Soil Liquefaction Potential in Different Seismic Zones of Bihar, India

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Abstract-Liquefaction potential analysis for the liquefiable as well as non-liquefiable soils of Bihar state has been performed in this paper based on the actual field data from three seismic zones, i.e. zone III, zone IV, and zone V. The analysis has been performed following the simplified procedure given in [1] and later modified in [2]. The results show that districts under seismic zone III are comparatively more resistant to liquefaction in most cases, districts of zone IV are relatively more prone to liquefaction up to a few depths, and districts of zone V are most liquefiable. Liquefaction resistance is primarily depending upon the fine content of soil and SPT N-values.

Keywords-standard penetration test; cyclic stress ratio; cyclic resistance ratio; soil liquefaction

I. INTRODUCTION

Liquefaction is the phenomenon in which the strength and stiffness of the soil are reduced by earthquake shaking and/or another dynamic loading. When an earthquake of suitable intensity shakes a deposit of loose saturated coarse-grained cohesionless soils, then the grain structures are triggered towards a more compact packing. However, it is not possible to drain off the pore water because it does not have sufficient time to do so during an earthquake. The pore water pressure then shoots outward because the applied stresses are taken up by the incompressible water and the effective stresses approach zero:

$$\sigma' = \sigma - u \quad (1)$$

where σ' is the effective stress, σ is the total stress, and u is pore water pressure.

In the case of cohesionless soil ($c = 0$), shear strength (τ) reduces to zero when effective stress approaches zero.

$$\tau = c + \sigma' \tan\phi' \quad (2)$$

where ϕ' is the effective internal resistance of the soil.

Liquefaction is one of the most disastrous seismic hazards. India has experienced the world's greatest earthquakes in the last few decades which lead to soil liquefaction and consequential damages.

Authors in [1] presented a simplified procedure for the evaluation of the liquefaction potential of soil using the assemblage of available field data of liquefied or non-liquefied soil during earthquakes. The author in [3] studied the field data from different countries for the evaluation of the liquefaction potential of soil in earthquake magnitude $M_{w} = 7.5$ and the result was then extended to earthquakes of other magnitudes and for silty soil. Authors in [4] presented a critical review of sandy soil deposits. It was found that the sand that has more than 10% fine content has a much higher resistance to liquefaction than clean sand having the same SPT N value. For clean sands with SPT N_1 values greater than 25, silty sands containing more than 10% fines with SPT N values greater than 20, or sandy silts with more than 20% clay will not undergo any extensive damage. Sands containing gravel particles have lower resistance than the clean sands without gravel for the same SPT N-values. Authors in [5] presented the influence of SPT procedures in the evaluation of liquefaction resistance. They also proposed the curve of liquefaction resistance for sands with the variations of SPT N-values and fines content. Authors in [6] proposed a simple correction factor to counteract the effect of overburden pressure on the results of the Standard Penetration Test (SPT) performed in sands. Authors in [7] studied the possible frequency of earthquakes in India and found that India has relatively higher frequencies of great earthquakes and lower frequencies of moderate earthquakes. Authors in [8] studied the liquefaction potential as per the case history of the Bihar-Nepal Earthquake on 21 August 1988. Based on three prevailing approaches, they found the differences with regard to relative density and depth of liquefaction potential and suggested further research. Authors in [9] studied the mechanism of liquefaction and soil failure during the 1994 Northridge earthquake with detailed subsurface investigations. They found that the variation of the Ground Water Table (GWT) in combination with the heterogeneous nature of alluvial fan sediments is responsible for complex patterns of ground deformation. Authors in [10] found that clay particles are mainly responsible for the liquefaction characteristics of the soil. Authors in [2] convened a workshop sponsored by the National Center for Earthquake Engineering Research (NCEER) with 20 experts to review developments in the field of liquefaction in the past. They have given many updates and augmentations to the simplified procedure proposed in [1]. Authors in [11] studied the

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likelihood of the initiation of soil liquefaction by SPT-based probabilistic and deterministic correlations. Authors in [12] closely studied the possible factor of the Bhuj 2001 earthquake and found that deep fluid inflow plays a crucial role in the intensity of disasters. Authors in [13] studied the Liquefaction Potential Index (LPI) of Mumbai city. They evaluated the factors of safety to predict the liquefaction potential along the depths of soil with a 2% probability of exceedance in 50 years using an SPT-based simplified procedure. Authors in [14] described the influence of earthquake ground motion on the liquefaction resistance of the soil. Authors in [15] investigated the paleoliquefaction from four sites in north Bihar and one site in eastern Uttar Pradesh. Based on the available data, they found the recurrence interval of 124 ± 63 years for great earthquakes like the 1934 earthquake in Bihar. They also concluded that the Plains of Bihar are most vulnerable to the seismic activity originating from the Himalayas as well as the terai Plains of Nepal. Authors in [16] studied the quality of groundwater in Bihar. Authors in [17] studied the post-earthquake effect in Kathmandu valley after Gorkha, Nepal earthquake on 25 April 2015. They found seven locations of sand blows based on geotechnical investigation records. Authors in [18] reinterpreted the dynamic behavior of sandy soils subjected to recent historical earthquakes in Japan and demonstrated that the aged soils have higher resistance towards liquefaction than that suggested by their current design code. Authors in [19] studied four districts of Bihar, i.e. Samastipur, Darbhanga, West-Champaran, and Araria based on reliability techniques for the prediction of seismic liquefaction. Authors in [20-26] described stability methods for the soil types in Bihar. Authors in [27] evaluated the effect of plasticity on the liquefaction potential of fine-grained soil in the seismically active regions of Bihar based on Multi-Linear Regression (MLR) analysis and reliability analysis, i.e. First Order Second Moment (FOSM), and established a co-relation between the factor of safety against liquefaction, reliability index, and liquefaction probability.

According to the literature survey, Bihar is one of the most vulnerable states concerning seismic activities. Tremendous work has been conducted in the field of liquefaction, but little in the region. This study has been done to overcome this shortcoming and to have more accurate predictions of liquefaction in the seismic zones of Bihar, i.e. zone III, zone IV, and zone V and their relative vulnerability towards liquefaction. Here, a general correlation between liquefaction potential, depth, fines content, and SPT-N value has been established to be used as a handy tool. The method adopted here for the analysis is the method recommended by Indian Standard which is originally based on the simplified empirical method of [1] and later on modified by different researchers in this field.

II. METHODOLOGY

The prime concern is to know whether the soil is susceptible to liquefaction or not, so that suitable measures can be adopted in advance if required. For this purpose, the Factor Of Safety (FOS) against liquefaction is estimated according to the method described in Annex F of Indian Standard code [28] IS 1893 (Part 1): 2016, which is based on the Simplified Procedure proposed in [1] and later modified in [2]. The proneness of soil towards liquefaction is assured by estimating the FOS at different depths below Natural Ground Level (NGL). The FOS is estimated by dividing the Cyclic Resistance Ratio (CRR) required to induce liquefaction in the soil by the Cyclic Stress Ratio (CSR) produced by an earthquake.

$$\mathrm{FOS} = \frac{\mathrm{CRR}}{\mathrm{CSR}} \quad (3)$$

A. *Evaluation of CSR*

Authors in [1] formulated the following expression for the calculation of (CSR):

$$\mathrm{CSR} = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{\mathrm{vo}}}{\sigma'_{\mathrm{vo}}}\right) r_d \quad (4)$$

where a_{max}= Peak Ground Acceleration (PGA) at the ground surface, g = gravity acceleration, σ_{vo}= total vertical stress at the point of interest, σ'_{vo}= effective vertical stress at the same point, and $r_d =$ reduction factor.

The value of the reduction factor was initially given in [1] which was later approximated in [29]:

$$r_d = \frac{1.000 - 0.4113z^{0.5} + 0.04052z + 0.001753z^{1.5}}{1.000 - 0.4177z^{0.5} + 0.05729z - 0.006205z^{1.5} + 0.001210z^2} \quad (5)$$

IS 1893 (part 1):2016 recommends using the ratio (a_{max}/g) equal to seismic zone factor if the value of PGA is not available.

TABLE I. SEISMIC ZONE FACTOR

Seismic zone factor	II	III	IV	V
Z	0.10	0.16	0.24	0.36

B. *Evaluation* of CRR

$$\mathrm{CRR} = CRR_{7.5}(MSF)K_\sigma K_\alpha \quad (6)$$

where $CRR_{7.5}$ = CCR for earthquake magnitude M_w = 7.5, MSF, K_σ, and K_α are the correction factors for earthquake magnitude other than 7.5 (commonly known as magnitude scaling factor), overburden stress, and static shear stress respectively.

Authors in [2] re-evaluated the 1982's data set to get the revised MSF given by:

$$\mathrm{MSF} = 10^{2.24} \,/\, M_w^{2.56} \quad (7)$$

The high overburden correction factor is required for a depth greater than 15m is [30]:

$$K_\sigma = (\sigma'_{\mathrm{vo}} \,/\, P_a)^{f-1} \quad (8)$$

where P_a is the atmospheric pressure measured in the same unit as effective overburden pressure (σ'_{vo}) and the value of f depends on relative density (D_r):

$$f = \begin{cases} 0.8\sim0.7 & \text{for } D_r = 40\% \text{ to } 60\% \\ 0.7\sim0.6 & \text{for } D_r = 60\% \text{ to } 80\% \end{cases} \quad (9)$$

As per the report correction for static shear stress [28], K_α, is required only for sloping ground which may be assumed to be in routine practice.

The SPT N-value measured in the field is corrected for the 60% hammer efficiency and standardized equipment using the expression:

$$N_{60} = NC_{60} \quad (10)$$

where $C_{60} = C_{HT} * C_{HW} * C_{SS} * C_{RL} * C_{BD}$ and C_{HT}, C_{HW}, C_{SS}, C_{RL}, and C_{BD} are the correction factors for the height of fall, hammer weight, sampler setup, rod length, and borehole diameter respectively.

The N_{60} value computed is normalized to approximately 100kPa effective overburden pressure as suggested in [6]:

$$(N_1)_{60} = C_N N_{60} \quad (11)$$

where:

$$C_N = (P_a/\sigma'_{vo})^{0.5} \leq 1.7 \quad (12)$$

Authors in [22] developed an equation for counteracting the effect of fines content to get an equivalent clean sand value $(N_1)_{60cs}$:

$$(N_1)_{60cs} = \alpha + \beta(N_1)_{60} \quad (13)$$

where:

$$a = 0 \qquad \beta = 1 \qquad \text{for } FC \leq 5\%$$

$$a = e^{[1.76 - \frac{190}{FC^2}]} \qquad \beta = 0.99 + \frac{FC^{1.5}}{1000} \qquad \text{for } 5\% < FC \leq 35\% \quad (14)$$

$$a = 0.5 \qquad \beta = 1.2 \qquad \text{for } FC > 35\%$$

An expression for cyclic resistance ratio for a 7.5 magnitude earthquake was formulated in [31] based on a clean sand base curve plot originally proposed in [5]:

$$CRR_{7.5} = \frac{1}{34-(N_1)_{60cs}} + \frac{(N_1)_{60cs}}{135} + \frac{50}{[10\times(N_1)_{60cs}+45]^2} - \frac{1}{200} \quad (15)$$

This expression is valid for $(N_1)_{60} < 30$. For $(N_1)_{60} \geq 30$, soils are too dense and non-liquefiable.

III. DATA ANALYSIS

Analysis has been done based on the big input data set which includes the depth of strata, its dry density, moisture content, fineness content, and SPT N-values. The rotary method of boring was adopted with a borehole diameter of 150mm throughout the project. For the analysis of the whole project the magnitude of the earthquake, M_w, was taken as 7.5. Three major district data from seismic zone III, five from seismic zone IV, and three from seismic zone V are summarized here in Tables II-IV for representation. The other districts from that zones show almost similar results. The soil of Nawada and Buxar districts has initially lower resistance to liquefaction which is almost near to the FOS-1 line but at 3m depth there is a sudden increase in the FOS of Buxar due to the increase in SPT N-value. Bhojpur has comparatively higher resistance against liquefaction in seismic zone III.

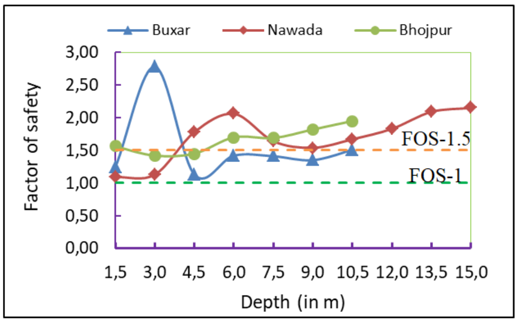

Fig. 1. Variation of the factor of safety with depth in seismic zone III

TABLE II. LIQUEFACTION ANALYSIS OF ZONE III (PGA: 0.16, MSF: 1, K_A: 1)

District	Depth (m)	Υ (kN/m³)	*FC*	*N-value*	σ_v (kPa)	σ'_v (kPa)	r_d	CSR	C_{60}	N_{60}	C_N	$(N_1)_{60}$	$(N_1)_{60CS}$	K_σ	$CRR_{7.5}$	CRR	FOS
Buxar GWT: 1.10m	1.50	19.62	95.20	10	29.43	25.51	0.990	0.12	0.65	6.50	1.70	11.04	13.75	1.00	0.15	0.15	1.24
	3.00	19.91	97.20	22	59.74	41.10	0.979	0.15	0.69	15.25	1.56	23.78	29.04	1.00	0.41	0.41	2.78
	4.50	19.72	97.20	14	88.73	55.38	0.969	0.16	0.74	10.31	1.34	13.85	17.12	1.00	0.18	0.18	1.13
	6.00	19.82	94.10	18	118.90	70.83	0.958	0.17	0.82	14.81	1.19	17.60	21.62	1.00	0.24	0.24	1.42
	7.50	19.82	94.20	20	148.62	85.84	0.943	0.17	0.82	16.46	1.08	17.76	21.82	1.00	0.24	0.24	1.41
	9.00	19.91	96.40	21	179.23	101.73	0.923	0.17	0.82	17.28	0.99	17.13	21.06	1.00	0.23	0.23	1.35
	10.50	19.91	96.60	23	209.10	116.89	0.894	0.17	0.87	19.92	0.92	18.43	22.61	1.00	0.25	0.25	1.51
Nawada GWT: 3.50m	1.50	18.64	3.20	9	27.96	27.96	0.990	0.10	0.65	5.85	1.70	9.94	9.94	1.00	0.11	0.11	1.09
	3.00	18.64	4.30	11	55.92	55.92	0.979	0.10	0.69	7.62	1.34	10.19	10.19	1.00	0.11	0.11	1.13
	4.50	18.34	5.00	22	82.55	72.74	0.969	0.11	0.74	16.20	1.17	18.99	18.99	1.00	0.20	0.20	1.78
	6.00	18.25	6.80	26	109.48	84.95	0.958	0.13	0.82	21.40	1.08	23.21	23.49	1.00	0.26	0.26	2.06
	7.50	18.25	2.70	25	136.85	97.61	0.943	0.14	0.82	20.57	1.01	20.82	20.82	1.00	0.23	0.23	1.64
	9.00	18.25	3.00	26	164.22	110.26	0.923	0.14	0.82	21.40	0.95	20.38	20.38	1.00	0.22	0.22	1.54
	10.50	18.25	6.30	28	191.59	122.92	0.894	0.14	0.87	24.26	0.90	21.88	22.05	1.00	0.24	0.24	1.67
	12.00	18.15	7.00	31	217.78	134.40	0.857	0.14	0.87	26.85	0.86	23.16	23.48	1.00	0.26	0.26	1.83
	13.50	18.05	3.10	35	243.68	145.58	0.811	0.14	0.87	30.32	0.83	25.13	25.13	1.00	0.29	0.29	2.09
	15.00	18.05	3.50	39	270.76	157.94	0.761	0.14	0.87	33.78	0.80	26.88	26.88	0.87	0.34	0.29	2.15
Bhojpur GWT: 6.90m	1.50	19.72	74.30	11	29.58	29.58	0.990	0.10	0.65	7.15	1.70	12.15	15.08	1.00	0.16	0.16	1.56
	3.00	19.72	84.60	12	59.15	59.15	0.979	0.10	0.69	8.32	1.30	10.81	13.47	1.00	0.15	0.15	1.42
	4.50	19.72	85.50	14	88.73	88.73	0.969	0.10	0.74	10.31	1.06	10.94	13.63	1.00	0.15	0.15	1.45
	6.00	19.82	79.30	17	118.90	118.90	0.958	0.10	0.82	13.99	0.92	12.83	15.90	1.00	0.17	0.17	1.70
	7.50	19.82	80.30	19	148.62	142.74	0.943	0.10	0.82	15.64	0.84	13.09	16.20	1.00	0.17	0.17	1.69
	9.00	19.91	77.40	23	179.23	158.63	0.923	0.11	0.82	18.93	0.79	15.03	18.53	1.00	0.20	0.20	1.82
	10.50	19.91	78.40	25	209.10	173.78	0.894	0.11	0.87	21.66	0.76	16.43	20.21	1.00	0.22	0.22	1.95

TABLE III. LIQUEFACTION ANALYSIS OF ZONE IV (PGA: 0.246, MSF: 1, K_A: 1)

District	Depth (m)	Υ (kN/m³)	*FC*	*N-value*	σ_v (kPa)	σ'_v (kPa)	r_d	CSR	C_{60}	N_{60}	C_N	$(N_1)_{60}$	$(N_1)_{60CS}$	K_σ	$CRR_{7.5}$	CRR	FOS
Nalanda GWT: 3.85m	1.50	18.25	92.95	5	27.37	27.37	0.990	0.15	0.65	3.25	1.70	5.52	7.13	1.00	0.09	0.09	0.57
	3.00	18.25	93.75	6	54.74	54.74	0.979	0.15	0.69	4.16	1.35	5.62	7.24	1.00	0.09	0.09	0.59
	4.50	18.34	90.95	11	82.55	76.17	0.969	0.16	0.74	8.10	1.15	9.28	11.64	1.00	0.13	0.13	0.78
	6.00	18.34	88.92	14	110.07	88.98	0.958	0.18	0.82	11.52	1.06	12.21	15.16	1.00	0.16	0.16	0.87
	7.50	18.44	91.32	17	138.32	102.51	0.943	0.20	0.82	13.99	0.99	13.82	17.08	1.00	0.18	0.18	0.91
	9.00	18.44	90.44	21	165.99	115.46	0.923	0.21	0.82	17.28	0.93	16.08	19.80	1.00	0.21	0.21	1.03
	10.50	18.44	92.59	24	193.65	128.41	0.894	0.21	0.87	20.79	0.88	18.35	22.52	1.00	0.25	0.25	1.19
	12.00	18.44	90.09	29	221.31	141.36	0.857	0.21	0.87	25.12	0.84	21.13	25.85	1.00	0.31	0.31	1.48
	13.50	18.74	91.20	30	252.95	158.28	0.811	0.20	0.87	25.99	0.79	20.66	25.29	1.00	0.30	0.30	1.47
	15.00	18.74	89.77	31	281.06	171.68	0.761	0.19	0.87	26.85	0.76	20.50	25.09	0.85	0.29	0.25	1.29
Patna GWT: 4.50m	1.50	19.33	90.90	7	28.99	28.99	0.990	0.15	0.65	4.55	1.70	7.73	9.78	1.00	0.11	0.11	0.72
	3.00	19.52	90.90	9	58.57	58.57	0.979	0.15	0.69	6.24	1.31	8.15	10.28	1.00	0.12	0.12	0.76
	4.50	19.62	90.90	12	88.29	88.29	0.969	0.15	0.74	8.84	1.06	9.40	11.78	1.00	0.13	0.13	0.85
	6.00	19.72	91.70	16	118.31	103.59	0.958	0.17	0.82	13.17	0.98	12.94	16.02	1.00	0.17	0.17	1.00
	7.50	19.72	91.70	20	147.89	118.46	0.943	0.18	0.82	16.46	0.92	15.12	18.65	1.00	0.20	0.20	1.08
	9.00	19.91	91.70	23	179.23	135.08	0.923	0.19	0.82	18.93	0.86	16.29	20.04	1.00	0.22	0.22	1.13
	10.50	19.91	92.90	24	209.10	150.24	0.894	0.19	0.87	20.79	0.82	16.96	20.85	1.00	0.23	0.23	1.17
	12.00	20.01	92.90	28	240.15	166.57	0.857	0.19	0.87	24.26	0.77	18.79	23.05	1.00	0.26	0.26	1.34
	13.50	20.01	92.90	30	270.17	181.88	0.811	0.19	0.87	25.99	0.74	19.27	23.62	1.00	0.27	0.27	1.42
	15.00	20.11	90.90	33	301.66	198.65	0.761	0.18	0.87	28.59	0.71	20.28	24.84	0.81	0.29	0.23	1.30
Saran GWT: 2.00m	1.50	19.23	92.70	6	28.84	28.84	0.990	0.15	0.65	3.90	1.70	6.63	8.45	1.00	0.10	0.10	0.65
	3.00	19.52	92.70	9	58.57	48.76	0.979	0.18	0.69	6.24	1.43	8.93	11.22	1.00	0.12	0.12	0.68
	4.50	19.62	92.70	10	88.29	63.77	0.969	0.21	0.74	7.36	1.25	9.22	11.57	1.00	0.13	0.13	0.61
	6.00	19.23	91.90	12	115.37	76.13	0.958	0.23	0.82	9.88	1.15	11.32	14.08	1.00	0.15	0.15	0.67
	7.50	19.23	91.90	15	144.21	90.25	0.943	0.24	0.82	12.34	1.05	12.99	16.09	1.00	0.17	0.17	0.73
	9.00	19.33	91.90	18	173.93	105.26	0.923	0.24	0.82	14.81	0.97	14.44	17.83	1.00	0.19	0.19	0.80
	10.50	19.33	93.00	23	202.92	119.53	0.894	0.24	0.87	19.92	0.91	18.22	22.37	1.00	0.25	0.25	1.04
	12.00	19.62	93.00	26	235.44	137.34	0.857	0.23	0.87	22.52	0.85	19.22	23.56	1.00	0.27	0.27	1.16
	13.50	19.62	93.00	28	264.87	152.06	0.811	0.22	0.87	24.26	0.81	19.67	24.10	1.00	0.28	0.28	1.25
	15.00	19.72	91.70	30	295.77	168.24	0.761	0.21	0.87	25.99	0.77	20.04	24.54	0.86	0.28	0.24	1.16
West Champaran GWT: 5.10m	1.50	19.13	94.90	28	28.69	28.69	0.990	0.15	0.65	18.19	1.70	30.93	37.61	1.00	0.00	0.00	0.00
	3.00	19.03	96.50	7	57.09	57.09	0.979	0.15	0.69	4.85	1.32	6.42	8.20	1.00	0.10	0.10	0.64
	4.50	19.03	96.60	6	85.64	85.64	0.969	0.15	0.74	4.42	1.08	4.77	6.23	1.00	0.08	0.08	0.54
	6.00	19.03	95.10	12	114.19	105.36	0.958	0.16	0.82	9.88	0.97	9.62	12.04	1.00	0.13	0.13	0.81
	7.50	19.23	95.30	23	144.21	120.66	0.943	0.18	0.82	18.93	0.91	17.23	21.18	1.00	0.23	0.23	1.31
	9.00	19.23	95.30	25	173.05	134.79	0.923	0.18	0.82	20.57	0.86	17.72	21.76	1.00	0.24	0.24	1.29
	10.50	19.33	95.40	28	202.92	149.95	0.894	0.19	0.87	24.26	0.82	19.81	24.27	1.00	0.28	0.28	1.47
Begusarai GWT: 4.00m	1.50	19.52	84.30	9	29.28	29.28	0.990	0.15	0.65	5.85	1.70	9.94	12.43	1.00	0.14	0.14	0.87
	3.00	19.52	84.30	11	58.57	58.57	0.979	0.15	0.69	7.62	1.31	9.96	12.45	1.00	0.14	0.14	0.89
	4.50	19.91	84.30	19	89.61	84.71	0.969	0.16	0.74	13.99	1.09	15.20	18.74	1.00	0.20	0.20	1.25
	6.00	19.91	84.30	23	119.49	99.87	0.958	0.18	0.82	18.93	1.00	18.94	23.23	1.00	0.26	0.26	1.46
	7.50	19.91	87.20	25	149.36	115.02	0.943	0.19	0.82	20.57	0.93	19.18	23.52	1.00	0.27	0.27	1.39
	9.00	19.91	87.20	26	179.23	130.18	0.923	0.20	0.82	21.40	0.88	18.75	23.00	1.00	0.26	0.26	1.30
	10.50	20.01	79.40	28	210.13	146.37	0.894	0.20	0.87	24.26	0.83	20.05	24.56	1.00	0.28	0.28	1.41
	12.00	20.01	79.40	30	240.15	161.67	0.857	0.20	0.87	25.99	0.79	20.44	25.03	1.00	0.29	0.29	1.47
	13.50	20.11	82.40	32	271.49	178.30	0.811	0.19	0.87	27.72	0.75	20.76	25.41	1.00	0.30	0.30	1.56
	15.00	20.11	82.40	38	301.66	193.75	0.761	0.18	0.87	32.92	0.72	23.65	28.88	0.82	0.40	0.33	1.80

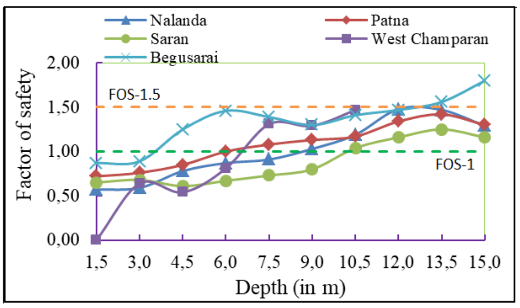

Fig. 2. Variation of the factor of safety with depth in seismic zone IV.

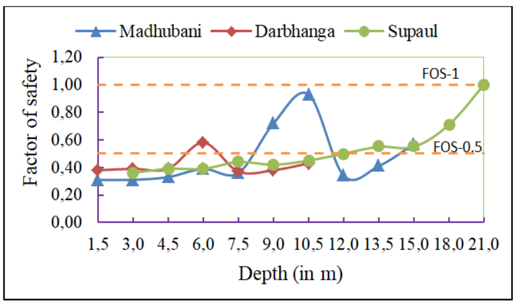

Fig. 3. Variation of the factor of safety with depth in seismic zone V.

TABLE IV. LIQUEFACTION ANALYSIS OF ZONE IV (PGA: 0.36, MSF: 1, K_A: 1)

District	Depth (m)	Υ (kN/m³)	*FC*	*N-value*	σ_v (kPa)	σ'_v (kPa)	r_d	CSR	C_{60}	N_{60}	C_N	$(N_1)_{60}$	$(N_1)_{60CS}$	K_σ	$CRR_{7.5}$	CRR	FOS
Madhubani GWT: 0.85m	1.50	17.96	23.20	3	26.95	20.57	0.990	0.30	0.65	1.95	1.70	3.31	7.73	1.00	0.09	0.09	0.31
	3.00	17.95	17.20	6	53.85	32.76	0.979	0.38	0.69	4.16	1.70	7.07	10.56	1.00	0.12	0.12	0.31
	4.50	18.04	93.68	9	81.20	45.40	0.969	0.41	0.74	6.63	1.48	9.84	12.30	1.00	0.13	0.13	0.33
	6.00	18.07	21.08	10	108.39	57.87	0.958	0.42	0.82	8.23	1.31	10.82	15.55	1.00	0.17	0.17	0.39
	7.50	18.05	13.30	12	135.35	70.11	0.943	0.43	0.82	9.88	1.19	11.79	14.23	1.00	0.15	0.15	0.36
	9.00	18.06	7.35	28	162.55	82.59	0.923	0.43	0.82	23.04	1.10	25.35	25.78	1.00	0.31	0.31	0.72
	10.50	18.29	6.73	32	192.07	97.40	0.894	0.41	0.87	27.72	1.01	28.09	28.38	1.00	0.38	0.38	0.93
	12.00	18.35	37.70	12	220.26	110.88	0.857	0.40	0.87	10.40	0.95	9.87	12.35	1.00	0.13	0.13	0.34
	13.50	18.43	41.34	15	248.77	124.68	0.811	0.38	0.87	12.99	0.90	11.64	14.46	1.00	0.15	0.15	0.41
	15.00	18.45	4.25	28	276.73	137.92	0.761	0.36	0.87	24.26	0.85	20.65	20.65	0.91	0.22	0.20	0.57
Darbhanga GWT: 2.30m	1.50	18.04	94.80	5	27.07	27.07	0.990	0.23	0.65	3.25	1.70	5.52	7.13	1.00	0.09	0.09	0.38
	3.00	18.57	93.10	7	55.70	48.83	0.979	0.26	0.69	4.85	1.43	6.94	8.83	1.00	0.10	0.10	0.39
	4.50	18.26	86.46	9	82.18	60.60	0.969	0.31	0.74	6.63	1.28	8.51	10.72	1.00	0.12	0.12	0.39
	6.00	18.22	16.75	15	109.31	73.02	0.958	0.34	0.82	12.34	1.17	14.45	18.24	1.00	0.19	0.19	0.58
	7.50	18.68	15.50	10	140.08	89.07	0.943	0.35	0.82	8.23	1.06	8.72	11.80	1.00	0.13	0.13	0.37
	9.00	18.61	16.70	11	167.47	101.75	0.923	0.36	0.82	9.05	0.99	8.97	12.44	1.00	0.14	0.14	0.38
	10.00	18.25	16.75	13	182.51	106.97	0.905	0.36	0.87	11.26	0.97	10.89	14.48	1.00	0.15	0.15	0.43
Supaul GWT: 1.00m	3.00	19.33	71.00	8	57.98	38.36	0.979	0.35	0.69	5.54	1.61	8.95	11.24	1.00	0.12	0.12	0.36
	4.50	19.33	7.00	13	86.97	52.63	0.969	0.37	0.74	9.57	1.38	13.19	13.43	1.00	0.14	0.14	0.39
	7.50	19.33	9.00	17	144.94	81.18	0.943	0.39	0.82	13.99	1.11	15.53	16.35	1.00	0.17	0.17	0.44
	9.00	19.33	8.00	18	173.93	95.45	0.923	0.39	0.82	14.81	1.02	15.16	15.65	1.00	0.17	0.17	0.42
	10.50	19.33	8.00	19	202.92	109.72	0.894	0.39	0.87	16.46	0.95	15.71	16.21	1.00	0.17	0.17	0.45
	12.00	19.33	8.00	22	231.91	124.00	0.857	0.37	0.87	19.06	0.90	17.11	17.63	1.00	0.19	0.19	0.50
	13.50	19.33	5.00	25	260.90	138.27	0.811	0.36	0.87	21.66	0.85	18.42	18.42	1.00	0.20	0.20	0.55
	15.00	19.33	6.00	28	289.89	152.55	0.761	0.34	0.87	24.26	0.81	19.64	19.76	0.88	0.21	0.19	0.55
	18.00	19.33	7.00	35	347.86	181.09	0.667	0.30	0.87	30.32	0.74	22.53	22.84	0.84	0.25	0.21	0.71
	21.00	19.33	8.00	44	405.84	209.64	0.598	0.27	0.87	38.12	0.69	26.32	26.96	0.80	0.34	0.27	1.00

In seismic zone IV, Begusarai has the highest resistance towards liquefaction as the district is liquefiable only up to 3.5m depth below NGL. Saran is liquefiable up to 10.5m depth below NGL which shows that this district is the most susceptible to liquefaction in seismic zone IV. All the districts of zone V have a factor of safety almost below the FOS-0.5 line which means that they are most susceptible to liquefaction. Madhubani has a sudden increase in factor of safety at 9m to 10.5m depth below NGL due to a slight decrease in fines content and drastically increase in SPT N-value.

IV. DISCUSSION

From the above data set, it is found that among the districts of seismic zone III, Buxar and Bhojpur have higher fines content than Nawada, whereas the SPT N-value of Nawada is comparatively high. Begusarai districts have comparatively lower fines content than the districts of seismic zone IV. Darbhanga district has a sudden decrease in fines content from 4.5m to 6m depth, whereas Madhubani shows two local peaks at 4.5m and 13.5m. Authors in [4] found that more than 10% of fines content values of soils are less liquefiable, but in the present study, it has been found that the fines content and SPT N- values are both critical factors for the liquefaction potential of the soil. Liquefaction may occur at higher or lower fines content values if the SPT-values are lower and higher respectively.

V. CONCLUSION

Based on the analysis results and the graphs of the FOS versus fines content and SPT N-value, the following conclusions have been made relative to the different seismic zones of Bihar:

In seismic zone III, the soil shows comparatively more resistance to liquefaction in most cases. The FOS value is more than 1 in all cases. Bhojpur shows comparatively more resistance to liquefaction, whereas Nawada shows the lowest resistance in the mentioned zone. The soil of seismic zone IV is relatively more prone to liquefaction. The soil of Begusarai district is liquefiable up to 3.5m depth below NGL. Saran district is more vulnerable to liquefaction up to 10.5m depth below NGL. The other districts in this zone show a similar trend of liquefaction up to certain depths. All the districts in seismic zone V are most liquefiable as their FOS is much lesser than 1. Madhubani shows the peak at 10.5m depth due to a slight decrease in fines content and a sudden increase in SPT N-value. The soil of Darbhanga district has quite a lower SPT N–value and decreasing fines content with the increase in depth below NGL.

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