Civil Engineering and Architecture 13(1): 543-558, 2025 http://www.hrpub.org
DOI: 10.13189/cea.2025.130134

Assessment of Liquefaction Potential in the Piura Region Using SPT and Shear Wave Velocity Measurements

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Received September 12, 2024; Revised November 12, 2024; Accepted December 23, 2024

Cite This Paper in the Following Citation Styles

(a): *[1] William Araujo , "Assessment of Liquefaction Potential in the Piura Region Using SPT and Shear Wave Velocity Measurements," Civil Engineering and Architecture, Vol. 13, No. 1, pp. 543 - 558, 2025. DOI: 10.13189/cea.2025.130134.*

(b): *William Araujo (2025). Assessment of Liquefaction Potential in the Piura Region Using SPT and Shear Wave Velocity Measurements. Civil Engineering and Architecture, 13(1), 543 - 558. DOI: 10.13189/cea.2025.130134.*

Abstract Liquefaction is a seismic geotechnical phenomenon whose impact on a city's infrastructure can be devastating. This process occurs when saturated soil temporarily loses its strength and stiffness in response to an applied stress, typically from earthquake shaking, leading to a fluid-like behavior. Countries with seismic activity, particularly those located near coastal areas or rivers, meet the basic requirements for liquefaction occurrence. The consequences of liquefaction can be catastrophic, causing buildings, roads, and bridges to sink or tilt, as well as creating large ground deformations and damaging underground utilities. The aim of this research is to analyze the liquefaction potential of the city of Piura, Peru. This region is particularly vulnerable due to its proximity to active seismic zones and the presence of loose, water-saturated soils. Two field tests were utilized to assess the potential for liquefaction: the Standard Penetration Test (SPT) and the Shear Wave Velocity Test (Vs). The methodology employed for this study involved gathering data from two key sources: the Construction Materials Testing Laboratory at the Universidad de Piura and the Geophysical Institute of Peru. Using this data, we applied the methodologies developed by Seed and Idriss (1971), Andrus and Stokoe (2000), Youd and Noble (1997), and Iwasaki et al. (1984) to assess the likelihood of liquefaction. The results of the research indicate that several of the tested areas exhibit a significant potential for liquefaction, especially in zones with loose sands and high groundwater levels. If an earthquake were to occur, the severity of damage, including settlements and structural failures, could be extensive, affecting critical infrastructure and posing a risk to public safety.

Keywords Liquefaction, SPT, Vs, Severity Index

1. Introduction

Liquefaction is a phenomenon that occurs when seismic waves propagating through saturated granular soil layers induce cyclic shear deformation and structural collapse. As this collapse occurs, the contacts between the grains are disrupted and the loads initially carried through particle contacts are transferred to the pore water and as there is no supporting capacity of the soil, the structure suffers damage [1]. The level of damage caused by liquefaction can be high, some significant examples can be shown: 1) The extensive liquefaction of reclaimed land in the Tokyo Bay area, from Shinkiba to the city of Chiba, was caused by the 2011 Tohoku earthquake 9.1Mw. Many houses settled significantly and tilted. In the city of Urayasu, 3,680 houses were more than partially destroyed. Sewage pipes broke, their joints were extruded from the ground, and many manholes were horizontally displaced [2]. 2) The soil liquefaction that occurred during the 2010 Maule earthquake 8.8Mw caused ground failures and lateral spreading. Several buildings suffered significant damage due to the foundation movements resulting from liquefaction. Liquefaction-induced ground failures also displaced and distorted coastal structures, adversely affecting the operation of some of Chile's key port facilities [3].

According to Alva [4], seismic liquefaction has occurred throughout history in the Region of Piura, leaving evidence such as the formation of small sand volcanoes, violent expulsion of water from the ground, intense cracking, and differential settlements. In 1857, an earthquake with no recorded magnitude occurred on August 20, producing a strong tremor lasting approximately 45 seconds, destroying buildings and causing the ground to open, from which black water emerged. Another event occurred in 1912, an 8.0 Mw earthquake on July 24, which severely affected the cities of Piura and Huancabamba, leaving only 1% of the cities habitable, with losses amounting to one and a half million Peruvian soles (four hundred thousand dollars). Evidence of soil liquefaction was observed in the dry riverbed of the Piura River, forming cracks with water surges, and damage to the railway embankment caused soil cracking in the port of Paita. In 1970, a 7.2 Mw earthquake on December 9 shook the city of La Huaca, resulting in 45 deaths. Evidence of liquefaction appeared as sand volcanoes and soil cracking in Querecotillo with a length of 500 m and an opening of 0.30 m. More recently, in 2021, a 6.1 Mw earthquake on July 30, with an epicenter west of Sullana [5], affected the District of Vichayal, District of Marcavelica, and District of La Union. Sand volcanoes were identified on San Lorenzo in the District of Vichayal (Paita Province), and the Locality of La Bomba (Sullana Province). These sand and water emissions had radii varying between 0.5 m to 1.5 m and appeared inside homes. Additionally, in the Locality of El Indio, continuous ground cracks with lengths of up to 10 m, or even more than 50 m discontinuously, appeared in the Vichayal, with the directions of these cracks varying.

The Region of Piura is located within the area known as the Pacific Ring of Fire, and thus is often affected by earthquakes of varying magnitudes. Tavera [6] argues that there is an accumulation of energy in the northern region of Peru that could be released in an earthquake of magnitude 7.5 Mw, raising concerns that such an event could impact many infrastructures. Additionally, the soil conditions in Piura are predominantly poorly graded sand or silty sands, with a water table that rises due to flooding processes in low-lying areas and exposure to climatic phenomena such as the El Niño events in 1985, 1998, and 2017 [7]. One of the benefits of studying liquefaction is to determine whether mitigation measures against this phenomenon are necessary, related to foundation design, and soil improvement techniques. Conducting this study is also important because it will help reinforce existing hazard maps, allowing to verify which areas are truly at high risk of liquefaction in Piura, thereby enabling us to prepare for the construction of housing to prevent and reduce damage.

2. Tectonic, Geotechnical and Hydrological Setting of Piura

According to the Geophysical Institute of Peru (IGP), Piura is in a high seismic risk zone because it lies on the Nazca Plate, which moves under the South American Plate and generates friction that releases energy in the form of earthquakes. Additionally, it has already experienced several major earthquakes throughout its history. The Geophysical Institute of Peru uses a methodology to identify the presence and location of asperities. Five anomalous zones, or asperities, have been identified, and based on their dimensions, the magnitude of seismic events has been estimated with a 75% probability for the next 50 years [6]. Figure 1 shows a probability map of acceleration and seismic return in Peru. The first asperity, A1, is in the southern region of Peru, primarily in the departments of Arequipa, Moquegua, and Tacna, associated with the 1868 earthquake.

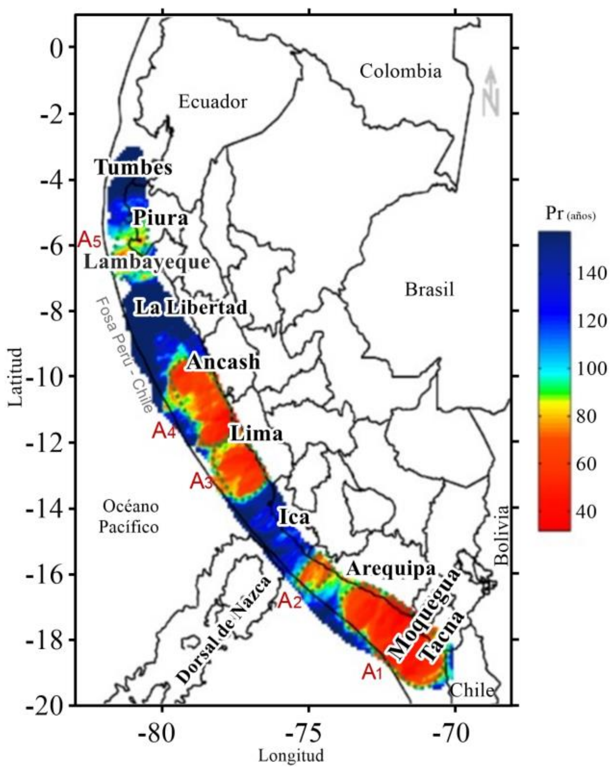

Figure 1. Seismic probability map of Peru adapted from Tavera (2014)

According to the dimensions of this asperity, an earthquake with a magnitude of 8.8 Mw is forecasted. However, the 2001 earthquake with a magnitude of 8.0 Mw released much of that energy, so there is a possibility of another earthquake with a magnitude of 8.2 Mw. The second asperity, A2, is located northwest of Arequipa and is associated with the 1913 earthquake. Due to this asperity, an earthquake with a magnitude of 7.5 Mw is forecasted. The third and fourth asperities, A3 and A4, are in the department of Lima and are associated with the 1746 earthquake, with the probability of an 8.8 Mw earthquake occurring. The last asperity, A5, is located between Lambayeque and Piura, associated with the 1619 earthquake, and corresponds to the occurrence of an earthquake with a magnitude of 7.5 Mw [6].

The [7] indicates that the area of the Piura region is located on recent Quaternary deposits, which were formed by the action of wind and water. These deposits are of two types: eolian deposits and alluvial deposits. The eolian deposits consist of very clean, poorly graded, and very loose fine sand. The alluvial deposits consist of sandy to silty soil, which is slightly dense and loose with a bearing capacity from 0.50 kg/cm² to 1.00 kg/cm². These deposits extend from the main channel of the Piura River to the West and East zones of the city of Piura and the Castilla districts. The eolian and alluvial deposits have a variable thickness, ranging from 3.0 m to 4.0 m up to an average of 8.0 m to 12.0 m. Beneath the recent Quaternary deposits are older deposits of lagoonal origin that consist of clay and silt, which are firm and impermeable. These deposits are found at the surface or at shallow depths in some specific areas of the city of Piura, such as the area of the San Martín oxidation lagoons, Santa Julia Lagoon, Coscomba Lagoon, and the road to Sullana. However, many of these lagoonal deposits are covered by a layer of very loose eolian sand, which can be up to 3.0 m to 4.0 m thick. In addition to the Quaternary and older deposits of Pleistocene age, which are of lagoonal and terrace origin, there are also eolian deposits from the Tertiary age, known as the Zapallal formation. Figure 2 shows a local geological map of the Piura region.

Regarding the water table level in Piura, it is observed that without the presence of the El Niño phenomenon, it is found at no less than 3 to 5 meters in some critical areas. Figure 3 shows a phreatic level map of Piura. However, during the occurrence of this phenomenon or during extraordinary rains, it can surface in much of the city.

This water level is caused by subsurface flows from rainwater or the Piura River itself and not from the actual groundwater table, which is located below a depth of 30 meters [7]. In areas located below an elevation of approximately 30 meters above sea level, which are in the southwestern part of Piura, deep flooding occurs in the most depressed areas and superficial flooding in the rest of the area.

For areas above an elevation of 30 meters above sea level, only superficial flooding occurs, where rainwater remains stagnant or has natural drainage due to its topographic characteristics. In the rest of the area, flooding from heavy rains is not significant. Consequently, during the El Niño phenomenon, the water table in the subsurface of Piura can be found at a depth of no more than 1.0 meter in critical areas. Therefore, this water level in the poorly graded sandy soils, during the El Niño phenomenon, results in these soils being fully saturated.

Figure 7. Safety factor versus depth in studied sites

Table 4 and Table 5 show probability values of liquefaction versus depth in the studied zones for PGA=0.30g and 0.45g, respectively. It is observed that the values shaded in red represent probabilities greater than 50%, indicating that the risk or impact of liquefaction is medium to extremely high. For boreholes BH2, BH7, BH8, BH9, and BH10, the top 10 meters of soil present this probability in both cases of PGA of 0.30g and 0.45g. Meanwhile, boreholes BH1, BH3, BH4, BH5, and BH6 show only a moderate to high probability of liquefaction up to 5 meters depth just in case of PGA=0.30g.

Regarding the severity of liquefaction observed in Piura, Table 6 indicates that in each borehole examined, the Iwasaki index consistently exceeds 15, suggesting a high risk of liquefaction across the region. This aligns with findings from researchers like Ishihara and Yoshimine [18], Ishihara [19] who emphasize that Iwasaki index values over 15 correspond to substantial soil deformation under seismic stress, further confirming the elevated liquefaction susceptibility in Piura. Therefore, it is concluded that the likelihood and potential impact of liquefaction in this area remain critically high.

Finally, in Table 7, all calculated settlements exceed 1 inch or 2.54 cm, which is the tolerable settlement for a typical building according to Peruvian regulations (NTP-E050). This indicates that the structural design may not comply with local building standards, potentially leading to structural integrity issues, safety concerns, and higher maintenance costs. Ensuring that settlements remain within the prescribed limits is crucial to maintaining the safety and longevity of the building.

The difference in the calculated settlements between boreholes BH-5, BH-8, and BH-10, despite having a similar soil profile, is mainly due to variations in the $N1_{60}$

values obtained for each borehole. Although the three boreholes share a similar soil composition, the $N1_{60}$ values vary significantly, especially in the shallow layers. Boreholes with lower $N1_{60}$ values, such as BH-8, indicate looser and more liquefaction-prone soils, resulting in greater volumetric deformation and, consequently, larger settlements. In contrast, boreholes with higher $N1_{60}$ values, like BH-15 and BH-10, reflect denser soils that are less prone to liquefaction, leading to smaller settlements. This variability in $N1_{60}$ values explains the observed differences in liquefaction-induced settlements, as the volumetric deformation directly depends on the compaction and density of the soil in each borehole.

Similarly, to the boreholes mentioned in the previous paragraph, the significant difference in the calculated settlements between boreholes BH-2, BH-7, and BH-9, ranging from 16.84 cm in BH-9 to 71.17 cm in BH-2, can primarily be attributed to variations in the $N1_{60}$ values at different depths within each borehole. Specifically, borehole BH-2 exhibits lower $N1_{60}$ values in the shallow layers, indicating looser soils that are more susceptible to liquefaction, thereby resulting in greater settlement. In contrast, boreholes BH-7 and BH-9 show higher $N1_{60}$ values in the upper layers, reducing the susceptibility to liquefaction and consequently leading to smaller induced settlements. Additionally, factors such as the depth and thickness of liquefaction-prone layers, potential variations in saturation, and local soil heterogeneity may also have influenced the results. In conclusion, the differences in $N1_{60}$ values, along with other geotechnical factors, provide an explanation for the observed variability in the calculated settlements.

Table 4. Probability values of liquefaction versus depth in the studied zones for PGA=0.30g

	BH-1	**BH-2**	**BH-3**	**BH-4**	**BH-5**	**BH-6**	**BH-7**	**BH-8**	**BH-9**	**BH-10**
Depth (m)	P_L	P_L	P_L	P_L	P_L	P_L	P_L	P_L	P_L	P_L
1	0.87	0.91	0.95	0.01	1.00	0.80	0.91	0.98	0.87	0.99
2	0.90	0.99	0.75	0.99	0.99	0.55	0.99	0.99	0.86	0.98
3	0.95	0.99	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
4	0.90	0.99	0.92	0.93	0.99	0.69	0.99	0.99	0.99	0.97
5	0.93	0.99	0.87	0.89	0.98	0.79	0.99	0.99	0.97	0.97
6	0.36	0.99	0.94	0.76	0.27	0.13	0.99	0.99	0.96	0.97
7	0.23	0.99	0.09	0.09	0.28	0.06	0.99	0.99	0.95	0.97
8	0.31	0.99	0.13	0.13	0.36	0.05	0.99	0.99	0.68	0.98
9	0.38	0.99	0.13	0.18	0.44	0.18	0.99	0.99	0.73	0.98
10	0.43	0.99	0.06	0.22	0.49	0.22	0.99	0.99	0.76	0.98

Table 5. Probability values of liquefaction versus depth in the studied zones for PGA=0.45g

	BH-1	**BH-2**	**BH-3**	**BH-4**	**BH-5**	**BH-6**	**BH-7**	**BH-8**	**BH-9**	**BH-10**
Depth (m)	P_L	P_L	P_L	P_L	P_L	P_L	P_L	P_L	P_L	P_L
1	0.96	0.96	0.97	0.98	0.03	1.00	0.97	1.00	0.96	1.00
2	0.97	0.97	1.00	0.91	1.00	1.00	1.00	1.00	0.96	1.00
3	0.99	0.99	1.00	0.90	0.90	0.90	0.90	0.90	0.90	0.90
4	0.97	0.97	1.00	0.98	0.98	1.00	1.00	1.00	1.00	0.99
5	0.98	0.98	1.00	0.96	0.97	0.99	1.00	1.00	0.99	0.99
6	0.66	0.66	1.00	0.98	0.92	0.57	1.00	1.00	0.99	0.99
7	0.51	0.51	1.00	0.25	0.25	0.58	1.00	1.00	0.98	0.99
8	0.61	0.61	1.00	0.35	0.35	0.67	1.00	1.00	0.88	0.99
9	0.68	0.68	1.00	0.34	0.44	0.73	1.00	1.00	0.91	0.99
10	0.72	0.72	1.00	0.17	0.50	0.77	1.00	1.00	0.92	0.99

Table 6. Evaluation of liquefaction potential with the severity index of Iwasaki et al. (1984) for a PGA = 0.30g and PGA=0.45g

Borehole	PGA: 0.30 g		PGA: 0.45 g	
	I_L [SPT]	I_L[Vs]	I_L [SPT]	I_L[Vs]
BH-1	46.57	41.41	31.05	27.61
BH-2	14.66	20.16	9.77	13.44
BH-3	56.44	66.04	40.91	44.02
BH-4	50.89	39.02	34.59	26.01
BH-5	40.32	57.24	26.88	38.21
BH-6	64.27	51.19	48.47	34.13
BH-7	17.62	20.16	11.75	13.44
BH-8	16.55	45.63	11.04	30.42
BH-9	32.44	38.76	21.63	25.84
BH-10	21.71	47.34	14.47	31.66

Table 7. Liquefaction-induced settlements for the 10 zones

Borehole	Calculated settlement [cm]
BH-1	11.32
BH-2	71.17
BH-3	10.84
BH-4	11.65
BH-5	29.21
BH-6	8.72
BH-7	66.97
BH-8	48.96
BH-9	16.84
BH-10	23.17

5. Conclusions

Based on the findings of the study, several key conclusions can be drawn regarding liquefaction risk and its implications in the Piura region. Firstly, analysis of grain size distribution curves (Figure 6) against Tsuchida's liquefaction contours indicates a prevalent probability of liquefaction across most zones. This aligns consistently with the liquefaction potential assessments using N and Vs values, highlighting the susceptibility of the region under specific seismic conditions.

Secondly, evaluation of liquefaction safety factors (FSL) depicted in Figure 7 reveals that all studied zones exhibit FSL values below 1 for both PGA scenarios of 0.30g and 0.45g. This highlights a significant vulnerability to liquefaction at these shaking levels, stressing the importance of incorporating seismic resilience into infrastructure planning.

Lastly, probabilistic assessments (Tables 5 and 6) demonstrate that significant portions of the studied areas exhibit probabilities of liquefaction exceeding 50%, particularly in shallow soil depths. Zones such as BH2, BH7, BH8, BH9, and BH10 present notable liquefaction risks in the upper 10 meters of soil, while others like BH1, BH3, BH4, BH5, and BH6 show moderate to high probabilities up to 5 meters depth. Additionally, severity assessments (Table 7) consistently show Iwasaki indices above 15 across all boreholes, indicating a high severity of liquefaction effects in Piura.

In summary, the comprehensive analysis reveals a critical liquefaction risk in Piura, characterized by widespread susceptibility to soil liquefaction and significant potential for structural settlements exceeding tolerable limits. These findings underscore the necessity for robust seismic hazard mitigation strategies, including improved building codes, foundation designs, and land-use planning practices to enhance resilience against liquefaction-induced hazards in the region. The variability in the calculated settlements from the boreholes is primarily due to differences in the geotechnical characteristics of the soils, particularly the $N1_{60}$ values at various depths. These values are indicative of the soil's density and compaction, which directly influence its susceptibility to liquefaction and, consequently, the induced settlements. Layers with lower $N1_{60}$ values exhibit looser soils that are more prone to liquefaction, resulting in greater settlements, whereas soils with higher values are less susceptible and generate smaller settlements. Additionally, factors such as the thickness of liquefaction-prone layers, soil saturation, and local heterogeneity also play an important role in the variability of the results. In summary, the interaction of these geotechnical factors determines the settlements induced by liquefaction, and understanding them is key to accurately assessing risks and designing appropriate solutions in areas prone to this phenomenon.

Acknowledgements

The author thank the Universidad de Piura and the Instituto Geofísico del Perú for providing the database used in this study.

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