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Assessment of Soil Liquefaction Potential Based on SPT Values at Some Ground Profiles in the North Central Coast of Vietnam

Nguyen Thi Nu*, Nguyen Thanh Duong, Bui Truong Son
Department of Engineering Geology, Hanoi University of Mining and Geology, Viet Nam

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Abstract

The North Central Coast of Vietnam has a wide distribution of loose sand which is often exposed on the surface. The thickness changes from a few meters to over ten meters. This sand with the loose state can be sensitive to the dynamic loads, such as earthquakes, traffic load, or machine foundations. It can be liquefied under these loadings, which might destroy the ground and buildings. The Standard Penetration Test (*SPT*) is widely used in engineering practice and its values can be useful for the assessment of soil liquefaction potential. Thus, this article presents some ground profiles in some sites in the North Central Coast of Vietnam and determines the liquefaction potential of sand based on *SPT* and using three parameters, including the Factor of Safety against Liquefaction (FS_{LIQ}), Liquefaction Potential Index (*LPI*), and Liquefaction Severity Number (*LSN*). The research results show that the FS_{LIQ}, *LPI*, and *LSN* values depend on the depth of sand samples and the *SPT* values. In this study, the sand distributed from 2.0 to 18.0m with $(N1)_{60cs}$ value of less than 20 has high liquefaction potential with FS_{LIQ}<1, *LPI* is often higher than 0.73, and *LSN* is often higher than 10. The results also show that many soil profiles have high liquefaction potential. These results should be considered for construction activities in this area.

Keywords: Liquefaction potential, sand, SPT, North Central Coast of Vietnam, potential.

Introduction

Vietnam is the country having a long coastline and includes three main regions: the Northern, the Central, and the Southern regions. In the Northern and Southern coastal areas, soft clay soil is mainly distributed in the deltas with the thickness varying from a few meters to more than 30-50 meters, which usually needs to be treated before construction [1-7]. The North Central Coast of Vietnam, including Thanh Hoa, Nghe An, Ha Tinh, Quang Binh, Quang Ngai, and Thua Thien Hue provinces, have complicated stratigraphy with different types of soft clay soil and loose to medium sand layers. The thickness of loose sand changes from a few meters to over ten meters. In this region, the demands for infrastructure development, such as building of roads and railway systems are on the rise. In particular, the loose sand layers are often distributed at the shallow depth and sensitive to the dynamic loads, such as earthquakes, traffic loads, and machine foundations. They can be liquefied under these loads and damage the buildings and constructions. Therefore, the liquefaction potential of sand in this region needs to be considered and evaluated.

To evaluate the liquefaction potential of sand, there are two methods that include deterministic and probabilistic approaches [8]. The deterministic method, or stress method, has been developed by Seed and Idriss [9] and modified several times. Seed and Alba [10] established the relationship between Cone Penetrometer Test and Standard Penetration Test (*CPT – SPT)* - liquefaction resistances and found the factors to calculate the liquefaction resistance of the soil. Youl *et al*. [11] recommended

*Email: nguyenthinu@humg.edu.vn

four field tests for evaluation of liquefaction resistance, including – *CPT*, *SPT*, shear – wave velocity (*Vs*) measurements, and the Backer Penetration Test (BPT) for gravelly sites. These authors also showed the advantages and disadvantages of each method in the evaluation of soil liquefaction. The main advantages of *CPT* were the abundance of data and high-quality control. The main advantage of SPT was also the occurrence of plentiful data. Besides, for *SPT*, sand samples could be taken to determine the fine content and other grain characteristics and then used to evaluate the liquefaction potential. It was also shown that the fine content (grain size distribution) affects the liquefaction potential of soil. Cetin *et al*. [12] recommended a new method with a combination of probabilistic and deterministic approaches for assessing the likelihood of liquefaction initiation. Idriss and Boulanger [13-15] presented and updated the examination of *SPT*-based liquefaction triggering procedures for cohesionless soils. Boulanger and Idriss [16] proposed the re-examination of *CPT*-based and *SPT*-based liquefaction triggering procedures for cohesionless soils. From the literature review, since the *SPT* and *CPT* values were abundant and popular, the data from *SPT* and *CPT* have been widely used to evaluate the liquefaction potential [17].

The liquefaction potential of soils can be evaluated by three parameters, including Liquefaction Evaluation Procedure – *LEP* [16, 18], Liquefaction Potential Index – *LPI* [19, 20] and Liquefaction Severity Number – *LSN* [11]. *LEP* can be used to predict the soil liquefaction potential through the Factor of Safety against Liquefaction (FS_{Liq}). One of the main advantages of the FS_{Liq} is that it can be used to classify soils, in which the soil will be liquefied if FS_{Liq} is less than 1.0 [16]. By contrast, the disadvantage of FS_{Liq} is that if it is greater than one, it does not confirm the safety against soil liquefaction [22]. *LPI* was proposed to the thickness of liquefiable and non – liquefiable soil layers as well as the value of the factor of safety against soil liquefaction (FS_{Liq}). The advantage of *LPI* is providing a unique value for the entire soil column instead of several safety factors at different layers and using the *SPT* data to classify the liquefaction potential of geological units [20, 23]. *LSN* reflected the more damaging effects of shallow liquefaction on residential lands and foundations [21]. Besides, *LSN* considered the volumetric densification strain within soil layers as a proxy for the severity of liquefaction land likely damage at the ground surface. Dixit *et al*. [24] used the *LPI* value to predict the potential of liquefaction of soil distributed in Mumbai city and discovered that the majority of the sites in the city have a high potential of liquefaction.

Previous studies indicated that the liquefaction potential of soil can be evaluated by several methods. However, there are limitations in using the three parameters of FS_{Liq}, *LPI*, and *LSN* to evaluate the liquefaction potential of sandy soil. Moreover, in Vietnam, the Standard Penetration Test (*SPT*) is widely used in site investigation. The data of *SPT* are available and mainly used for design foundation. The use of *SPT* values for evaluating the soil liquefaction potential is still limited. Therefore, the main objective of this study is to evaluate the sand liquefaction potential by three parameters (FS_{Liq}, *LPI*, and *LSN*) in the North Central Coast of Vietnam based on *SPT* values. The relationship between *SPT* values and FS_{Liq}, *LPI* and *LSN*, and the variation of the latter three parameters with depth will be clarified.

Materials and methods

As reported from site investigation, the ground profiles in the North Central Coast of Vietnam are mostly loose sand and exposed on or near the surface [25-30]. To evaluate the liquefaction potential of sand in the North Central Coast of Vietnam (Figure-1), *SPT* values and the samples from the boreholes were collected. The soil samples were used to determine particle size and classify the soil. The SPT was conducted in the boreholes with an interval of 1.5~2m in depth. The geological cross section in 10 sites is plotted in Figure-2. In general, the soil profiles in all studied sites include two layers: the upper layer is sand (1) and the lower layer is clay soil (2). The depth of distribution and the *SPT* values for the sand layer are shown in Table-1. As reported, the sandy soil in all sites belongs to marine deposits (mQ_2^3) or marine - windy deposits (mvQ_2^3) with loose to medium state. These deposits are often exposed on the surface with a thickness that ranges from a few meters to ten meters [25-30].

Table 1- The depth of distribution and SPT values for sand layers collected from boreholes in the North Central Coast of Vietnam

No	Location	Layer		
		Upper layer (Sand)		
		Depth, m	*SPT* values	Type of soil
1	Nghi Son, Tinh Gia, Thanh Hoa province – Site 1	9.3-12.7	4-22	*SP - SM*
2	Hoang Hoa, Thanh Hoa province - Site 2	4.5-5.3	6-10	*SC-SM, SP-SM*
3	Nong Cong, Thanh Hoa province – Site 3	4.3-7.6	8-13	*SP, SP-SM*
4	Ca Lang Port, Tinh Gia, Thanh Hoa province – Site 4	2.8-3.6	3-5	*SP, SP-SM*
5	Steel Factory, Nghi Son, Tinh Gia, Thanh Hoa province – Site 5	12.4-18.9	4-9	*SP, SP-SM*
6	Vinh, Nghe An province – Site 6	3.5-8.8	5-8	*SP*
7	Cua Lo Port, Nghe An province – Site 7	2.5-6.7	1-6	*SP-SM*
8	Vung Ang Port, Ha Tinh province – Site 8	5.5-11.7	5-24	*SC-SM*
9	Formusa Ha Tinh province – Site 9	2.7-16.8	5-26	*SP, SP-SM*
10	Hai Lang, Quang Tri province – Site 10	6.9-15.6	3-38	*SP, SP-SM*

Figure 1 - The location of soil samples in the North Central Coast of Vietnam

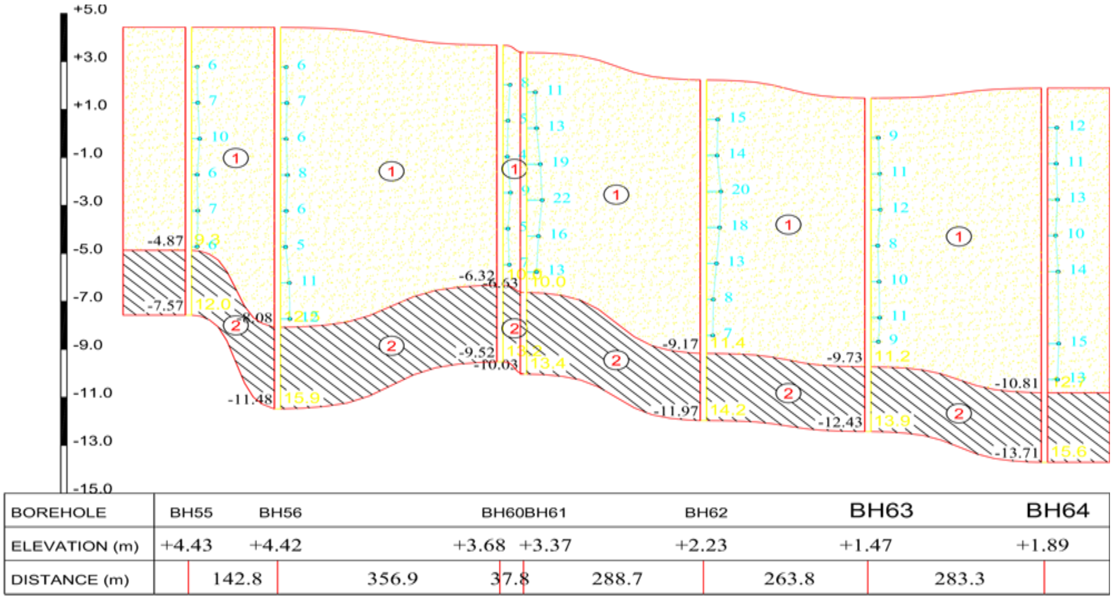

Figure 2a - The geological section at Nghi Son, Tinh Gia, Thanh Hoa province (Site 1) in the North Central Coast of Vietnam

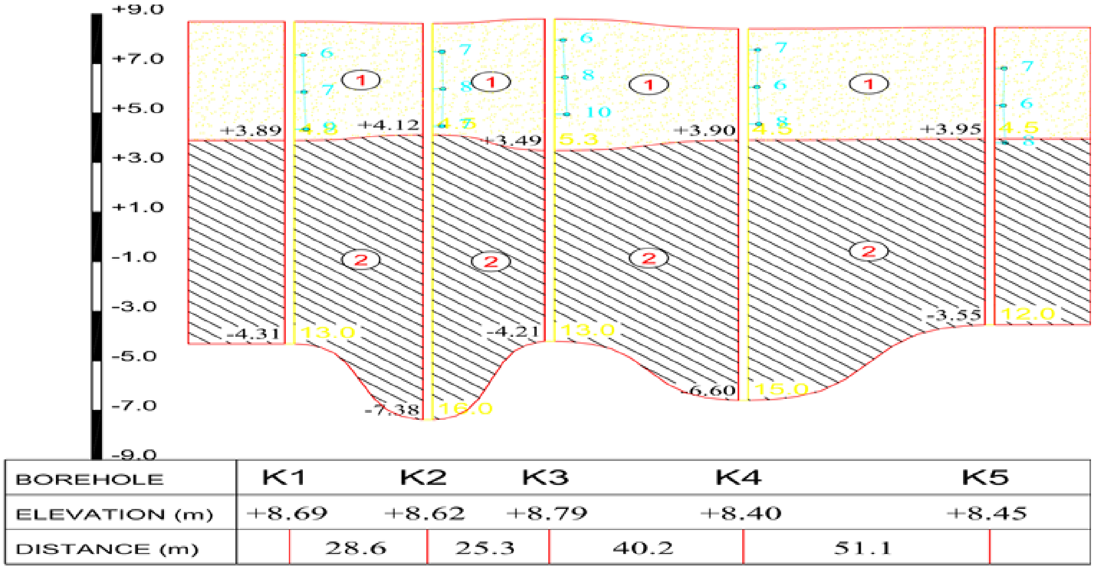

Figure 2b - The geological section at Hoang Hoa, Thanh Hoa provice (Site 2) in the North Central Coast of Vietnam

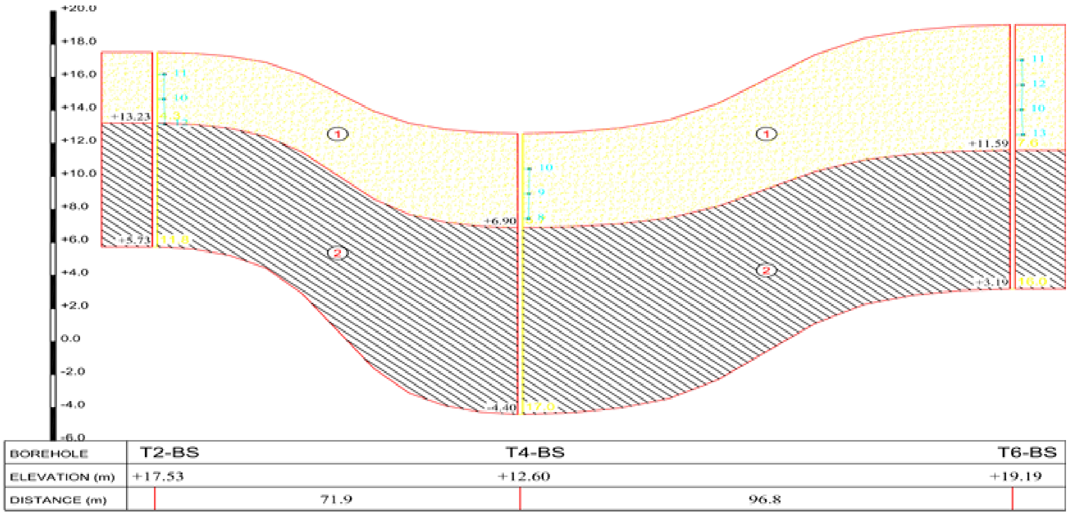

Figure 2c- The geological section at Nong Cong, Thanh Hoa province (Site 3) in the North Central Coast of Vietnam

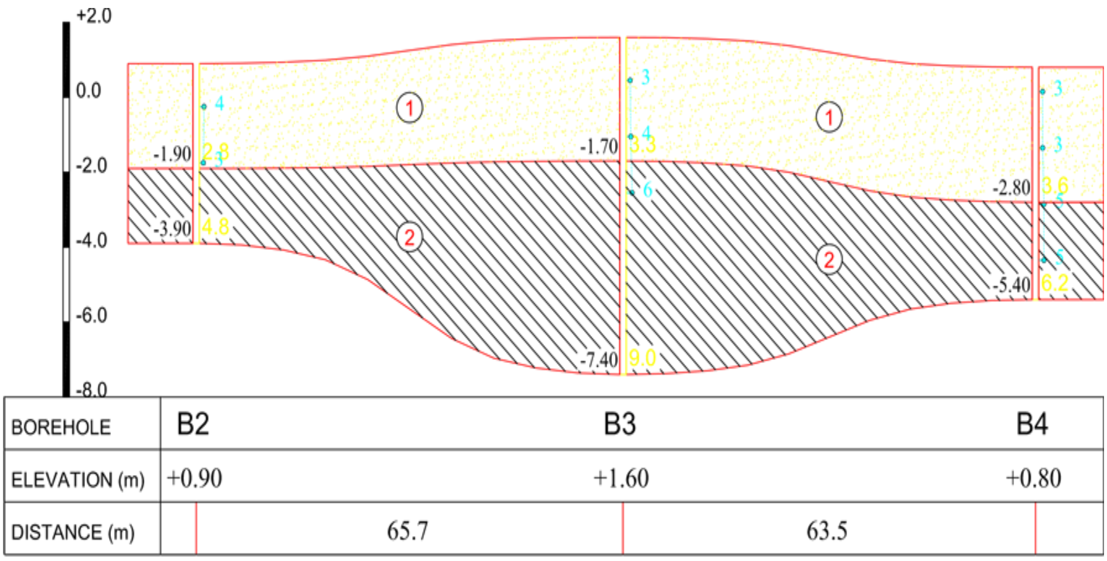

Figure 2d - The geological section at Ca Lang Port, Tinh Gia, Thanh Hoa province (Site 4) in the North Central Coast of Vietnam

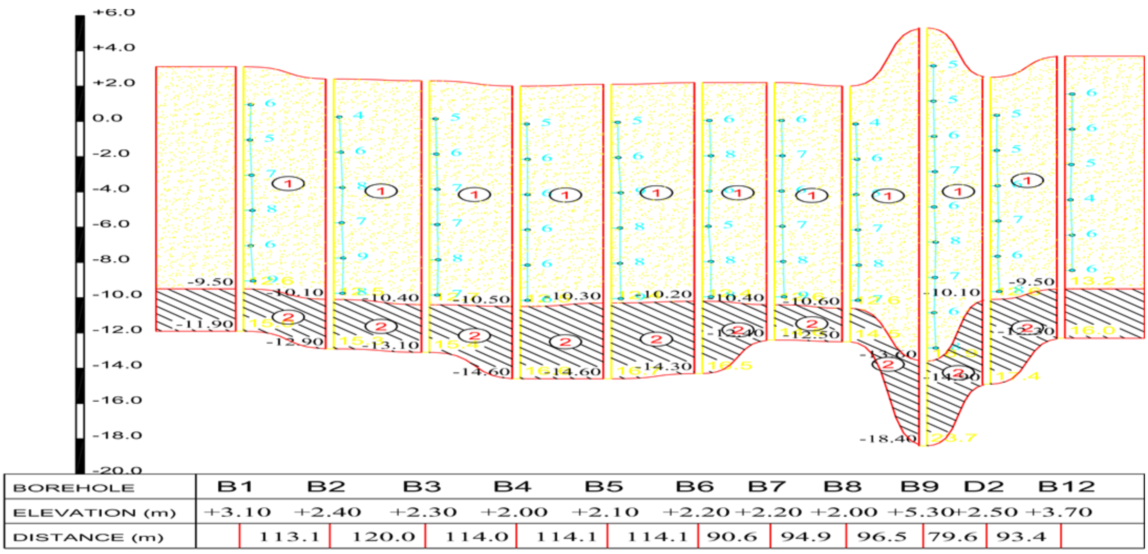

Figure 2e - The geological section at Steel Factory, Nghi Son, Tinh Gia, Thanh Hoa province (Site 5) in the North Central Coast of Vietnam

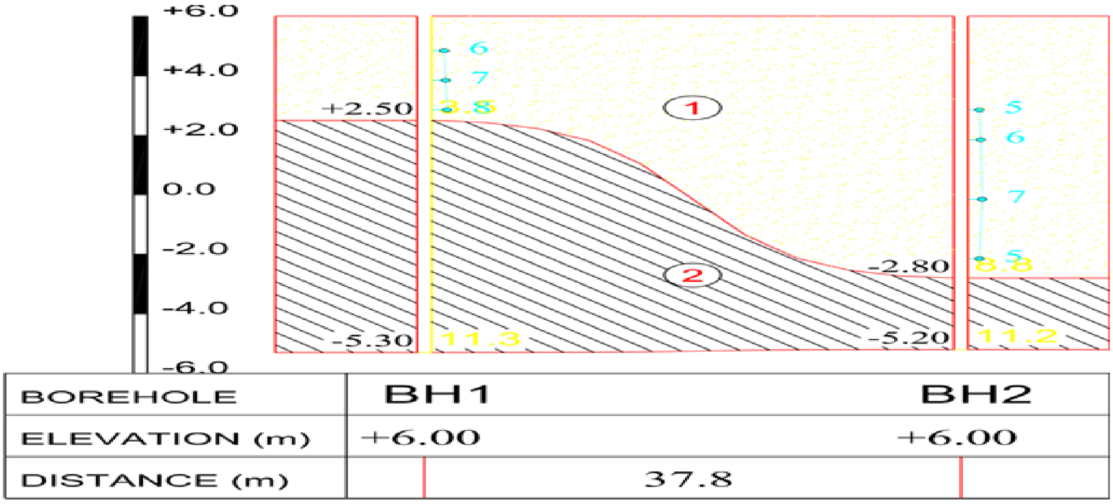

Figure 2f - The geological section at Vinh, Nghe An province (Site 6) in the North Central Coast of Vietnam

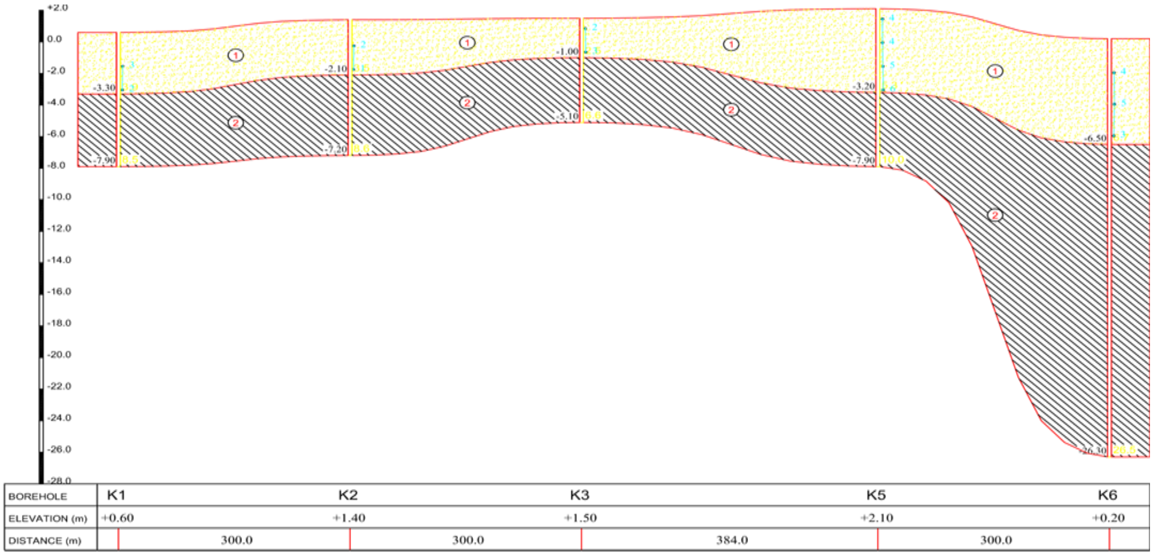

Figure 2g - The geological section in Cua Lo Port, Nghe An province (Site 7) in the North Central Coast of Vietnam

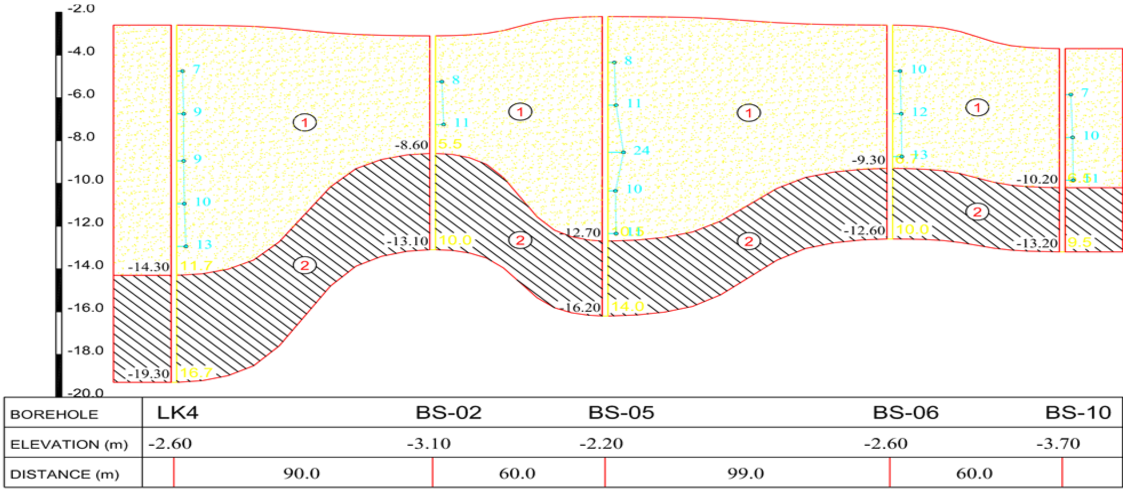

Figure 2h - The geological section at Vung Ang Port, Ha Tinh province (Site 8) in the North Central Coast of Vietnam

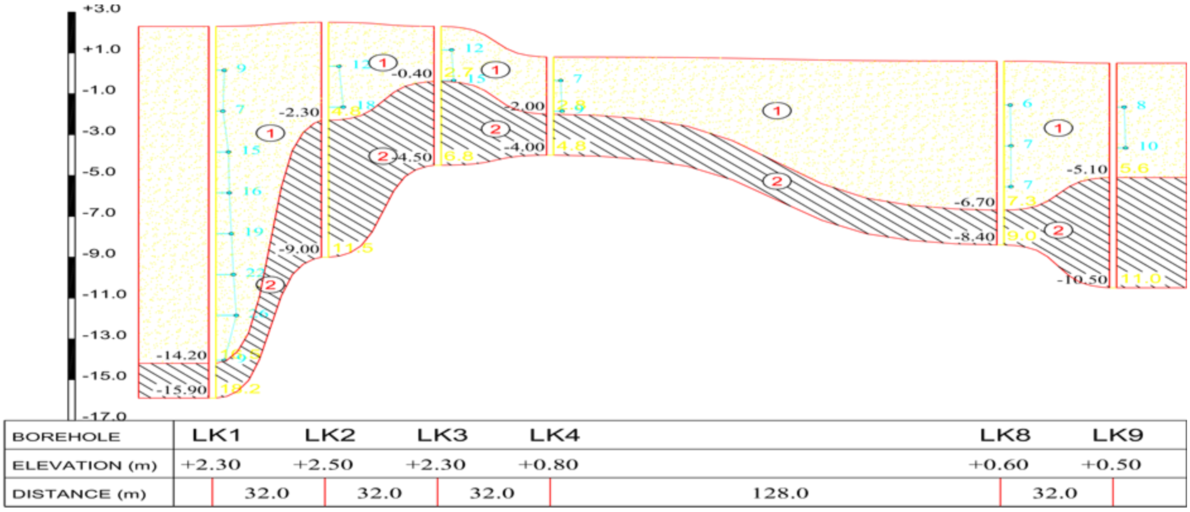

Figure 2i - The geological section in Formusa Ha Tinh Province (Site 9) in the North Central Coast of Vietnam

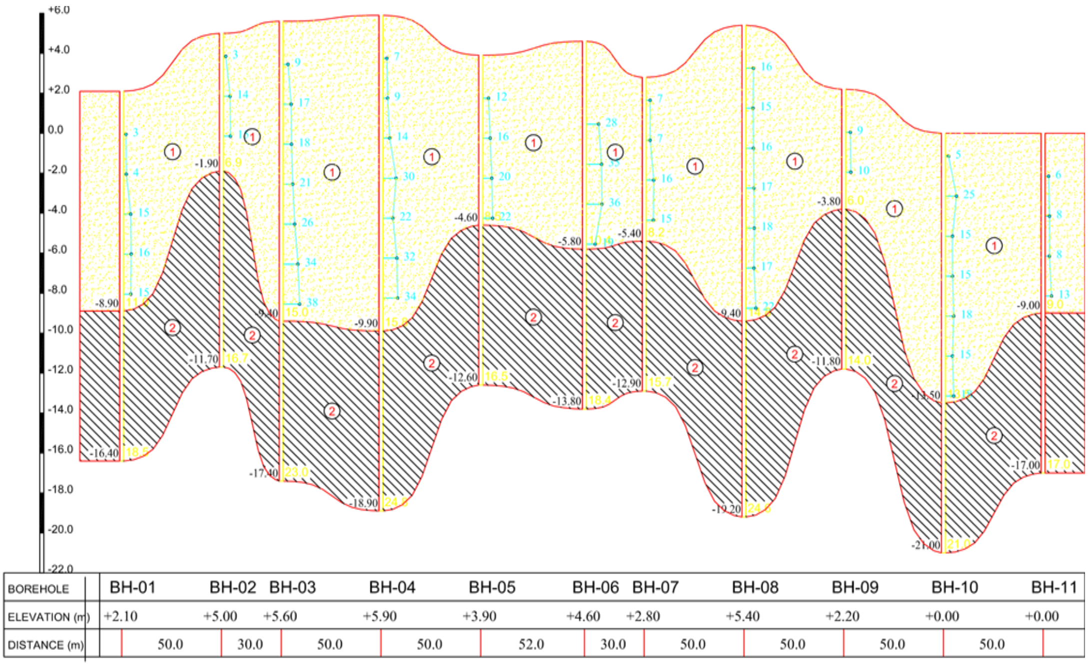

Figure 2j - The geological section in Hai Lang, Quang Tri Province (Site 10) in the North Central Coast of Vietnam

In these profiles, 58 boreholes were used for *SPT* tests. The *SPT*s were conducted under *ASTM D1586*. The samples were collected from standard penetration tests and used for particle size distribution test under *ASTM D422*.

According to the results of *SPT*, the standard resistance (*N)* values change from 1 to 38 blows with the average value of 9 blows. From experimental results, it can be seen that the *SPT* value is normally smaller than 15 blows and sand is in a loose state. The highest value of *SPT* is found at Site 10, and the four sites with *SPT* values of more than 15 blows are Sites 1, 8, 9, 10 (Figures- 2,3 and Tables- 1, 4).

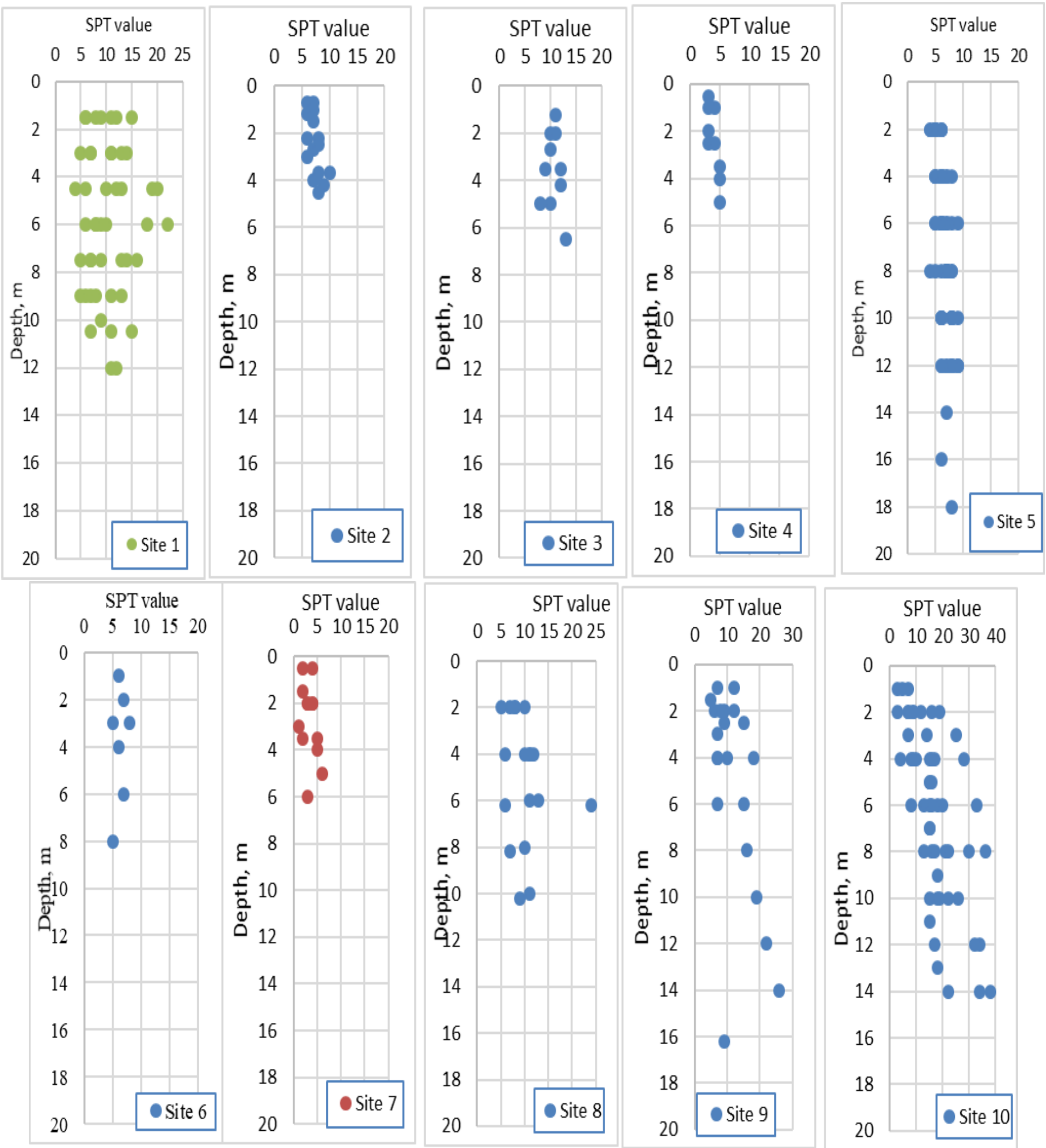

Figure 3. Variation of *SPT* values with depths in different locations of the North Central Coast of Vietnam

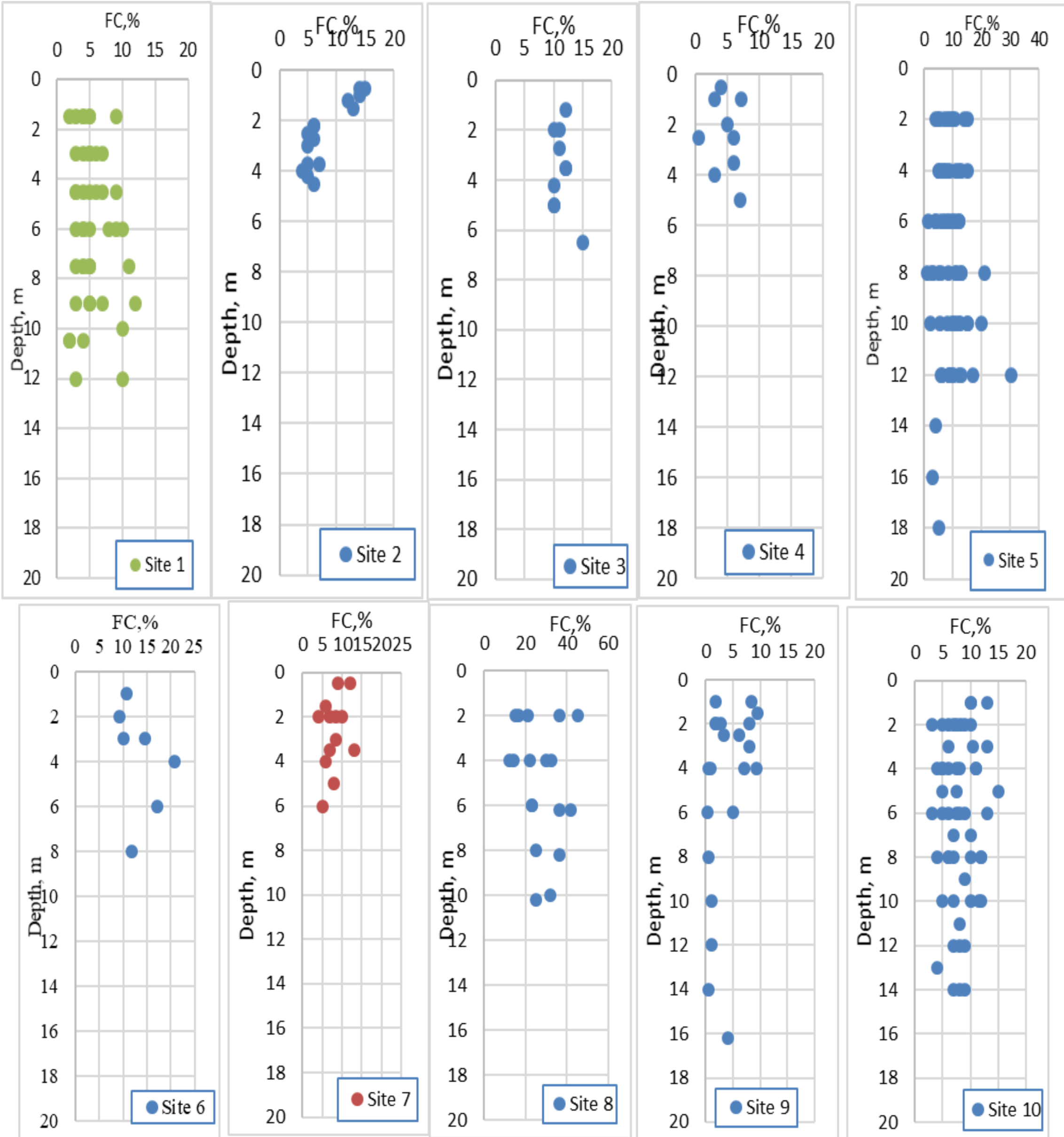

Figure 4 - The fine contents (<0.075mm) in soils at different depths in different locations of the North Central Coast of Vietnam.

The variation of fine contents of soil (<0.075 mm) in different locations in the studied area is shown in Figure- 4. The fine contents of soil (<0.075mm) change from 0.3% to 45.3% with the average content of 9%, showing significant changes from site to site. The highest fine content in the soil is found at Site 8. The smallest fine content in sand is at Sites 9 and 4. The soils almost belong to *SP*, *SP-SM* (Poorly graded sand, poorly graded sand with silt).

In this study region, the maximum of ground surface acceleration values found in Ha Tinh, Nghe An, Quang Binh, Thanh Hoa, Quang Tri, and Thua Thien Hue are 0.1172*g*, 0.1102g, 0.095*g*, 0.062*g*, 0.1439g, and 0.0573*g*, respectively (*TCVN 9386:2012*). For the protection of construction, this region has the highest ground surface acceleration of 0.1439g and the value of the Importance Factor (γ_I) is 1.25. Thus, the maximum horizontal ground surface acceleration value is a_{max} = *0.180g*, which is equivalent to a moment magnitude of earthquake value of *M=7*. In the past, in Vietnam, the highest earthquake occurred in Dien Bien province along the Ma river fault with the magnitude of 6.75. As predicted, the maximum earthquake magnitude of 7 occurs in Vietnam within a return period of 123 years [31]. Thus, the earthquake magnitude of 7 will be chosen for this investigation.

In the present study, the *SPT*-based *LEP*, as reported in Boulanger & Idriss [16], will be used for assessing the factor of safety against liquefaction (FS_{Liq}):

$$FS_{Liq} = \frac{CRR}{CSR} \quad (1)$$

where *CSR* - The earthquake-induced cyclic stress ratio; *CRR* - The cyclic resistance ratio, as computed by Boulanger & Idriss [16]. If the factor of safety is less than 1.0, the soils will be liquefied. If the factor of safety is greater than 1.0, liquefaction will be unlikely to occur.

Then, the *LPI*, as reported in Iwasaki et al. [19] and modified by Sonmez [20], will be calculated. The equation of *LPI* is presented as follows:

$$LPI = \int_0^{20} F_1 W(z) dz \quad (2)$$

where $W(z)$= 10-0.5z, F_1=1- FS_{Liq} for FS_{Liq}<1.0, F_1=0 for FS_{Liq}>1.0 and z is the depth below the ground surface (m). From the *LPI*, the potential liquefaction can be classified as shown in Table- 2.

Table 2- Liquefaction potential classification based on *LPI* [19]

LPI	**Liquefaction potential**
0	Non - liquefied
0< *LPI*≤2	Low
2< *LPI*≤5	Moderate
5< *LPI*≤15	High
LPI>15	Very high

Finally, –the *LSN* was calculated according to Tonkin and Taylor [20] as follows:

$$LSN = 1000 \int \frac{\varepsilon_v}{z} dz \quad (3)$$

where ε_v is the estimated post-liquefaction volumetric strain (%), as calculated by the Zhang et al [21] method and z is the depth (m) below the ground surface. Based on the *LSN*, the potential liquefaction can be classified as shown in Table- 3.

Table 3- Liquefaction potential classification based on *LSN* [21]

LSN	**Liquefaction potential**
0-10	Little to no expression of liquefaction, minor effects
10-20	Minor expression of liquefaction, some sand boils
20-30	Moderate expression of liquefaction, with sand boils and some structural damage
30-40	Moderate to severe expression of liquefaction, settlement can cause structural damage
40-50	A major expression of liquefaction, undulation and damage to the ground surface, severe total and differential settlement of structures
>50	Severe damage, extensive evidence of liquefaction at surface, severe total and differential settlements affecting structures, damage to services

Results and discussion

From the *SPT* value, the normalized standard penetration resistance values $(N1)_{60cs}$ was calculated according to Boulanger and Idriss [16] as follows:

$$(N_1)_{60cs} = (N_1)_{60} + \Delta(N_1)_{60} \quad (5)$$

$$\Delta(N)_{60} = exp\left\{1.63 + \frac{9.7}{FC+2} - \left(\frac{15.7}{FC+2}\right)^2\right\} \quad (6)$$

where $(N_1)_{60}$ is normalized to an overburden pressure of approximately 1 atm (approximately 101.3kPa) and a hammer energy ratio of 60 percent; *FC* is fine content (%).

$$N_{60} = C_N C_E C_B C_R C_S N_M \quad (7)$$

$$(N_1)_{60} = C_N . N_{60}. \quad (8)$$

where $C_N C_E C_B C_R C_S$ are the overburden correction factor, hammer energy ratio, borehole diameter correction, sampler correction, and rod length correction, respectively, and N_M is field measured *N* values.

N_{60} is standardized, energy-corrected, and denoted as

$$N_{60} = \frac{E_m C_B C_s C_R N}{0.6} \quad (9)$$

where E_m is hammer efficiency; N is the measures SPT value.
The overburden correction factor, C_N , can be denoted as [14]:

$$C_N = \left(\frac{P_a}{\sigma'_v}\right)^m \leq 1.7 \tag{10}$$

$$m = 0.784 - 0,0768\sqrt{(N_1)_{60cs}} \tag{11}$$

with $(N_1)_{60cs}$ values are limited to 46 values for the use in these expressions.

The relationship between $(N_1)_{60cs}$, CRR, and FS_{Liq} is shown in Figure-5 and the relationship between FS_{Liq} and $(N_1)_{60cs}$ is plotted in Figure-6. The variation of FS_{Liq} is also shown in Figure-7. These figures show that the liquefaction potential depends on the depth of soils as well as $(N_1)_{60cs}$ values.

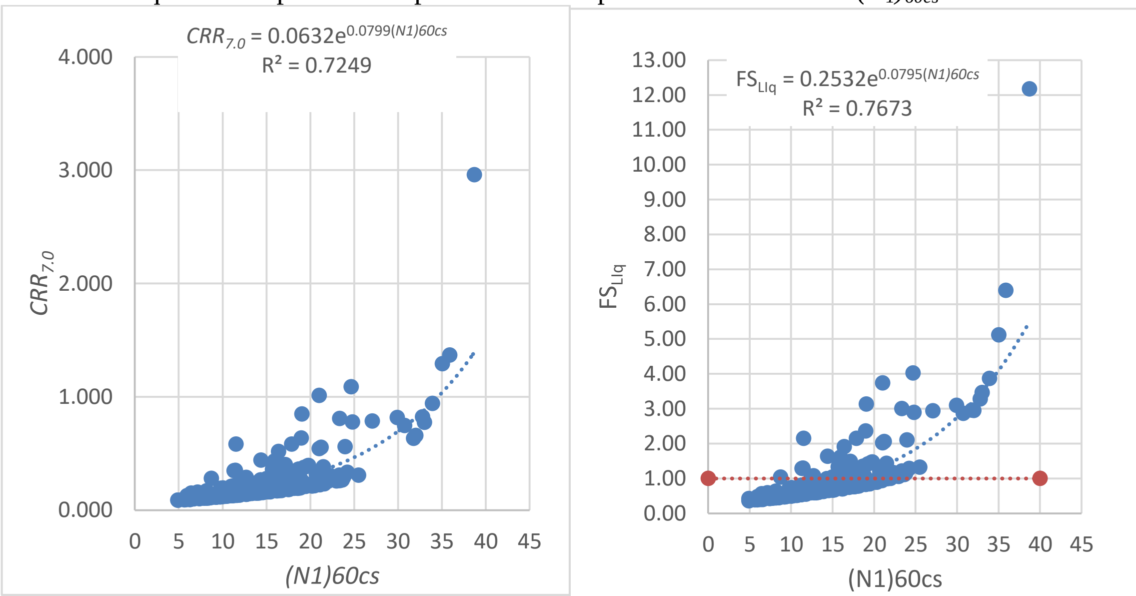

Figure 5- The variation of $CSR_{7.0,}$ and FS_{LiQ} with $(N_1)_{60cs}$

For the moment magnitude of the earthquake of 7.0 and peak ground acceleration of 0.180g, the liquefaction probability is almost smaller than 1.0; it is considered that the soil layer will be liquefied under this cyclic loading. There are 190 of 264 SPT values with $FS_{LiQ} < 1.0$, with the soil having a high potential of liquefaction. Ahmad *et al*. [32] indicated that the liquefaction potential was affected by different soil conditions, the validity of case history data, and calculation methods.

Table 4- Results of calculating soil liquefaction potential in the North Central Coast of Vietnam

Parameters	**Value**	**Sites**									
		Site 1	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 7**	**Site 8**	**Site 9**	**Site 10**
SPT value	Max	22	10	13	5	9	8	6	24	26	38
	Min	4	6	8	3	4	5	1	5	5	3
	Average	10.3	7.3	10.6	3.9	6.6	6.3	3.4	9.9	11.7	16.9
FC, %	Max	12.0	15.0	15.0	7.1	30.1	20.8	13.0	45.3	9.6	15.0
	Min	2.0	4.0	10.0	0.5	1.0	9.2	4.0	12.0	0.3	3.0
	Average	5.4	8.2	11.3	4.6	9.3	13.5	8.0	27.1	3.9	8.1
$(N_1)_{60cs}$	Max	30.8	24.9	28.1	10.8	14.1	17.3	17.1	36.2	31.4	42.5
	Min	5.4	8.8	12.2	5.1	4.6	8.4	2.8	13.0	7.5	5.2
	Average	14.2	14.4	18.8	7.4	9.4	12.7	7.3	18.1	16.4	21.5
FS_{Liq}	Max	6.5	5.5	5.3	2.0	0.9	2.0	3.4	6.7	10.6	46.1
	Min	0.4	0.5	0.6	0.4	0.4	0.5	0.3	0.6	0.4	0.4
	Average	0.9	1.5	1.4	0.8	0.5	0.9	0.8	1.3	1.4	3.0
LPI	Max	43.5	18.2	18.3	25.3	54.8	34.7	34.3	25.7	47.5	26.1
	Min	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.0	0.0	0.0
	Average	17.7	7.2	5.1	10.9	27.7	12.5	12.9	8.7	8.6	5.3
LSN	Max	33.8	20.5	25.9	22.4	40.3	28.7	25.5	31.2	38.6	42.4
	Min	5.9	0.0	2.8	0.0	9.4	0.0	5.7	9.9	0.0	0.0
	Average	22.1	11.8	16.1	11.7	25.2	15.9	14.1	20.4	18.3	23.5

As shown in Figures- 6 , 7 and Table- 4, the FS_{Liq} is very different among sites. The lowest FS_{Liq} value is at Site 5 and varies from 0.4 to 0.9 at the depth from 2.0 to 18.0, with the range of $(N_1)_{60cs}$ is from 4.6 to 14.1. Whereas, the highest FS_{Liq} value is at Sites 8-10 with the range of 0.3 to 46.1, while $(N_1)_{60cs}$ ranges from 5.2 to 42.5. At these Sites, if the depth is smaller than 3.0, the FS_{Liq} values are higher than 1.0 and the liquefaction does not occur. However, many $(N_1)_{60cs}$ values at depths from 2m to 8m are higher than 21.0, leading to values of FS_{Liq} of higher than 1, with the soil having no liquefaction. Thus, at these sites, the potential liquefaction is not clear and depends on the $(N_1)_{60cs}$ values. At Site 1, the $(N_1)_{60cs}$ value varies from 5.4 to 30.8 and the FS_{Liq} changes from 0.4 to 6.5. The liquefaction may not occur when $(N_1)_{60cs}$ is higher than 12.3 at the depth of 1.5m and higher than 18.8 at the depth of 3.5 to 6.0m. $(N_1)_{60cs}$ values at Site 2 range from 8.8 to 24.9 and the FS_{Liq} varies from 0.5 to 5.5. At Sites 3 and 4, the FS_{liq} changes from 0.6 to 5.3 and 0.4 to 2.0, respectively, when $(N_1)_{60cs}$ values vary from 12.2 to 28.1and 5.1 to 10.8, respectively. At Site 6, the $(N_1)_{60cs}$ values range from 8.4 to 17.3 and the FS_{Liq} varies from 0.5 to 2.0. Only one value of FS_{Liq} is higher than 1 (FS_{Liq} = 2.0), when $(N_1)_{60cs}$ value is 17.3 at the depth of 1.0m. At Site 7, the $(N_1)_{60cs}$ values vary from 2.8 to 17.1 and the FS_{Liq} changes from 0.3 to 3.4. Two values of FS_{Liq} are higher than 1 (FS_{Liq} = 1.68; 3.43) ,when $(N_1)_{60cs}$ values are 8.7, 17.1 at depth of 0.5m.

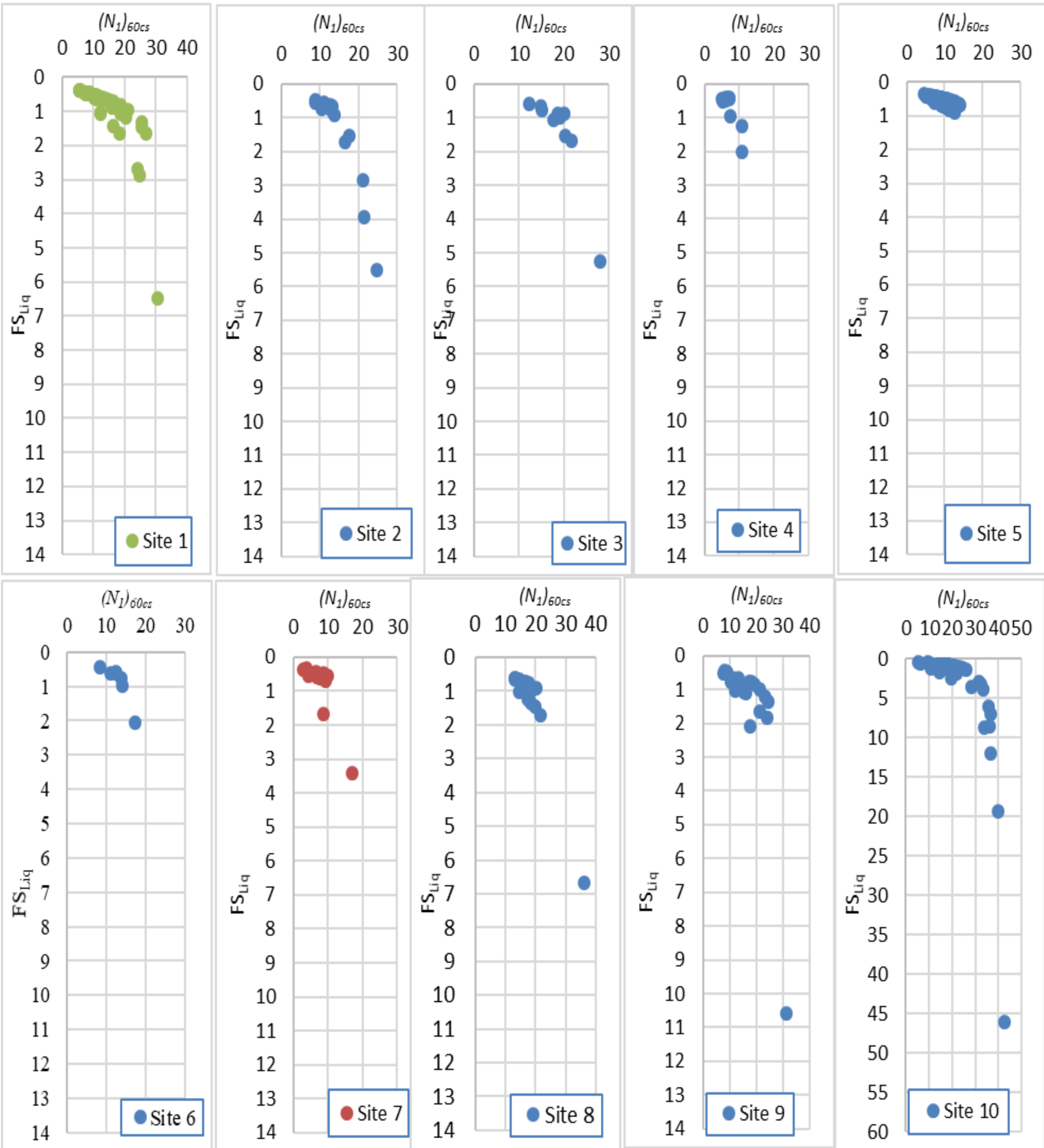

Figure 6- The variation of FS_{Liq} with $(N_1)_{60cs}$ values

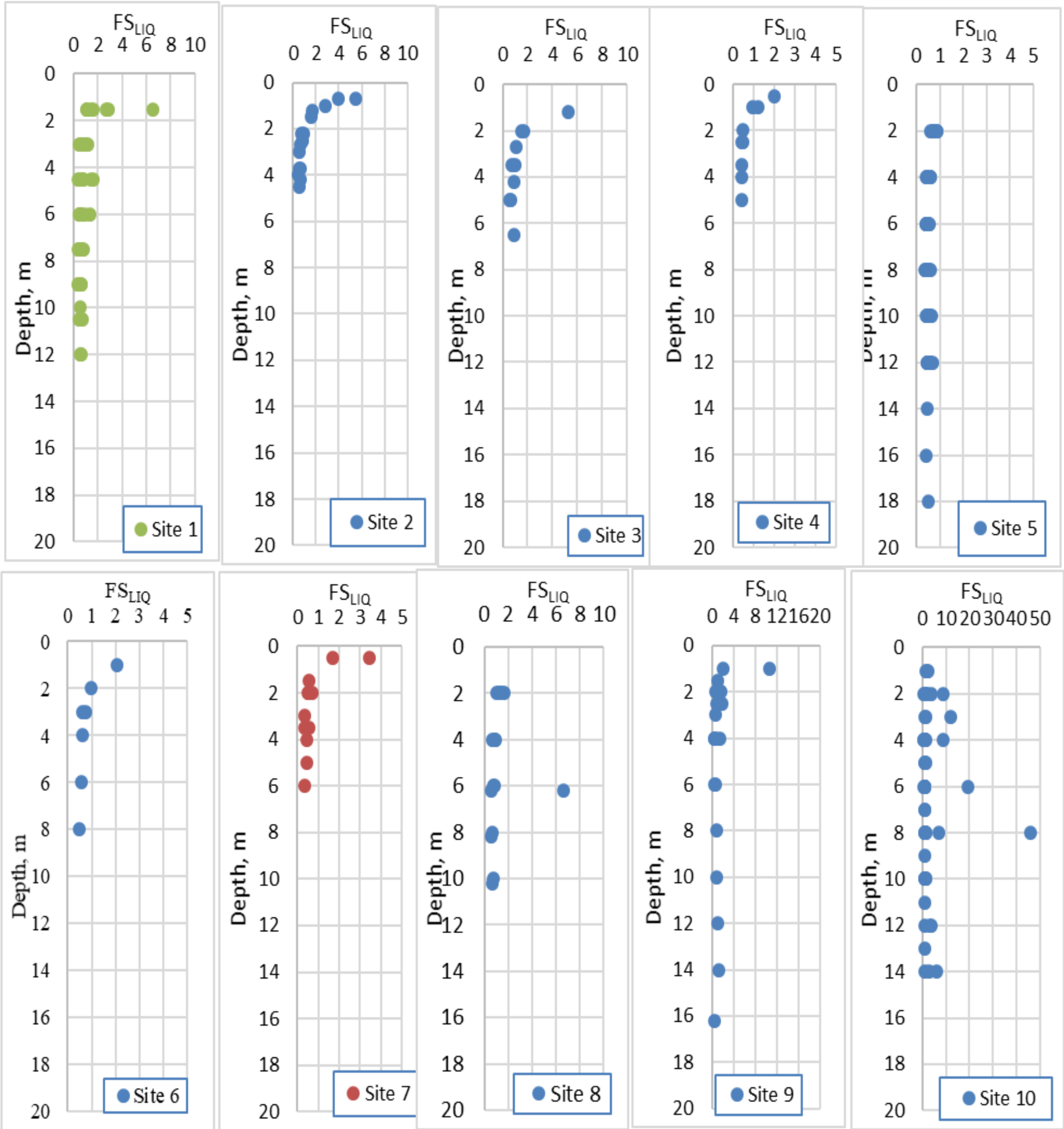

Figure 7- The variation of FS_{LiQ} with depths

Figure-8 and Table-4 show the variation of *LPI* with depth at different sites. At sites 1-4 and 6-7, *LPI* ranges from 0.0 to 43.5. There is non – liquefaction at the depth of under 2.0 m. It is consistent with the FS_{LiQ}, if the FS_{LiQ} >1, where the liquefaction does not occur. At these sites, liquefaction potential is from low to high. At Site 5, the *LPI* changes from 2.1 to 54.8. It seems that the potential of liquefaction is from low to high. However, at this Site, *LPI* is almost higher than 15, so there is a high potential of liquefaction. At Sites 8-10, the *LPI* varies from 0.0 to 47.5. There are many *LPI* values that are equal to zero, especially in Site 10. This indicates that the potential of liquefaction is very low or non – liquefaction. It is believed that the FS_{LiQ} >1 and the $(N_1)_{60cs}$ in these Sites are higher than those in other Sites.

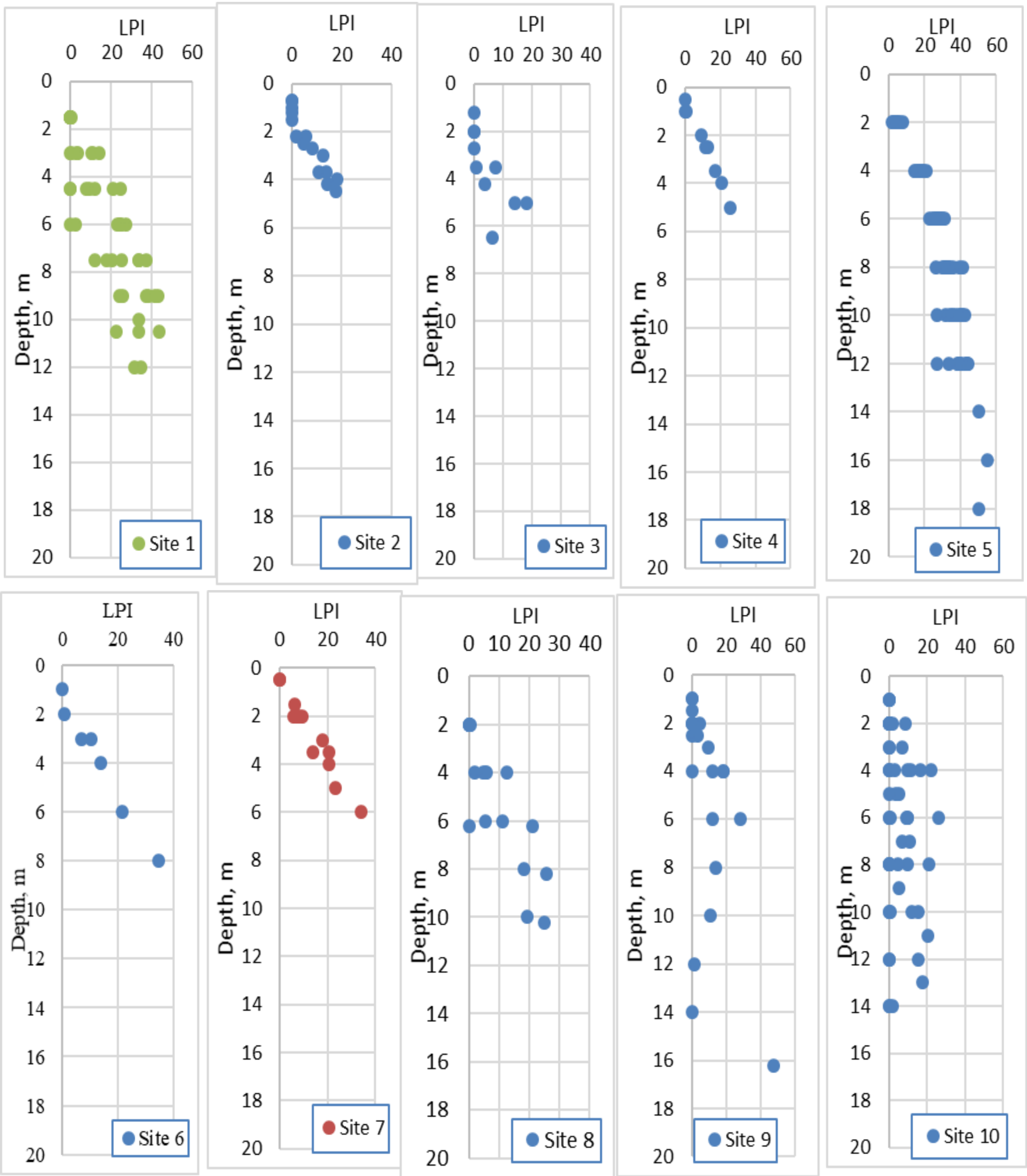

Figure 8 -The variation of *LPI* with depth

The variation of *LSN* with depth is presented in Figure-9. It can be seen that the *LSN* changes from 0 to 42.4 and *LSN* increases with increasing depth. It is also shown that at the depth is less than 2 m, the *LSN* is smaller than 10, and liquefaction potential is low.

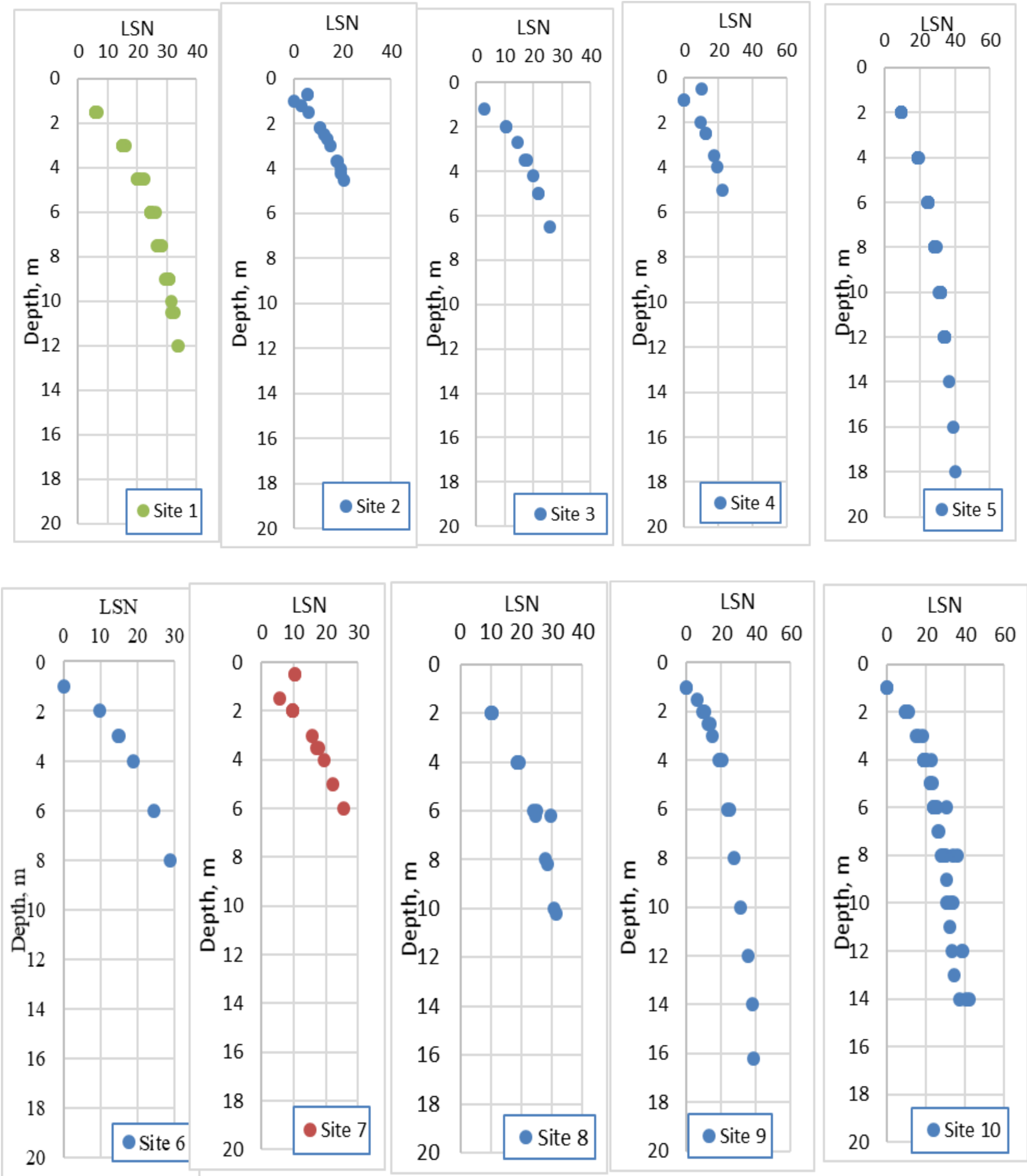

Figure 9- The variation of *LSN* with depths

Conclusions

Based on the results obtained from this study, some conclusions can be drawn.

The thickness of the sand layer in the North Central Coast of Vietnam varies from a few meters to more than ten meters and it is often exposed on the surface. The *SPT* values change from 1 to 38 with an average value of 9. The fine contents (<0.075 mm) change from 0.3% to 45.3%.

The potential liquefaction of sand layers in this region depends on the *SPT* values and the distribution depth. Sandy soils have different potential of liquefaction. The highest potential of liquefaction is found at Site 5 and the lowest potential is at Site 10. The sand distributed from 2.0 to 18.0m with $(N1)_{60cs}$ value of less than 20 has liquefaction potential with $FS_{LIQ} <1$, *LPI* that is often higher than 0.73, while *LSN* is often higher than 10.

The results of the present study can be used to predict the liquefaction potential of soil for building construction in the North Central Coast of Vietnam.

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