

# A Study of Earthquake Induced Liquefaction Potential Risk based on Standard Penetration Test (SPT) N-Value

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## Abstract

Bhutan lies within the seismically active Himalayan belt; however, the country currently lacks a national seismic zonation map, and structural designers rely on the seismic zonation map of India for earthquake-resistant design. As per the seismic zonation map of India, the northeastern region of India is classified under Seismic Zone V, which represents the highest level of seismic activity. Given Bhutan's similar tectonic and geological setting, the country is also exposed to significant seismic risk. Despite this vulnerability, there is very limited research on the liquefaction potential of foundation soils in Bhutan, which is an important factor influencing the stability and performance of infrastructure during earthquakes. Assessing liquefaction risk is therefore essential for improving the resilience and sustainability of infrastructure development in the country. In this study, the liquefaction potential of the foundation soil is evaluated based on the Standard Penetration Test (SPT) N-values. The analysis is based on data maintained by the Bhutan Standards Bureau (BSB) on the Standards Penetration Test N-value and other related geotechnical parameters. The liquefaction potential is assessed based on a simplified stress-based method with an assumption that the fineness of the soil is less than 5% ( $FC < 5\%$ ) and the soil is expected to be 100% saturated during the summer monsoon season. The findings indicate that the liquefaction is likely to occur in areas such as Paro, Thimphu, Wangdue Phodrang, Samtse, Gelephu, and Gedu for an earthquake of magnitude as low as 5.5 at a foundation depth of 1.5 m. These findings highlight the importance of incorporating liquefaction potential assessment, ground improvement measures, and appropriate foundation design in future infrastructure projects.

This study contributes to the limited geotechnical engineering literature in Bhutan and provides preliminary insights that can support engineers, planners, and policymakers in improving earthquake resilience and infrastructure safety.

**Key Words:** Soil liquefaction, Standard Penetration Test (SPT), seismic hazard, geotechnical engineering, earthquake risk, Bhutan

## 1. INTRODUCTION

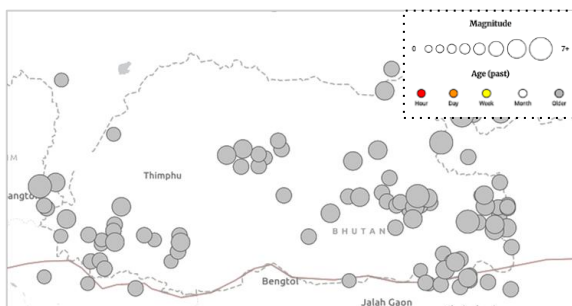
Soil liquefaction is a complex geotechnical phenomenon that poses a significant threat to the built environment during seismic events. It occurs primarily in saturated or partially saturated cohesionless soils, where sudden cyclic loading from an earthquake causes a rapid increase in excess pore water pressure. As this pressure rises to meet the overburden stress, the effective stress of the soil reduces to zero, resulting in a total loss of shear strength and stiffness (Dillon & Wardlaw, 2010). The physical manifestation of this process often involves ground failure, lateral spreading, and the loss of bearing capacity, which can lead to

catastrophic damage to buildings, bridges, and critical lifelines.

The global impact of liquefaction-induced failure is well-documented. Historical precedents, such as the 1964 Niigata earthquake in Japan, demonstrated how entire structures could tilt or sink despite remaining structurally intact (U.S. Geological Survey, 2025). More recently, the 2018 Sulawesi disaster in Indonesia highlighted the lethal potential of flow liquefaction, which resulted in massive landslides and significant loss of human life. Flow liquefaction occurs when the soil loses its shear strength completely and flows like a liquid.

Further, widespread damage to infrastructure

was reported due to earthquake-induced liquefaction, which occurred in the north and north-eastern part of India (Gupta, 1993). These events underscore the critical need to incorporate liquefaction potential assessments and rigorous mitigation plans into the design and implementation phases of infrastructure projects. In the context of the Himalayan region, seismic risk is an ever-present reality due to active tectonic convergence. The Kingdom of Bhutan, located in this high-risk zone, documented the occurrence of two major earthquakes of magnitude greater than 8 ( $M > 8$ ) since A.D. 1150  $\pm$  100, the most recent occurred after A.D. 1570  $\pm$  80, which corresponds to A.D. 1713 (Berthet, et al., 2014). It experienced its most recent significant seismic event in 2009—a magnitude 6.1 earthquake in the eastern region. While seismic activity in Bhutan has been relatively moderate in recent years, paleoseismic studies along the Main Frontal Thrust (MFT) indicate a high probability of recurrence, with an estimated return period of 550  $\pm$  210 years (Stevens et al., 2020). The apparent seismic gap observed in the USGS database may be attributed to strain partitioning, whereby up to one-third of the total  $\sim$ 18 mm/year crustal shortening is accommodated by basement-cored uplift of the Shillong Plateau (Diehl et al., 2017). This mechanism effectively prolongs the recurrence interval of major seismic events.



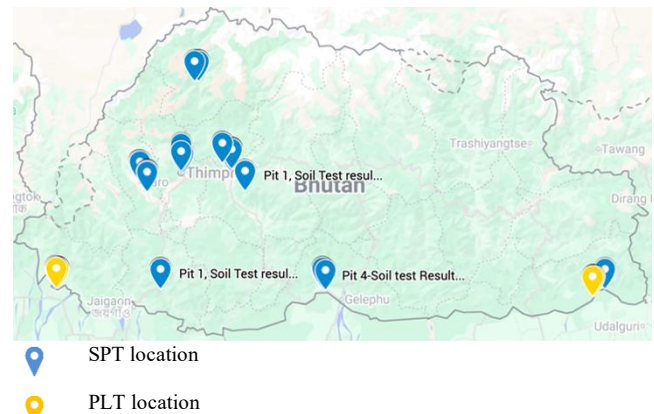
**Fig. 1:** NEIC (1900– 2026) seismicity of Bhutan for shallow depth (<35 km)

Furthermore, the oblique convergence between the Indian and Eurasian plates results in significant transcurrent deformation within the Indian plate across its depth extent. The geological and geophysical characteristics of Bhutan differ notably from those of other Himalayan regions, owing to the prevalence of strike-slip faulting, the presence of out-of-sequence thrusts, and the tectonic influence of deformation associated with

the Shillong Plateau (Drukpa, Velasco, & Doser, 2006).

As Bhutan continues to undergo rapid urbanization and infrastructure expansion, often within alluvial valleys characterized by high groundwater tables and unconsolidated sediments, the vulnerability to liquefaction increases. Therefore, there is an urgent need for a systematic assessment of the liquefaction potential of foundation soils across the country. Such evaluations are essential to mitigate economic losses, safeguard infrastructure, and, most importantly, prevent the loss of life during future seismic events.

## 2. MATERIALS AND METHOD



**Fig. 2:** Coverage of the standard penetration test (SPT) by Bhutan Standards Bureau

### 2.1 Data Sources

The primary data for this study were sourced from the geotechnical database maintained by the Metrology and Laboratory Services Division of the Bhutan Standards Bureau (BSB), under the Ministry of Industry, Commerce, and Employment. The dataset predominantly covers various locations within the western region of Bhutan.

Subsurface exploration was conducted via trial pits with surface dimensions of 1.5 m depth, 1.5m width, and 1.5 m length. In-situ testing was performed using the Standard Penetration Test (SPT), carried out in accordance with IS 2131: Method for Standard Penetration Test for Soils. Testing was conducted at depths extending until hard ground or refusal was encountered. The SPT N values reported in the data source are corrected for overburden pressure and dilatancy

correction( $N_{60}$ ). In this study, the fines content of the soil is assumed to be less than 5%, and hence the corrected SPT N-value for clean sand is equal to the corrected SPT N-value from the field  $\{(N_1)_{60cs}=(N_1)_{60}\}$  (Tohidi, Arellano, & Pezeshk, 2025)

## 2.2 Method for liquefaction potential assessment

The liquefaction potential is dependent on the intensity of seismic activity and the soil's inherent resistance to liquefaction. The soil's resistance to liquefaction depends on the key geotechnical parameters such as the depth of water table, SPT-N values, dry density, specific gravity, and fines content, with SPT being one of the most established and reliable methods for the geotechnical site investigation. In this study, the liquefaction potential is assessed based on the commonly used simplified stress based method established by (Youd & Idriss, 2001). The evaluation procedure consists of 3 steps,

1. Evaluation of Cyclic stress ratio (CSR)
2. Evaluation of Cyclic Resistance Ratio (CRR)
3. Determination of factor of safety (FS) (Mishra, Sil, & Das, 2024)

The soil is predicted to liquefy when the earthquake induced Cyclic Stress Ratio exceeds the Cyclic Resistance Ratio (CRR) or the factor of safety against liquefaction triggering is less than 1 (Sasmayaputra & Oktafiani, 2025).

Although during the time of testing, the water levels in all the test pits were observed to be below the 1.5m depth, the significant variation in the amount of rainfall between the dry winter season and wet monsoon seasons indicates that the wet monsoon season could trigger the rise in water level, flooding, and landslides. The average difference of rainfall recorded between January and July across the stations in Zhemgang, Trashy Yangtse, Paro, Haa, Mongar, Sarpang, Trashigang, Gasa, Tsirang, Bumthang, Thimphu, and Punakha from 1996 to 2016 is 427.25mm (Meteorology (NCHM), 2017).

### 2.2.1. Computation of Cyclic Stress Ratio (CSR)

The Cyclic Stress Ratio (CSR) is the stress induced on the soil layer due to an earthquake.

To evaluate CSR, the simplified method described by (Youd & Idriss, 2001) formulated by (Seed & Idriss, 1971) is adopted.

$$CSR = \frac{\tau_{av}}{\sigma'_{vo}} = 0.65 x \left( \frac{\alpha_{max}}{g} \right) \left( \frac{\sigma_{vo}}{\sigma'_{vo}} \right) r_d \quad (Eq. 1)$$

where  $\alpha_{max}$  = the peak horizontal acceleration at the ground surface generated by the earthquake.

$g$  = acceleration due to gravity;  $\sigma_{vo}$  and  $\sigma'_{vo}$  are total and effective vertical overburden stresses, respectively; and  $r_d$  = stress reduction coefficient.

$$r_d = 1 - 0.00765z \quad \text{for } z \leq 9.15m \quad (Eq. 2)$$

Where  $Z$  is the depth below ground surface in meters.

The peak ground acceleration ( $\alpha_{max}$ ) is the measure of intensity of earths shaking at a given point. The generic peak ground acceleration (PGA) value of 0.4g corresponding to the seismic Zone V is given in IS : 1893 - 1984 (Reaffirmed 2022) (Standards, Bureau of Indian, 2022), however, the studies indicate that PGA values could exceed 1g, especially in the southern part of Bhutan. The PGA values from the seismic hazard map of Bhutan for 10% chance in 50 years is obtained for this study (Stevens, Risi, Roux-Mallouf, Drukpa, & Hetényi, 2020). Table 2 provides the estimate of the PGA values.

**Table 1:** The PGA values estimated from the seismic hazard map by (Stevens, Risi, Roux-Mallouf, Drukpa, & Hetényi, 2020).

Location	PGA(g)	Location	PGA (g)
Gasa	0.4	Trashy Yangtse	0.4
Trongsa	0.7	Mongar	0.65
Thimphu	0.75	Punakha	0.8
Phuntsholing	0.85	Gelephu	1
Tashigang	0.6	Paro	0.8
Bumthang	0.7	S/Jongkhar	1.1

### 2.2.2. Evaluation of the cyclic resistance ratio (CRR)

Cyclic Resistance Ratio (CRR) or liquefaction resistance is the capacity of the soil to resist liquefaction (Boulanger & Idriss, 2014).

For the evaluation of CRR at an earthquake of magnitude 7.5, the equation formulated with the clean sand adjustment for fine content is used as given below (Boulanger & Idriss, 2014). For this

study, the soils are assumed to be clean sand with a fines content  $\leq 5\%$ .

$$CRR_{7.5, \sigma'_v=1 atm} = \exp\left(\frac{(N_1)_{60}}{14.1} + \left(\frac{(N_1)_{60}}{126}\right)^2 - \left(\frac{(N_1)_{60}}{23.6}\right)^3 + \left(\frac{(N_1)_{60}}{25.4}\right)^4 - 2.8\right) \#(Eq. 3)$$

The earthquakes of magnitude less than or greater than 7.5, the magnitude scale factor proposed by Idriss (1996) is adopted (Youd & Idriss, 1997). The SPT N-value obtained from the data is already corrected for overburden pressure and dilatancy. The N-value is further corrected for Energy ratio, borehole diameter, Rod length, and sampling method as per the values given in Table 2.

$$(N_1)_{60} = C_E C_B C_R C_S (N)_{60} \#(Eq. 4)$$

The corrections for the borehole diameter are not applicable in this study, since test pits of 1.5m width, depth, and length were used instead of a borehole.

**Table 2:** Corrections to SPT N-value as modified by Robertson and Wride and listed by (Youd & Idriss, 2001)

Factor	Equipment variable	Term	Correction
Energy ratio	Donut Hammer	$C_E$	0.5 to 1.0
	Safety Hammer		0.7 to 1.2
	Automatic-Trip Donut-Type Hammer		0.8 to 1.3
Borehole diameter	65mm to 115mm	$C_B$	1
	150 mm		1.05
	200 mm		1.15
Rod Length	3m to 4 m	$C_R$	0.75
	4m to 6m		0.85
	6m to 19 m		0.95
	10 to 30 m		1
	>30 m		<1
Sampling method	Standard sampler	$C_S$	1
	Sampler without liner		1.1 to 1.3

**2.2.3. Factor of Safety (FS)**

The likelihood of failure or liquefaction is expressed as a Factor of Safety (FS), defined by the ratio:

$$F_s = \frac{CRR}{CSR} \#(Eq. 4)$$

The sample analysis of liquefaction potential is given in Table 3.

**Table 3:** Sample calculation of the liquefaction potential analysis at an Earthquake of Magnitude 7.5

SI	Location Name	CSR	N1(60)	CRR	F <sub>s</sub>	Liquefaction Potential
1	Pit 1- Thimphu	0.48	7.31	0.10	0.21	YES
2	Thimphu 1	0.48	16.09	0.17	0.34	YES
3	Pit 1- Pamtsho	0.48	17.92	0.18	0.38	YES
4	Thimphu	0.48	13.16	0.14	0.29	YES
5	Pit 1- Paro Town	0.51	17.55	0.18	0.35	YES
6	Paro	0.51	10.97	0.12	0.24	YES
7	Pit 1- Shaba	0.51	13.16	0.14	0.27	YES
8	Pit 01- Shaba	0.51	32.18	0.66	1.29	NO
9	Pit 2- Shaba	0.51	5.85	0.09	0.18	YES
10	Pit 3- Shaba	0.51	29.98	0.48	0.94	YES

The detailed analysis is attached as Appendix-1

**3. RESULTS AND DISCUSSION**

Based on the geotechnical parameters derived from the Bhutan Standards Bureau database, the seismic zonation map by (Stevens, Risi, Roux-Mallouf, Drukpa, & Hetényi, 2020), the liquefaction potential was rigorously evaluated.

The computation of the Factor of Safety (FS) against liquefaction revealed significant seismic liquefaction vulnerability across the location, such as Paro, Thimphu, Wangdue Phodrang, Samtse, Gelephu, and Gedu, with an expected rise in water table during the monsoon season. Across all the locations that the Bhutan Standards Bureau database has covered, the study has predicted that the liquefaction could occur at a magnitude as low as 5.5 at a depth of 1.5m, except for Paro. At this magnitude, the earthquake-induced cyclic stress ratio (CSR) exceeds the cyclic resistance ratio (CRR) of the in-situ soil.

This is mainly due to high seismic activity in this region, which leads to higher peak ground acceleration (PGA). Notable differences were observed when comparing the liquefaction potential evaluated based on the generalised PGA value of 0.4g (given by the Indian Standard) and the PGA values from seismic zonation map (Stevens, Risi, Roux-Mallouf, Drukpa, & Hetényi, 2020).

**Table 4:** Sample calculation of the liquefaction potential analysis for an earthquake of Magnitude 5.5

The detailed analysis is attached as Appendix-2

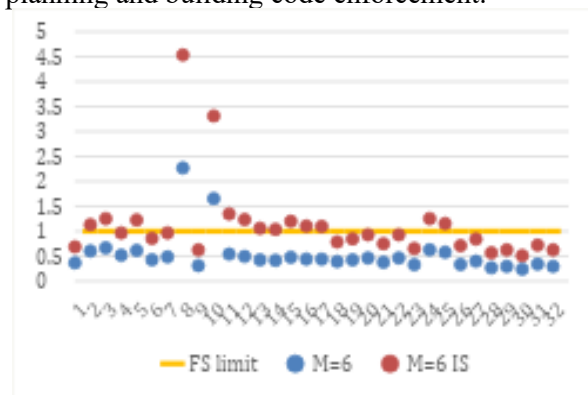
Sl	Location Name	CSR	CRR	F <sub>s</sub>	Liquefac tion potential
1	Pit 1- Thimphu	0.48	0.22	0.46	YES
2	Thimphu 1	0.48	0.36	0.76	YES
3	Pit 1- Pamtsho	0.48	0.40	0.83	YES
4	Thimphu	0.48	0.31	0.65	YES
5	Pit 1- Paro Town	0.51	0.39	0.77	YES
6	Paro	0.51	0.27	0.53	YES
7	Pit 1- Shaba	0.51	0.31	0.60	YES

8	Pit 01- Shaba	0.51	1.46	2.83	NO
9	Pit 2- Shaba	0.51	0.20	0.39	YES
10	Pit 3- Shaba	0.51	1.06	2.07	NO

The detailed analysis is attached as Appendix-2

It was observed that, for earthquake magnitudes of 6.0 and below, at a depth of 1.5 m, a significant number of locations could experience liquefaction when evaluated based on seismic zonation data. In contrast, certain areas such as Thimphu, Gelephu, and Lobesa may not experience liquefaction when evaluated using the PGA values from the Indian Standard. This result suggests that further studies on seismic zonation map of Bhutan are critical for the accurate liquefaction risk assessment in the event of an earthquake.

For structures with a standard foundation depth of 1.5m, the analysis indicates that the supporting soil lacks sufficient shear strength to maintain stability during the design-level earthquake with a magnitude greater than 7.5 (M>7.5). These results indicate that for development in areas covered by this study, shallow foundations may be inadequate without significant ground improvement or a transition to deep foundation systems. The findings further suggested that the liquefaction risk assessment requires immediate attention in regional urban planning and building code enforcement.



**Fig 3:** Comparison of liquefaction potential based on PGA values from the Indian Standard and PGA from (Stevens, Risi, Roux-Mallouf, Drukpa, & Hetényi, 2020) for an earthquake of magnitude 6 at a depth of 1.5

#### 4. LIMITATION

The scope of this study was constrained by the limited availability of Standard Penetration Test (SPT) data from the Bhutan Standards Bureau database. In the absence of grain size distribution data, as well as Atterberg limits (liquid limit and plastic limit), the fines content of the soil was assumed to be less than 5%. This assumption may not accurately reflect in-situ conditions, as findings by (Tokimatsu & Yoshimi, 1983) demonstrate that soils with fines content exceeding 10% exhibit greater resistance to liquefaction compared to clean sands at equivalent SPT N-values. Additionally, a generalized assumption was made that the soil profile becomes fully saturated during the monsoon season due to intense rainfall; however, this condition may not be uniformly applicable across all sites. Additionally, borehole diameter correction to SPT N-values was deemed not applicable, as the tests were conducted in test pits with dimensions of 1.5 m × 1.5 m × 1.5 m, rather than conventional boreholes.

#### 5. CONCLUSION AND RECOMMENDATIONS

##### 5.1 Summary of findings

This study evaluated the liquefaction potential of foundation soils based on the geotechnical database of the Bhutan Standards Bureau. The result concludes that the risk of liquefaction potential is imminent in the areas covered, such as Paro, Thimphu, Wangdue Phodrang, Samtse, Gelephu, and Gedu at an earthquake of magnitude as low as 5.5, posing a significant risk to the structural integrity of existing and planned infrastructure, especially during the summer monsoon season. Hence, immediate attention for liquefaction potential assessment is necessary for the infrastructure development and urban town planning in Bhutan as the re-occurrence of the high magnitude earthquake is inevitable. The ground improvement techniques to improve the relative density, deep foundation, and seismic monitoring to better characterise the site-specific response are recommended for future infrastructure development.

##### 5.2 Recommendations for further study

This research addresses the existing gap in liquefaction risk assessment within Bhutan. To

provide designers with a more comprehensive understanding of these risks, future studies should focus on expanded geographical coverage and detailed liquefaction mapping. Furthermore, it is recommended that subsequent analyses incorporate site-specific Peak Ground Acceleration (PGA) values and precise fine content data.

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**Appendix 1: Liquefaction potential analysis at an earthquake of magnitude 7.5**

Site details			CSR computation									CRR computation					FOS	Liquefaction potential
S	Location	Name of Location	Peak ground acceleration by earthquake (g)	Acceleration due gravity (g)	Unit weight (kn/m <sup>3</sup> )	Depth of Foundation(m)	Depth of water table (m)	Total overburden stresses	Effective overburden stress	Stress reduction coefficient (rd)	CSR	Corrected SPT N-value N1(60)	CRR at 7.5 magnitude	Magnitude of earthquake	Magnitude scaling factor	CSR		
1	POINT (89.6293 27.4813)	Pit 1-Thimphu	0.75	1.00	20.70	1.50	below 1.5 m	31.05	31.05	0.99	0.48	7.31	0.10	7.50	1.00	0.10	0.21	YES
2	POINT (89.6336 27.471)	Thimphu 1	0.75	1.00	19.07	1.50	below 1.5 m	28.61	28.61	0.99	0.48	16.09	0.17	7.50	1.00	0.17	0.34	YES
3	POINT (89.6337 27.5155)	Pit 1-Pamtsho	0.75	1.00	16.15	1.50	below 1.5 m	24.23	24.23	0.99	0.48	17.92	0.18	7.50	1.00	0.18	0.38	YES
4	POINT (89.6444 27.4697)	Thimphu	0.75	1.00	18.00	1.50	below 1.5 m	27.00	27.00	0.99	0.48	13.16	0.14	7.50	1.00	0.14	0.29	YES
5	POINT (89.4073 27.4325)	Pit 1-Paro Town	0.80	1.00	12.62	1.50	below 1.5 m	18.93	18.93	0.99	0.51	17.55	0.18	7.50	1.00	0.18	0.35	YES
6	POINT (89.4103 27.4315)	Paro	0.80	1.00	19.22	1.50	below 1.5 m	28.83	28.83	0.99	0.51	10.97	0.12	7.50	1.00	0.12	0.24	YES
7	POINT (89.45087 27.38416)	Pit 1-Shaba	0.80	1.00	13.68	1.50	below 1.5 m	20.52	20.52	0.99	0.51	13.16	0.14	7.50	1.00	0.14	0.27	YES
8	POINT (89.4513 27.38435)	Pit 01-Shaba	0.80	1.00	13.91	1.50	below 1.5 m	20.87	20.87	0.99	0.51	32.18	0.66	7.50	1.00	0.66	1.29	NO

9	POINT (89.45081 27.38449)	Pit 2- Shaba	0.80	1.00	13.4 3	1.50	bel ow 1.5 m	20.1 5	20.15	0.99	0. 51	5.85	0.09	7.50	1.00	0.0 9	0. 18	YES
10	POINT (89.45107 27.38396)	Pit 3- Shaba	0.80	1.00	13.8 2	1.50	bel ow 1.5 m	20.7 3	20.73	0.99	0. 51	29.98	0.48	7.50	1.00	0.4 8	0. 94	YES
11	POINT (90.39 26.9117)	Pit 4- Geleph u	1.00	1.00	17.9 4	1.50	bel ow 1.5 m	26.9 1	26.91	0.99	0. 64	19.23	0.20	7.50	1.00	0.2 0	0. 31	YES
12	POINT (90.3825 26.926)	Pit 5- Geleph u	1.00	1.00	13.7 6	1.50	bel ow 1.5 m	20.6 4	20.64	0.99	0. 64	17.62	0.18	7.50	1.00	0.1 8	0. 28	YES
13	POINT (90.395 26.9186)	Pit 11- Geleph u	1.00	1.00	13.3 8	1.50	bel ow 1.5 m	20.0 7	20.07	0.99	0. 64	14.84	0.15	7.50	1.00	0.1 5	0. 24	YES
14	POINT (90.3856 26.9205)	Pit 13- Geleph u	1.00	1.00	18.0 0	1.50	bel ow 1.5 m	27.0 0	27.00	0.99	0. 64	14.48	0.15	7.50	1.00	0.1 5	0. 24	YES
15	POINT (90.387 26.9212)	Pit 14 - Geleph u	1.00	1.00	18.0 0	1.50	bel ow 1.5 m	27.0 0	27.00	0.99	0. 64	17.11	0.17	7.50	1.00	0.1 7	0. 27	YES
16	POINT (90.3822 26.9269)	Pit 15- Geleph u	1.00	1.00	18.0 0	1.50	bel ow 1.5 m	27.0 0	27.00	0.99	0. 64	15.58	0.16	7.50	1.00	0.1 6	0. 25	YES
17	POINT (90.3985 26.9161)	Pit 24 - Geleph u	1.00	1.00	18.0 0	1.50	bel ow 1.5 m	27.0 0	27.00	0.99	0. 64	15.50	0.16	7.50	1.00	0.1 6	0. 25	YES
18	POINT (27.4914,8 9.9012)	Pit 1- Tencho ling	0.80	1.00	15.0 8	1.50	bel ow 1.5 m	22.6 2	22.62	0.99	0. 51	9.51	0.11	7.50	1.00	0.1 1	0. 22	YES
19	POINT (89.8963 27.4807)	Pit 2- Tencho ling	0.80	1.00	15.2 5	1.50	bel ow 1.5 m	22.8 8	22.88	0.99	0. 51	10.82	0.12	7.50	1.00	0.1 2	0. 24	YES

20	POINT (89.903 27.4901)	Pit 3- Tencho ling	0.80	1.00	15.4 5	1.50	bel ow 1.5 m	23.1 8	23.18	0.99	0. 51	12.43	0.14	7.50	1.00	0.1 4	0. 26	YES
21	POINT (89.9031 27.49)	Pit 1- Tencho ling	0.80	1.00	15.9 2	1.50	bel ow 1.5 m	23.8 8	23.88	0.99	0. 51	8.78	0.11	7.50	1.00	0.1 1	0. 21	YES
22	POINT (89.9031 27.49)	Pit 2- Tencho ling	0.80	1.00	15.7 4	1.50	bel ow 1.5 m	23.6 1	23.61	0.99	0. 51	12.43	0.14	7.50	1.00	0.1 4	0. 26	YES
23	POINT (89.9726 27.3871)	Pit 1- khotok ha	0.80	1.00	15.4 6	1.50	bel ow 1.5 m	23.1 9	23.19	0.99	0. 51	6.58	0.10	7.50	1.00	0.1 0	0. 19	YES
24	POINT (89.85334 27.51771)	Pit 1- Lobesa	0.80	1.00	16.1 5	1.50	bel ow 1.5 m	24.2 3	24.23	0.99	0. 51	17.94	0.18	7.50	1.00	0.1 8	0. 36	YES
25	POINT (89.85346 27.51759)	Pit 2- Lobesa	0.80	1.00	15.8 0	1.50	bel ow 1.5 m	23.7 0	23.70	0.99	0. 51	16.42	0.17	7.50	1.00	0.1 7	0. 33	YES
26	POINT (89.5228 26.9211)	Pit 1- Gedu	0.85	1.00	12.6 6	1.50	bel ow 1.5 m	18.9 9	18.99	0.99	0. 55	7.86	0.10	7.50	1.00	0.1 0	0. 19	YES
27	POINT (89.5225 26.9216)	Pit 2- Gedu	0.85	1.00	13.0 1	1.50	bel ow 1.5 m	19.5 2	19.52	0.99	0. 55	10.71	0.12	7.50	1.00	0.1 2	0. 23	YES
28	POINT (88.9766 26.926)	(SPT Pit2) (Yoese ltse	0.85	1.00	16.3 4	1.50	bel ow 1.5 m	24.5 1	24.51	0.99	0. 55	4.39	0.08	7.50	1.00	0.0 8	0. 15	YES
29	POINT (88.968 26.9275)	(SPT Pit 5) (Yoese ltse	0.85	1.00	18.0 5	1.50	bel ow 1.5 m	27.0 8	27.08	0.99	0. 55	5.85	0.09	7.50	1.00	0.0 9	0. 17	YES
30	POINT (88.968 26.9275)	(SPT Pit 4) (Yoese ltse	0.85	1.00	16.9 0	1.50	bel ow 1.5 m	25.3 5	25.35	0.99	0. 55	2.93	0.07	7.50	1.00	0.0 7	0. 14	YES

31	POINT (88.9626 26.9293)	(SPT Pit 3)(Yoe seltse	0.85	1.00	17.1 4	1.50	bel ow 1.5 m	25.7 1	25.71	0.99	0. 55	8.04	0.10	7.50	1.00	0.1 0	0. 19	YES
32	POINT (91.8292 26.8857)	(SPT Pit 1)(Yoe seltse	0.85	1.00	15.8 6	1.50	bel ow 1.5 m	23.7 9	23.79	0.99	0. 55	5.85	0.09	7.50	1.00	0.0 9	0. 17	YES

**Appendix 2: Liquefaction potential analysis for an earthquake of magnitude 5.5**

Site details			CSR computation									CRR computation					FOS	Liqu facti on poten tial
sl	Location	Name of Location	Peak groun d acce ratio n by earth quak e (g)	Accel eratio n due gravi ty (g)	Unit weight (kn/m 3)	Dept h of Founda tion(m)	Dept h of water table (m)	Total over burde n stress es	Effect ive overb urden stress	Stre ss red ucti on coef ficient (rd)	CSR	Corre cte SPT N- value N1(60 )	CRR at 7.5 magn itude	Magn itude of earth quak e	Magn itude scalin g factor	CRR		
1	POINT (89.6293 27.4813)	Pit 1- Thimphu	0.75	1.00	20.70	1.50	below 1.5 m	31.05	31.05	0.99	0.48	7.31	0.10	7.50	2.20	0.22	0.46	YES
2	POINT (89.6336 27.471)	Thimphu 1	0.75	1.00	19.07	1.50	below 1.5 m	28.61	28.61	0.99	0.48	16.09	0.17	7.50	2.20	0.36	0.76	YES
3	POINT (89.6337 27.5155)	Pit 1- Pamtsho	0.75	1.00	16.15	1.50	below 1.5 m	24.23	24.23	0.99	0.48	17.92	0.18	7.50	2.20	0.40	0.83	YES
4	POINT (89.6444 27.4697)	Thimphu	0.75	1.00	18.00	1.50	below 1.5 m	27.00	27.00	0.99	0.48	13.16	0.14	7.50	2.20	0.31	0.65	YES
5	POINT (89.4073 27.4325)	Pit 1- Paro Town	0.80	1.00	12.62	1.50	below 1.5 m	18.93	18.93	0.99	0.51	17.55	0.18	7.50	2.20	0.39	0.77	YES
6	POINT (89.4103 27.4315)	Paro	0.80	1.00	19.22	1.50	below 1.5 m	28.83	28.83	0.99	0.51	10.97	0.12	7.50	2.20	0.27	0.53	YES
7	POINT (89.45087 27.38416)	Pit 1- Shaba	0.80	1.00	13.68	1.50	below 1.5 m	20.52	20.52	0.99	0.51	13.16	0.14	7.50	2.20	0.31	0.60	YES
8	POINT (89.4513 27.38435)	Pit 01- Shaba	0.80	1.00	13.91	1.50	below 1.5 m	20.87	20.87	0.99	0.51	32.18	0.66	7.50	2.20	1.46	2.83	NO

9	POINT (89.45081 27.38449)	Pit 2- Shaba	0.80	1.00	13.43	1.50	below 1.5 m	20.15	20.15	0.99	0.51	5.85	0.09	7.50	2.20	0.20	0.39	YES
10	POINT (89.45107 27.38396)	Pit 3- Shaba	0.80	1.00	13.82	1.50	below 1.5 m	20.73	20.73	0.99	0.51	29.98	0.48	7.50	2.20	1.06	2.07	NO
11	POINT (90.39 26.9117)	Pit 4- Gelephu	1.00	1.00	17.94	1.50	below 1.5 m	26.91	26.91	0.99	0.64	19.23	0.20	7.50	2.20	0.43	0.67	YES
12	POINT (90.3825 26.926)	Pit 5- Gelephu	1.00	1.00	13.76	1.50	below 1.5 m	20.64	20.64	0.99	0.64	17.62	0.18	7.50	2.20	0.40	0.62	YES
13	POINT (90.395 26.9186)	Pit 11- Gelephu	1.00	1.00	13.38	1.50	below 1.5 m	20.07	20.07	0.99	0.64	14.84	0.15	7.50	2.20	0.34	0.53	YES
14	POINT (90.3856 26.9205)	Pit 13- Gelephu	1.00	1.00	18.00	1.50	below 1.5 m	27.00	27.00	0.99	0.64	14.48	0.15	7.50	2.20	0.33	0.52	YES
15	POINT (90.387 26.9212)	Pit 14 - Gelephu	1.00	1.00	18.00	1.50	below 1.5 m	27.00	27.00	0.99	0.64	17.11	0.17	7.50	2.20	0.38	0.60	YES
16	POINT (90.3822 26.9269)	Pit 15- Gelephu	1.00	1.00	18.00	1.50	below 1.5 m	27.00	27.00	0.99	0.64	15.58	0.16	7.50	2.20	0.35	0.55	YES
17	POINT (90.3985 26.9161)	Pit 24 - Gelephu	1.00	1.00	18.00	1.50	below 1.5 m	27.00	27.00	0.99	0.64	15.50	0.16	7.50	2.20	0.35	0.55	YES
18	POINT (27.4914,89. 9012)	Pit 1- Tencholing	0.80	1.00	15.08	1.50	below 1.5 m	22.62	22.62	0.99	0.51	9.51	0.11	7.50	2.20	0.25	0.49	YES
19	POINT (89.8963 27.4807)	Pit 2- Tencholing	0.80	1.00	15.25	1.50	below 1.5 m	22.88	22.88	0.99	0.51	10.82	0.12	7.50	2.20	0.27	0.53	YES
20	POINT (89.903 27.4901)	Pit 3- Tencholing	0.80	1.00	15.45	1.50	below 1.5 m	23.18	23.18	0.99	0.51	12.43	0.14	7.50	2.20	0.30	0.58	YES
21	POINT (89.9031 27.49)	Pit 1- Tencholing	0.80	1.00	15.92	1.50	below 1.5 m	23.88	23.88	0.99	0.51	8.78	0.11	7.50	2.20	0.24	0.47	YES
22	POINT (89.9031 27.49)	Pit 2- Tencholing	0.80	1.00	15.74	1.50	below 1.5 m	23.61	23.61	0.99	0.51	12.43	0.14	7.50	2.20	0.30	0.58	YES

23	POINT (89.9726 27.3871)	Pit 1- khotokha	0.80	1.00	15.46	1.50	below 1.5 m	23.19	23.19	0.99	0.51	6.58	0.10	7.50	2.20	0.21	0.41	YES
24	POINT (89.85334 27.51771)	Pit 1- Lobesa	0.80	1.00	16.15	1.50	below 1.5 m	24.23	24.23	0.99	0.51	17.94	0.18	7.50	2.20	0.40	0.78	YES
25	POINT (89.85346 27.51759)	Pit 2- Lobesa	0.80	1.00	15.80	1.50	below 1.5 m	23.70	23.70	0.99	0.51	16.42	0.17	7.50	2.20	0.37	0.72	YES
26	POINT (89.5228 26.9211)	Pit 1- Gedu	0.85	1.00	12.66	1.50	below 1.5 m	18.99	18.99	0.99	0.55	7.86	0.10	7.50	2.20	0.23	0.42	YES
27	POINT (89.5225 26.9216)	Pit 2- Gedu	0.85	1.00	13.01	1.50	below 1.5 m	19.52	19.52	0.99	0.55	10.71	0.12	7.50	2.20	0.27	0.50	YES
28	POINT (88.9766 26.926)	(SPT Pit2)(Yoes eltse	0.85	1.00	16.34	1.50	below 1.5 m	24.51	24.51	0.99	0.55	4.39	0.08	7.50	2.20	0.18	0.33	YES
29	POINT (88.968 26.9275)	(SPT Pit 5)(Yoeselt se	0.85	1.00	18.05	1.50	below 1.5 m	27.08	27.08	0.99	0.55	5.85	0.09	7.50	2.20	0.20	0.37	YES
30	POINT (88.968 26.9275)	(SPT Pit 4)(Yoeselt se	0.85	1.00	16.90	1.50	below 1.5 m	25.35	25.35	0.99	0.55	2.93	0.07	7.50	2.20	0.16	0.30	YES
31	POINT (88.9626 26.9293)	(SPT Pit 3)(Yoeselt se	0.85	1.00	17.14	1.50	below 1.5 m	25.71	25.71	0.99	0.55	8.04	0.10	7.50	2.20	0.23	0.42	YES
32	POINT (91.8292 26.8857)	(SPT Pit 1)(Yoeselt se	0.85	1.00	15.86	1.50	below 1.5 m	23.79	23.79	0.99	0.55	5.85	0.09	7.50	2.20	0.20	0.37	YES