderate	Low	Nil
Late Pleistocene	Low	Nil	Nil

On the basis of soil resource maps, geomorphological maps, earthquake hazard maps, flood hazard maps and ground water table data of the area as reported in Figures1 to 4 and using Tables1 to 4, various geological, geomorphological and seismic units in the study region have been identifiedand have been reported in Table 5. These units have been considered in order to prepare Grade-I liquefaction susceptibility map for the State.

Table 5: Critical Units of Study Region

Lithology	Geomorphology	Water Table	Anticipated PGA (g)as per IS:1893-2002	Liquefaction
Sands and Non-Plastic Silts	Flood plains, River beds, Young deposits (age<500 years)	0 to 10 m	0.24, corresponding to zone IV	Likely
Loams	Holocene deposits	10 to 20 m	0.16, corresponding to zone III	Possible
Clays and Plastic Silts	Pleistocene and older deposits	>20 m	0.10, corresponding to zone II	Not likely

LIQUEFACTION ASSESSMENT

1. Lithology

Lithological characteristics like grain size and depth of soil deposits play a crucial role in determining the magnitude of ground shaking. It is because in granular soils and artificial fills (loose), the shear wave velocity (V_s) is very low and subsequent ground shaking is very high. Moreover, ground shaking during an earthquake is further amplified by the granular soils. Soils formed by processes that lead to a uniform grain size distribution and deposition in loose state are likely to liquefy when saturated (Sitharam et al., 2004).

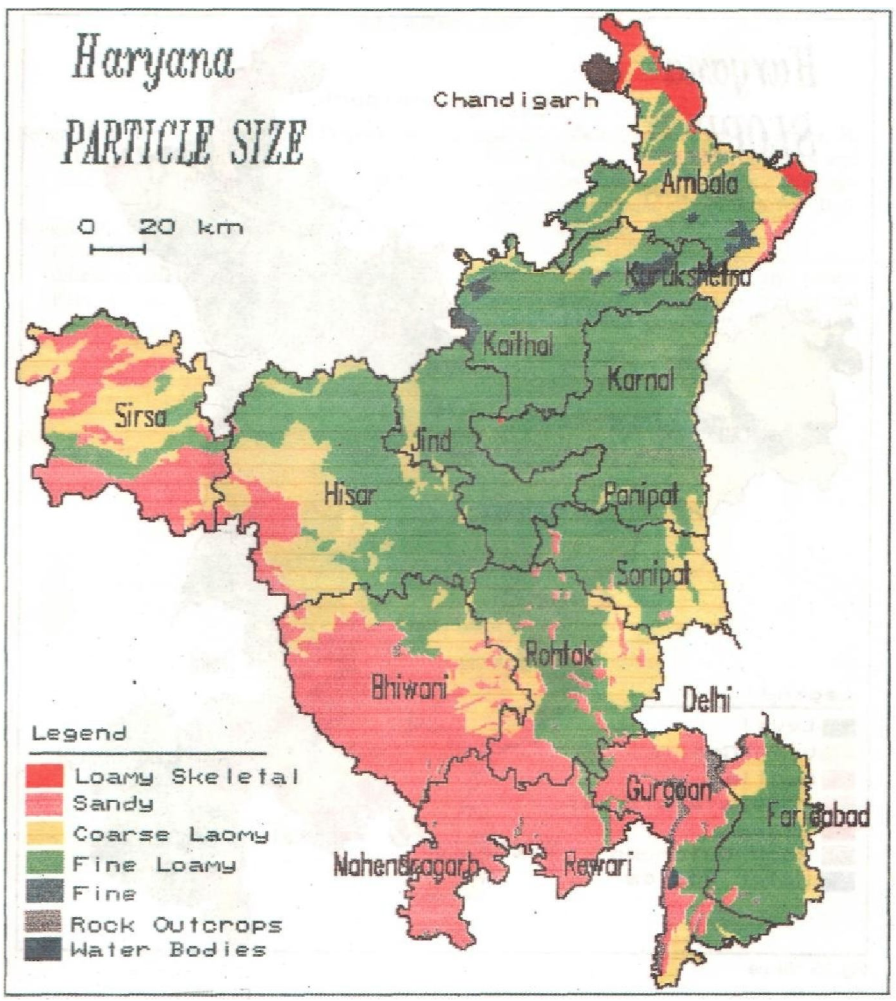

Fig. 3 Soil Resource Map (Sachdev et al., 1995)

A soil resource map has been developed by National Bureau of Soil Survey and Land Use Planning (Sachdev et al., 1995) at a scale of 1:250000 has been used in the study and is shown in Figure 3. It has been observed that in districts of Bhiwani, Gurgaon, Mahendragarh, Rewari and some parts of Sirsa and Hisar, sand is the major soil type. Hence, these districts are highly susceptible to liquefaction during earthquakes. In districts of Ambala, Kaithal, Kurukshetra and Mewat, large areas with fine grained soils have been observed, which makes these regions less susceptible to liquefaction. In most parts of Panchkula District, rock layer has been observed at surface or at shallow depth, which makes the region not or less susceptible to liquefaction hazard.

In other regions, loamy soils are found in abundance, which makes them moderately susceptible to liquefaction. However, for loamy soils, strong experimental basis is required to conclude whether they would liquefy or not during earthquakes (Boulanger and Idriss, 2006).

2. Geomorphology

Flood plains are expected to have sand deposits underneath silt-clay layers (Beroya and Aydin, 2007). Hence these floods plains are susceptible to liquefaction during earthquakes. A large part of Haryana along National Highway-1 comes under the category of flood plains as shown in Figure 1.Another important geomorphological unit is age of the deposit. Young deposits are more susceptible to liquefaction as compared to the older deposits. A map describing the age of soil deposits of Haryana prepared by Geological Survey of India (GSI, 1973) is shown in Figure 4. It has been observed that soil deposits in Haryana belong to Holocene and Pleistocene age group. Hence their susceptibility to liquefaction is moderate to high.

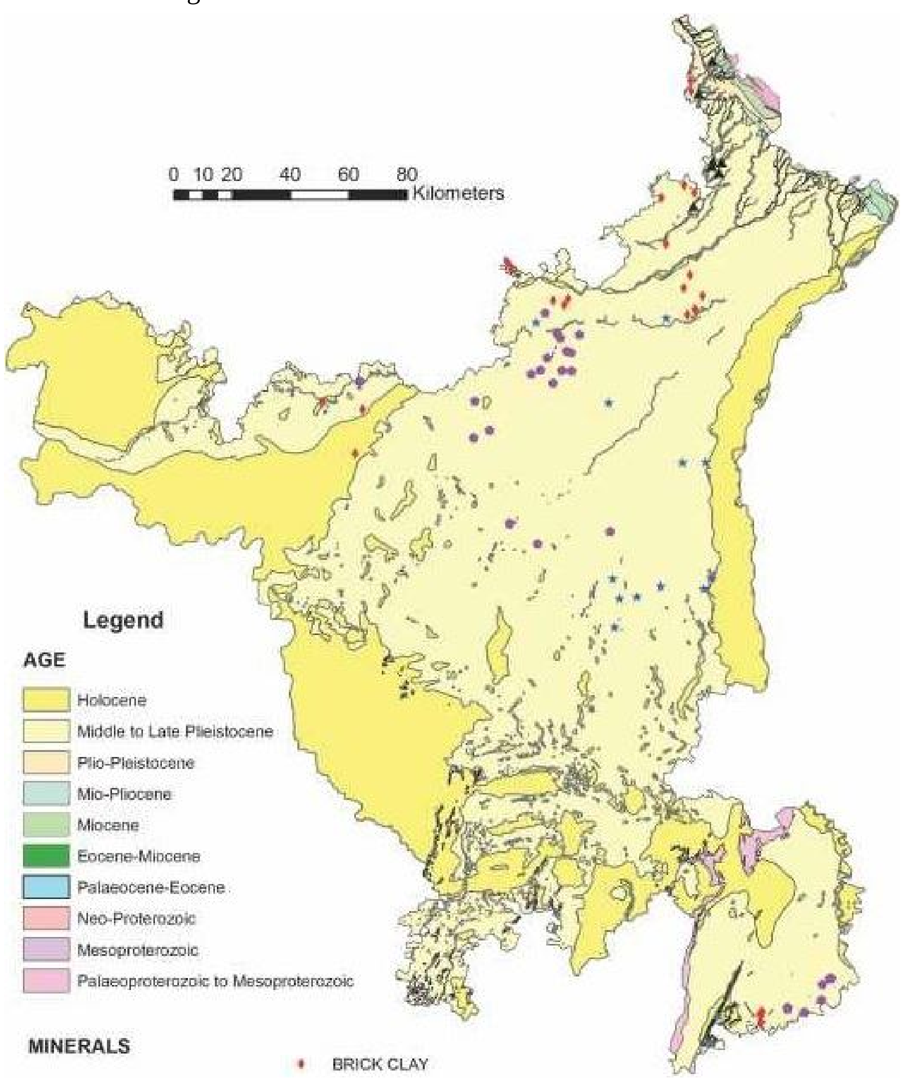

Fig. 4 Geomorphological Mapof Haryana (GSI, 1973)

3. Depth of Ground Water Table

Liquefaction is most likely to occur in areas where ground water table lies within 10 m of the ground surface. There are few instances of liquefaction having occurred in areas with ground water table deeper than 20 m. Ground water conditions in State of Haryana have been analysed using ground water data collected by Central Ground Water Board, Chandigarh (CGWB, 2013) and have been mapped using nearest neighbour interpolation as shown in Figure 5.

In many districts of Haryana, the depth of ground water table is within the liquefiable zone i.e. less than 20 m. Also, some of the districts are dealing with the problem of subsurface water logging. These regions are highly susceptible to liquefaction during earthquakes. However, in district of Gurgaon, ground water table is 30 to 40 m below ground level, which makes the region very less susceptible to liquefaction.

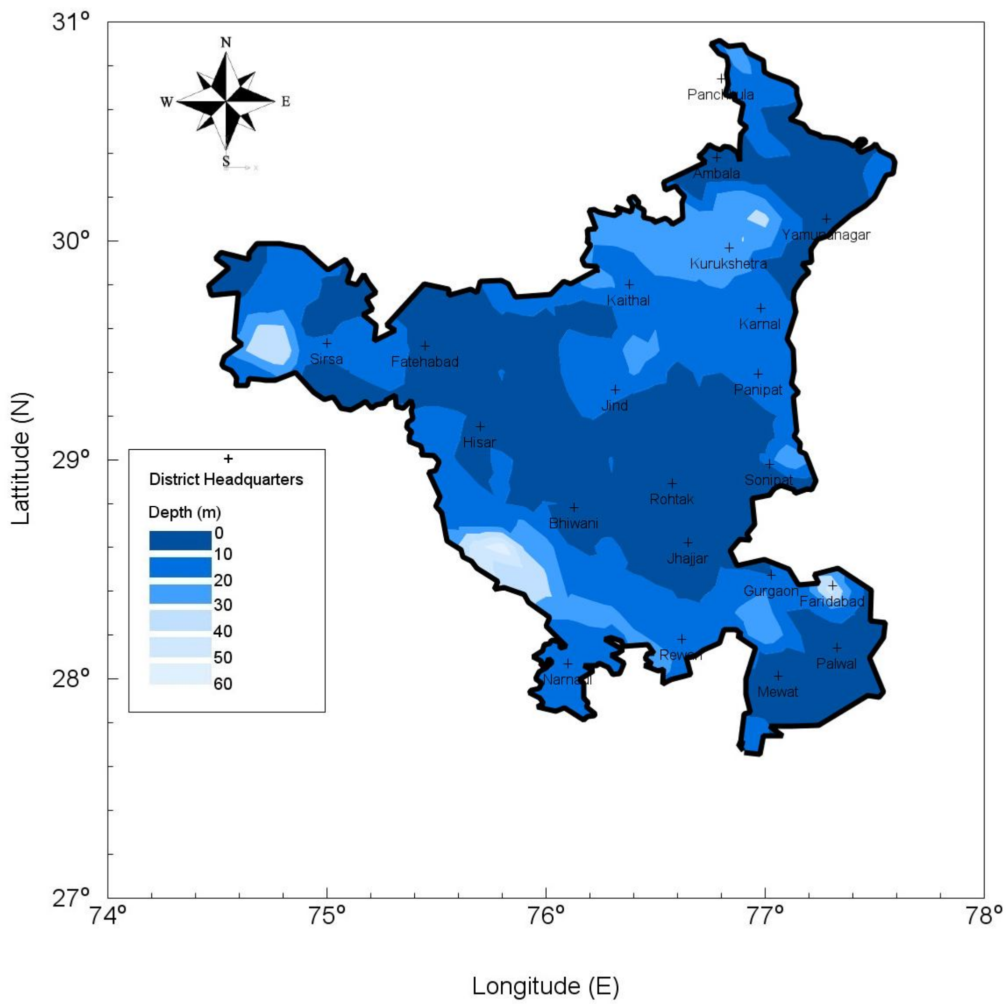

Fig. 5 Water Table Map

4. Seismic History of Haryana

In order to understand seismicity of Haryana, data regarding past earthquakes with magnitude$\geq$2.0 have been collected for a period of 55 years (1960-2014) from online portal of Indian Meteorological Department (IMD, 2014). It has been observed that during January1960 to November 2013, there have been 46 earthquakes in Haryana and nearby areas having magnitude (M) ranging from 2.3 to 6.0. Also, it has been observed that in districts of Sonipat, Rohtak and Jhajjar, maximum number of seismic events have occurred.

However, districts of Sirsa, Fatehabad, Hisar, Kaithal, Karnal, Panipat, Yamuna Nagar, Panchkula, Mewat and Palwal have been reported as seismically less active. In rest of the districts, few incidents of noticeable earthquakes have been reported.

No major earthquake has yet occurred in the state, but possibility is not ruled out as a large area of Haryana lies in Zone IV. Moreover, adjoining state of Delhi also falls in Zone IV and if any major earthquake occurs in Delhi, it would impact the surrounding area of 300 km. Experts predict that in the coming 50 years the region is bound to be hit by a severe earthquake of magnitude more than 6.0 on the Richter's scale. There is 80% probability of occurrence of an earthquake of the magnitude 7.0. This forecast is based on the detailed analysis of past earthquakes and underground movement of the region backed up by satellite imageries (Srow, 2013). Greater numbers of tectonic activities have occurred in Sonipat, Rohtak and Jhajjar districts during a short span of time, which makes them susceptible to liquefaction too.

5. Liquefaction Susceptibility of State of Haryana

Liquefaction susceptibility of the State of Haryana has been assessed by integrating the available information from earthquake hazard maps, flood hazard maps, ground water profile, lithological maps and other relevant reports of various government organizations. Various geomorphological, geological and seismic units have been identified in the study area. The analysis has been carried out following Saaty's Analytical Hierarchy Process (Saaty, 1990). Analytical Hierarchy Process (AHP) is a multiple criteria mathematical evaluation method in decision making tools, specifically used for dealing with problems of spatial nature. A comparison matrix has been constructed on a scale of 1-3, 1 indicates that the two units are equally important, 2 shows that one unit is somewhat important than other and 3 implies that one element is moderately important than other. If an element is less significant than the others then it is indicated by reciprocals of 1-3 values (i.e. 1/1 to 1/3). The comparison matrix prepared for the study is reported in Table 6.

Table 6: Comparison Matrix

Units	Geomorphology	Lithology	PGA	Water Table
Geomorphology	1	1/3	1/3	1/3
Lithology	3	1	1/2	1/2
PGA	3	2	1	1/2
Water Table	3	2	2	1

Using the comparison matrix, weightage corresponding to each unit has been calculated. It is carried out by converting elements of comparison matrix into decimals and then calculating the principle Eigen vector of the matrix. This process is repeated until the Eigen vector solution becomes equal or very close to the previous iteration. The final Eigen vector represents the weights of different units. A value of 0.044 has been observed as consistency ratio, which shows that the weightages developed are very much consistent. The rating of features for each unit has also been normalized between 0 to 1 (Nath, 2004) to ensure that no unit exerts influence beyond its determined weightage. Influence factors corresponding to each feature (i.e. normalized ratings) have been calculated using the Equation (1):

$$x_i = \frac{R_j - R_{min}}{R_{max} - R_{min}} \tag{1}$$

Weightages of various units and influence factors of their features have been suggested in Table 7. Overall susceptibility to liquefaction has been determined in terms liquefaction susceptibility value ($L_s \leq 1$), which is simply summation of product of weightages of the units and influence factor of respective features Equation (2).

$$L_s = 0.2047\, I_L + 0.0965\, I_G + 0.4094\, I_W + 0.2895\, I_P \tag{2}$$

Where, I_L=Influence factor for lithology, I_G=Influence factor for geomorphology, I_W=Influence factor for water table and I_P=Influence factor for peak ground acceleration.

The state has been classified into three zones of liquefaction susceptibility viz., high ($L_s \geq 0.8$), moderate ($0.5 < L_s < 0.8$) and low ($L_s \leq 0.5$). However in case of clays and rocks susceptibility to liquefaction is always considered low irrespective of the value of L_s. The analysis has been carried out for 243 locations for which all required data were available and a Grade-I liquefaction susceptibility map has been prepared using nearest neighbour interpolation model as shown in Figure 6.

Table 7: Weightage, Rank, Influence factor and Susceptibility of Various Units and Features Identified in the Study Region

Unit	Weights	Features	Rating	Influence Factor	Susceptibility
Lithology	0.2047	Sands and Non Plastic Silts	3	1	High
		Loams	2	0.5	Medium
		Clays, Plastic Silts or Rock Outcrop	1	0	Low
Geomorphology	0.0965	Flood plains, river beds , Young deposits (age<500 years)	3	1	High
		Holocene deposits	2	0.5	Medium
		Pleistocene and older deposits	1	0	Low
Water Table	0.4094	0 to 10 m	3	1	High
		10 to 20 m	2	0.5	Medium
		>20 m	1	0	Low
Anticipated PGA as per IS:1893-Part 1	0.2895	0.24g, corresponding to zone IV	3	1	High
		0.16g, corresponding to zone III	2	0.5	Medium
		0.10g, corresponding to zone II	1	0	Low

It has been observed that districts of Ambala, Faridabad, Jhajjar, Palwal, Rohtak, Sonipat and Yamunanagar are highly susceptible to liquefaction during earthquakes. It is because these regions are basically flood plains with water table at shallow depth and fall in Zone IV of Seismic Zoning Map of India with maximum PGA of 0.24g. However, in these districts, areas with deep water table have been observed to be moderately susceptible to liquefaction.

The districts of Bhiwani, Fatehabad, Gurgaon, Hisar, Karnal, Panipat and Rewari have been observed to be moderately susceptible to liquefaction during earthquakes. This can be attributed to high depth of water table in these regions. Moderate risk of liquefaction in these districts can also attributed to the fact that these areas are not flood plains and their geomorphology varies from Holocene to Pleistocene and older deposits.

However, in above mentioned districts, regions with shallow water table and higher earthquake hazard have shown high susceptibility to liquefaction. In Panchkula district, gravelly soils are found in abundance and hence the region is moderately susceptible to liquefaction. Moreover, in Panipat City, susceptibility to liquefaction has been observed to be low. The districts Bhiwani and Fatehabad fall in Zone III of Seismic Zoning Map of India with maximum PGA of 0.16g and it is a contributing factor in moderate susceptibility to liquefaction of these areas.

Apart from this, in districts Jind, Kaithal, Kurukshetra, Mahendragarh, Mewat and Sirsa susceptibility to liquefaction is quite low. This can be attributed to high depth of water table in these areas. Moreover, a large area in these regions falls in Zone III of Seismic Zoning Map of India. Also, geomorphology for these areas varies from Pleistocene to older deposits.

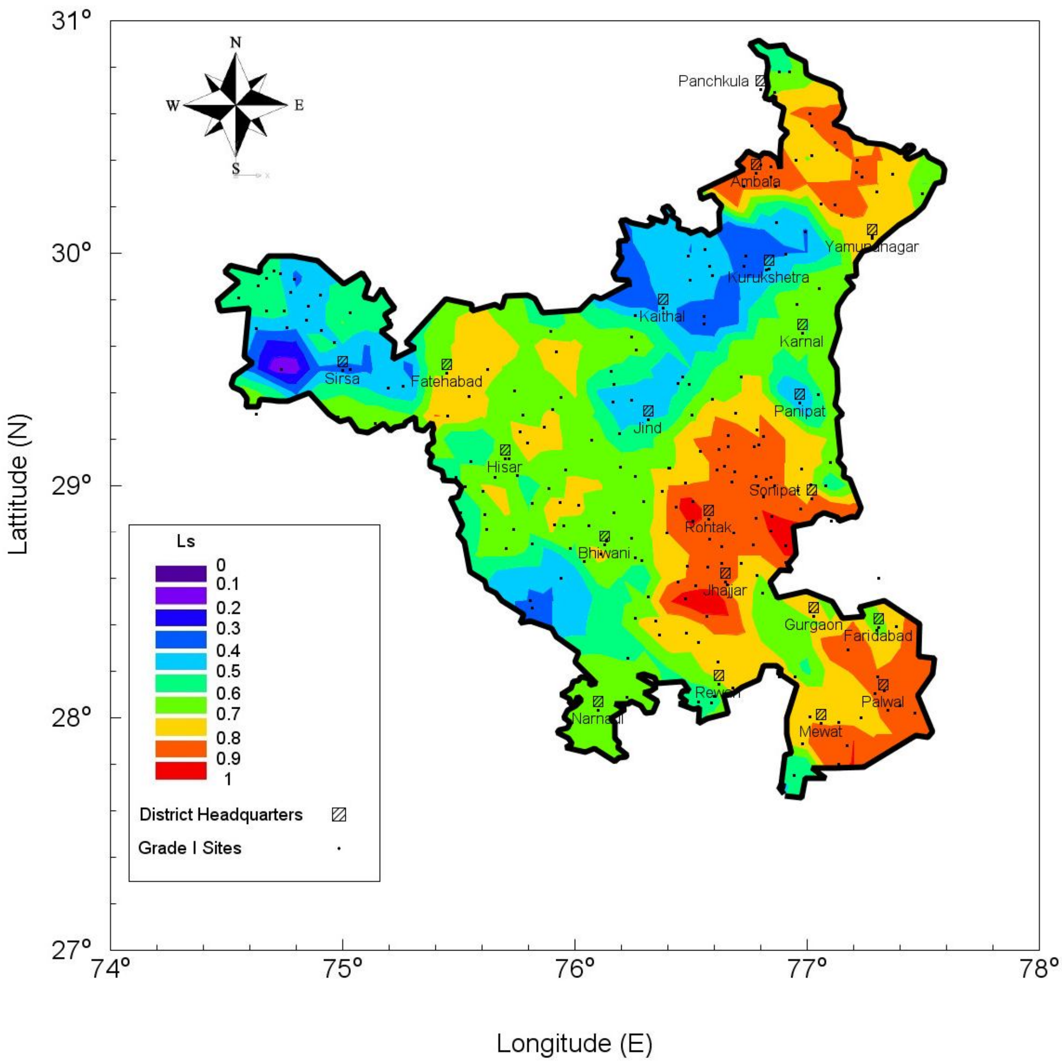

Fig. 6 Grade-I Liquefaction Susceptibility Map

VALIDATION OF RESULTS

Liquefaction susceptibility determined using proposed method has been randomly verified by analysing borehole data indicating Standard penetration test (SPT) values in the study area using semi-empirical procedure developed by Idriss and Boulanger (2006). The procedure is summarized below:

1. Appropriate soil type: Determine if the soil has the ability to liquefy during an earthquake.
2. Groundwater table: The soil must be below GWT. The liquefaction analysis could also be performed if it is anticipated that the groundwater table will rise in future, and thus the soil will eventually be below the groundwater table.
3. Cyclic stress ratio (CSR): Determine CSR that will be induced by the earthquake.
4. Cyclic resistance ratio (CRR): By using the standard penetration resistance test data, the CRR of the in-situ soil is determined.
5. Factor of safety (FOS): FOS = CRR/CSR. The higher the factor of safety, the more resistant the soil is to liquefaction. However, soil that has a factor of safety slightly greater than 1.0 may still liquefy during an earthquake. For example, if a lower layer liquefies, then the upward flow of water could induce liquefaction of the layer that has a factor of safety slightly greater than 1.0.

Typical boreholes showing location, depth and recorded SPT values have been shown in Figure 7. It has been observed that in most of the cases, areas identified using Grade-I technique as low, moderate and high susceptible to liquefaction, results given by semi-empirical procedure are quite comparable. The results have been reported in Table 8.

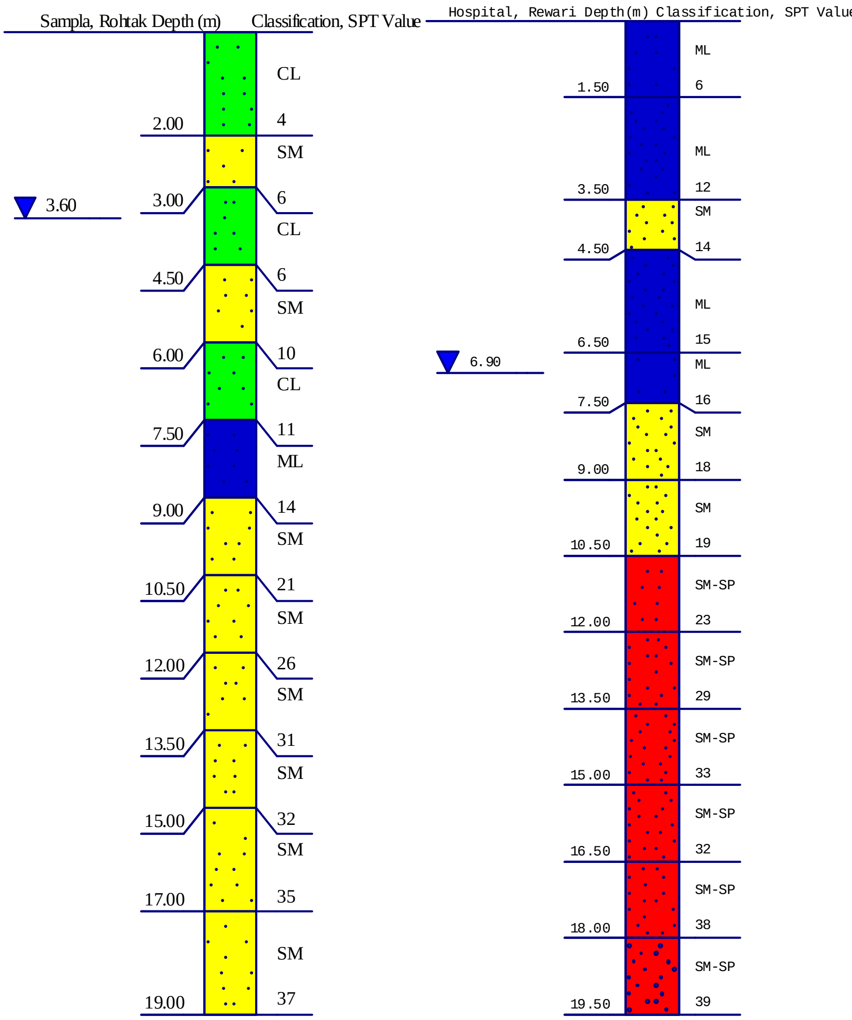

Fig. 7 Typical bore-logs showing soil classification and SPT values along the depth

Table 8: Comparison between Liquefaction Susceptibility Determined using Grade-I Technique and Semi- Empirical Procedure

Site No.	Location	Grade - I Technique		Idriss and Boulanger, 2006 (SPT Based Semi- Empirical Procedure)					
		L_s	Susceptibility	Depth for Minimum Factor of Safety (m)	Minimum C.S.R	Minimum C.R.R	Minimum F.O.S	Zonesof Liquefaction (m)	Susceptibility
1	Scout and Guide Hostel, Ambala	0.898	High	2	0.155	0.130	0.838	2, 9	High
2	R.O.B, Ambala City, Ambala	0.898	High	16.5	0.224	0.241	1.076	NIL	Moderate
3	Bus Stand, Tosham, Bhiwani	0.759	Moderate	1.5	0.103	0.131	1.273	NIL	Low
4	Sector 56, Faridabad	0.795	Moderate	10.5	0.139	0.150	1.079	NIL	Moderate
5	Labour court, Sector 12, Faridabad	0.795	Moderate	3	0.153	0.155	1.010	NIL	Moderate
6	R.O.B at	0.705	Moderate	6	0.131	0.167	1.272	18	Low

	BhattuMandi, Fatehabad								
7	Sector 38, Gurgaon	0.392	Low	1.5	0.155	0.148	0.954	1.5	Moderate
8	NRFM&TI Training Centre, Hisar	0.657	Moderate	0.9	0.104	0.101	0.972	0.9	Moderate
9	Hansi, Railway Station, Hisar	0.657	Moderate	1.5	0.103	0.132	1.273	NIL	Low
10	PWD Rest House, Beri, Jhajjar	0.801	High	1.5	0.206	0.132	0.639	1.5 - 9	High
11	Sector 6, Bahadurgarh, Jhajjar	0.801	High	3	0.207	0.162	0.782	1.5 - 4.5	High
12	Railway Station, Jind City	0.452	Low	6	0.099	0.174	1.761	NIL	Low
13	Bridge on KalayatSajuma Road, Kaithal	0.452	Low	4.5	0.145	0.173	1.192	NIL	Low
14	Sector 13, Karnal	0.597	Moderate	4	0.174	0.137	0.788	4	Moderate
15	Village Kurali, Indri Road, Karnal	0.597	Moderate	0.9	0.156	0.157	1.007	NIL	Moderate
16	VibhutiMandir Complex, Kurukshetra	0.392	Low	24	0.117	0.119	1.020	NIL	Moderate
17	R.O.B on Markanda river, Shahabad, Kurukshetra	0.488	Low	3.5	0.152	0.133	0.877	3.5 - 15.5	High
18	STP, Narnaul, Mahindragarh	0.699	Moderate	3	0.102	0.172	1.69	NIL	Low
19	Medical College, Nooh, Mewat	0.699	Moderate	1.6	0.155	0.166	1.072	NIL	Moderate
20	Health Centre, Nagina, Mewat	0.795	Moderate	1	0.156	0.116	0.746	1 -2, 6-9	High
21	Government College, Sector 18, Panipat	0.392	Low	4.5	0.151	0.156	1.037	NIL	Low
22	IOCL Refinery, Panipat	0.801	High	10	0.248	0.162	0.653	7.5 - 10	High
23	Sector 17, Panchkula	0.591	Moderate	5	0.150	0.137	0.915	1, 3, 5	Moderate
24	Sector 21, Part 3, Panchkula	0.591	Moderate	4.5	0.151	0.480	3.183	NIL	Low
25	4G Telecom Tower, Hodal, Palwal	0.801	High	2	0.155	0.102	0.662	2, 16-20	High
26	Railway Station, Palwal	0.801	High	1.5	0.155	0.148	0.955	1.5	Moderate
27	I.T.I Tankri, Rewari	0.747	Moderate	1.5	0.155	0.187	1.204	NIL	Low
28	Pushpanjli Hospital, Rewari City	0.747	Moderate	12	0.169	0.143	0.842	1.5, 12 - 13.5, 16.5	High
29	R.O.B at Sampla, Rohtak	0.801	High	9	0.202	0.157	0.774	3, 6, 9 - 10.5	High
30	Sector 1, Rohtak	0.801	High	9	0.276	0.153	0.555	1.5 - 10.5	High

	City, Rohtak								
31	Bridge Over Sheranwali Channel, Near Village Keshpura, Sirsa	0.355	Low	1	0.065	0.123	1.887	NIL	Low
32	R.O.B Near Railway Station, Sonipat	0.850	High	2	0.151	0.124	0.820	4.5, 24	High
33	4-Lane Bridge Near Village Barwasni, Sonipat	0.801	High	3	0.153	0.107	0.701	1.5 - 4.5	High
34	Sugar Mill, Bilaspur, Yamunanagar	0.801	High	12	0.219	0.162	0.742	6 - 12	High
35	SabziMandi, Yamunanagar	0.699	Moderate	4.5	0.151	0.141	0.933	4.5 - 6	Moderate

CONCLUSION

Grade-I liquefaction hazard mapping for the State of Haryana has been done on the basis of geological and geomorphological characteristics of the area. On the basis of that following conclusions have been drawn:

1. Soil resource maps, geomorphological maps, earthquake hazard maps and ground water table data have been used for assessing liquefaction susceptibility. The analysis has been carried out following Saaty's Analytical Hierarchy Process (Saaty, 1990). The state has been classified into three zones of liquefaction susceptibility viz., high ($L_s \geq 0.8$), moderate ($0.5 < L_s < 0.8$) and low ($L_s \leq 0.5$).However in case of clays, susceptibility to liquefaction is always considered low irrespective of the value of L_s.
2. It has been observed that districts of Ambala, Faridabad, Jhajjar, Palwal, Rohtak, Sonipat and Yamunanagar are highly susceptible to liquefaction during earthquakes. It is because these regions are basically flood plains with water table at shallow depth and fall in Zone IV of Seismic Zoning Map of India with maximum PGA of 0.24g.
3. The districts of Bhiwani, Fatehabad, Gurgaon, Hisar, Karnal, Panipat and Rewari have been observed to be moderately susceptible to liquefaction during earthquakes. This can be attributed to high depth of water table in these regions. In Panchkula district, gravelly soils are found in abundance and hence the region is moderately susceptible to liquefaction.
4. In districts Jind, Kaithal, Kurukshetra, Mahendragarh, Mewat and Sirsa susceptibility to liquefaction is quite low. This can be attributed to high depth of water table in these areas. Moreover, a large area in these regions falls in Zone III of Seismic Zoning Map of India. Also, geomorphology for these areas varies from Pleistocene to older deposits.
5. Liquefaction susceptibility determined using proposed method has been verified by analysing boreholes in the study area using semi-empirical procedure developed by Idriss and Boulanger (2006). It has been observed that in most of the cases, areas identified using Grade-I technique as low, moderate and high susceptible to liquefaction, results given by semi-empirical procedure are quite comparable.
6. Regional studies based on geological and geomorphological data would not be a substitute to detailed site specific investigation, but could indicate areas where thorough investigation is required.

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REFERENCES

1. Beroya, M.A.A. and Aydin, A. (2007). “First Level Liquefaction Hazard Mapping of Laoag City, North Philippines”, Nat Hazards, Vol. 43, No. 3, pp. 415-430.
2. BIS (2002). “IS 1893 (Part1): 2002-Indian Standard Criteria for Earthquake Resistant Design of Structures, Part1: General Provisions and Buildings (Fifth Revision)”, Bureau of Indian Standards, New Delhi.
3. BMTPC (2007). “Vulnerability atlas of India”, First Revision, Ministry of Housing & Urban Poverty Alleviation, Government of India.
4. Boulanger, R.W. and Idriss, I.M. (2006). “Liquefaction Susceptibility Criteria for Silts and Clays”, J. Geotech. Geoenviron. Eng., Vol. 132, No. 11, pp. 1413–1426.
5. CGWB (2013). “Ground Water Level Information”, Central Ground Water Board, Ministry of Water Resources, Government of India. http://gis2.nic.in/cgwb/Gemsdata.aspx. Accessed on 21 November 2013.
6. DTCP (2010). “Report on Preparation of Sub Regional Plan for Haryana Sub-region of NCR”, Scott Wilson India Private Limited.
7. GSI (1973). “Geological and Mineral Map of Haryana”, Map and Cartography Division, Geological Survey of India, Kolkata.
8. GSI (2012). “Geology and Mineral Resources of Haryana”, Geological Survey of India, Miscellaneous Publication No. 30, Part 17, Second Revised Edition, Lucknow.
9. Ganapathy, G.P. and Rajawat, A.S. (2012). “Evaluation of Liquefaction Potential Hazard of Chennai City, India: Using Geological and Geomorphological Characteristics”, Nat Hazards, Vol. 64, No. 2, pp. 1717-1729.
10. Government of Haryana (2016). “Haryana at a glance”, Government of Haryana, Chandigarh. http://www.haryana.gov.in/knowharyana/haryanaglance.html. Accessed in April 2016.
11. IMD (2014). “Earthquake Records”, Indian Metrological Department, Delhi. http://www.imd.gov.in/. Accessed in November 2013.
12. Idriss, I.M. and Boulanger, R.W. (2006). “Semi-empirical Procedures for Evaluating Liquefaction Potential during Earthquakes”, Soil Dynamics and Earthquake Engineering, Vol. 26, pp. 115 - 130.
13. Iwasaki, T., Tokida, K., Tatsuoka, F., Watanabe, S., Yasuda, S. and Sato, H. (1982). “Microzonation for Soil Liquefaction Potential using Simplified Methods”, Proceedings 3rd International Earthquake Microzonation Conference, Vol. 3, pp. 1319–1330.
14. Kotoda, K., Wakamatsu, K. and Oya, M. (1988). “Mapping Liquefaction Potential based on Geomorphological Land Classification”, Proceedings of Ninth World Conference on Earthquake Engineering, Tokyo-Kyoto, Japan, Vol.3.
15. Mohanty, W.K., Walling, M.Y., Nath, S.K. and Pal, I. (2007). “First Order Seismic Microzonation of Delhi, India using Geographic Information System”, Nat Hazards, Vol. 40, No. 2, pp. 245-260.
16. Nath, S.K. (2004). “Seismic Hazard Mapping in the Sikkim Himalaya through GIS Integration of Site Effects and Strong Ground Motion Attributes”, Nat Hazards, Vol. 31, No. 2, pp. 319–342.
17. Sachdev, C.B., Lal, T., Rana, K.P.C. and Sehgal, J. (1995). “Soils of Haryana: Their Kinds, Distribution, Characterization and Interpretations for Optimising Land Use”, NBSS Publ., Vol.44.
18. Obermeier, S.F. (1996). “Use of Liquefaction Induced Features for Seismic Analysis-An overview of How Seismic Liquefaction Features can be Distinguished from other Features and How their Regional Distribution and Properties of Source Sediment can be used to Infer the Location and Strength of Holocene Paleo-earthquakes”, Engineering Geology, Vol. 44, pp. 1-76.
19. Puri, N. and Jain, A. (2015). “Deterministic Seismic Hazard Analysis for the State of Haryana, India”, Indian Geotech J., DOI 10.1007/s40098-015-0167-1.

20. Rajendran, K., Rajendran, C.P., Thakkar, M. and Tuttle, M.P. (2001). "The 2001 Kutch (Bhuj) Earthquake: CoseismicSurface Features and Their Significance", CurrSci, Vol. 80, No. 11.
21. Saaty, T.L. (1990). "How to Make a Decision: The Analytic Hierarchy Process", European Journal of Operational Research, Vol. 48, pp. 9-26.
22. Sitharam, T.G., Raju, L.G. and Sridharan, L. (2004). "Dynamic Properties and Liquefaction Potential of Soils", CurrSci, Vol. 87, No. 10.
23. Srow, S.P. (2013). "Disaster Management Plan, Panipat District", Department of Revenue and Disaster Management, Government of Haryana.
24. TCEGE (1999). "Manual for Zonation on Seismic Geotechnical Hazards (Revised Version)", Technical Committee for Earthquake Geotechnical Engineering Publication of the Japanese Geotechnical Society, pp. 209, Tokyo, Japan.
25. Wakamatsu, K. (1992). "Evaluation of Liquefaction Susceptibility Based on Detailed Geomorphological Classification", Proceedings of Technical Papers of Annual Meeting, Architectural Institute of Japan, Vol. B, pp. 1443–1444.
26. Youd, T.L. and Perkins, D.M. (1978). "Mapping Liquefaction Induced Ground Failure Potential", Journal of Geotechnical Engineering Division, Vol. 104, pp. 433-446.