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Research

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# Use of Shear Wave Velocity in Evaluation of Soil Layer's Condition After Liquefaction

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## ABSTRACT

After liquefaction occurrence, summits on the surface of the earth and inside the soil layers that damage the structures based on them or buried structures and vital arteries. In the last two decades, various quasi-experimental methods have been presented to determine the amount of strain (siting) and shear strain maximum based on field data and laboratory data. The main purpose of this study was to compare the results of evaluation of the potential of liquefaction occurrence from the viewpoint of the risk of occurrence and the amount of settling after the occurrence of liquefaction on in the soil layers based on the use of the results of the standard penetration resistance (SPT) and shear wave velocity ( $V_s$ ) along the path 2nd line of Tabriz metro. In this study, 54 borehole loops were first collected along the line 2 of the metro mentioned. Then, the liquefaction potential in the studied area is based on the proposed methods and the liquefaction risk index (LPI) is estimated. Then, the amount of probable sum of the soil layers due to liquefaction occurred based on the results of the two proposed methods. The results of the research show that the two methods are not suitable for matching and the risk of liquefaction arising from the SPT method is less than the  $V_s$  method. Also, the prediction of the amount of settling after the occurrence of liquefaction in the soil layers has more amount based on the shear wave velocity method in comparison with the standard penetration resistance test method.

**Keywords:** Liquefaction, settlement, standard penetration resistance test (SPT), shear wave velocity ( $V_s$ ).

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## 1. INTRODUCTION

Liquefaction is a phenomenon that is due to hardening and soil resistance due to rotational forces such as earthquakes under drainage conditions and simultaneously with increasing cavity water pressure [1,2]. Before the earthquake, the water pressure of the cavity is relatively small, but when the soil, and especially a sand sediment, is subjected to vibration, it tends to accumulate and reduce the volume. In this case, if drainage is not possible, the water in the sand sediment increases and its amount is equal to the overhead pressure, so that the effective stress is equal to zero. Under these conditions, the sand will not have any shear strength and will become liquid, which ultimately will be called soil liquefaction. [3] Due to this process, some layers will be denser on the ground, and often asymmetrical stacks are observed on the ground. Other layers remain in very loose conditions and will be subject to re-emergence during future earthquakes. Occurrence of liquefaction can affect buildings, bridges, coastal

structures, vital arenas, slopes and many other built-in appliances in different ways. Liquefaction is associated with various phenomena such as increased pore pressure, sand burst and various deformation states [4]. In recent years, several laboratory and field studies have been proposed to evaluate soil leakage resistance. Regarding the significant effect of sample handicap on the properties of soil rocks, field methods are more accurate in determining the characteristics of these soils. SID and Mohammad et al. [5] and Robertson et al. [6] compared the applications of laboratory and field tests to determine the dynamic variables of the soil to find that field tests are a rapid and effective method for obtaining the characteristics of soil grazing. At present, the simplest and most commonly used method is SPT standard penetration resistance. However, in recent years,  $V_s$  has found a good position due to the continuous nature of the soil profile, and the increase in the database. [7-9] The main objective of this study is to evaluate the rate of

settling of soil layers after liquefaction using shear wave velocity ( $V_s$ ) field method. Also, in this study, the results of two methods of evaluation of soil layering after liquefaction by SPT and shear wave velocity ( $V_s$ ) are compared using empirical relationships between them. Considering that a large part of the earthquake damage is due to the occurrence of various seismic geotechnical phenomena [10], one of which is sand liquefaction and impermeable saturation layers; therefore, in this field, research has been carried out in advance. Further, they will be dealt with. Lee and Albeiza (1974) studied the amount of settling in saturated sands after cavernous water pressures, based on information from periodic loading experiments. It was concluded that the amount of strain of the volume for the conditions that flow with no increase in the size of the soil grains, decreasing relative densities and increasing the excess pore pressure of the water increases [11]. Ishihara et al. (1992) conducted research to estimate the settlement (volume strain) after the initial liquefaction. They observed that the amount of settlement mainly depends on the maximum shear strain and the density of the soil and does not correlate with the effective stress of the overhead. They presented the curve based on the relationship between relative density and volume strain after primary liquefaction in terms of maximum shear strain and observed that with increasing shear strain, the volume of strain increases after initial liquefaction [12]. Tokimatsu and Seed (1987) presented a simple method for analyzing and estimating the sediment potential in saturated or dry sandy soils under earthquake. They found that the main factors controlling the sedimentation in sandy soils are the ratio of stress and shear strain to the maximum caused by the earthquake [13]. In case that in dry soils and semi-saturated sandy soils, induced periodic strains due to earthquake are the main factor [14]. By combining these factors mentioned with the largest earthquake and number of standard penetration resistance, they provided charts for the estimation of the settlement. The results presented by them indicate that there is an appropriate coordination between the Field Observation arising from the earthquake and the estimation produced from the settlement summation of the graphs. In order to estimate the settlement after the occurrence of liquefaction, the correlation between the results of coastal and laboratory studies were determined, then the volume strain and maximum

shear strain for soil and soil unsaturated were calculated. The weaknesses of the proposed method are that it is only for clean sand, and the correction coefficient has not been provided to affect the fine grain percentage [15, 16]. The results of study, use of the Liquefaction potential of the Cone Penetration Resistance Test (CPT) based on the proposed scheme of Song et al. [17] and the shear wave velocity ( $V_s$ ), using the proposed scheme by Dumbser Etal [18], comparing Application of the empirical relationships between them, and by using the IVASAKI method [19], calculated the Liquefaction Incidence Index (PL) for both of these methods. The study area was part of southern and southeast of Tehran and analyzed 67 boreholes. The results showed that the evaluation of the liquefaction potential using the two methods mentioned above was no proper coordination and compliance with the three empirical relationships, assuming the conditions of the cementation and non-cementation for soils. Also, the magnitude of the risk of liquefaction in the study area based on the values of the liquefaction potential index was less than the CPT test compared to the  $V_s$  method. In addition, the results of the experiments showed that the use of existing core strata correlates might evaluated the cyclic resistance of silty sand blends more when its silt content is 60%. The results of this study with relatively consistent of Andrus and Stoke for clean sand and fine-grained samples was above 30%. It also showed that the increase of fine-grained material increased the final volumetric strain of liquefaction [20]. In Bajaj et al. Study, the effect of different parameters on soils potential liquefaction was studied, and reliability of the results was obtained as effective parameters in engineering decisions. They compared the results of the evaluation of liquefaction potential based on two methods of standard penetration test (SPT) and energy, and showed that there is not a proper fit between the two methods. In addition, the energy method has a greater risk of potential liquefaction rather than the SPT. They said the main factors affecting the inconsistency are the distance between Tabriz metro 2nd line 2 to the northern fault of Tabriz, the location of the earthquake center and the correction factors assumptions in the SPT method [21]. According to this literature reviews in this study, use of shear wave velocity in evaluation of soil layer's condition after liquefaction investigated.

## 2. MATERIALS AND METHOD

In this research, the coefficient of reliability estimation against the occurrence of liquefaction in each borehole has been calculated at different depths. This coefficient in each depth is determined by calculating the quotient stress ratio (CSR) produced by the earthquake, as well as the determination of the ratio of periodic resistance ratio (CRR) and the calculation of the ratio of the two parameters. Then, the Liquefaction Potential (PL) is calculated for each borehole in different depths. Estimating the maximum acceleration of the earth's surface in determining the liquefaction potential is a requirement of work, which also requires seismic studies. The acceleration used in this study was the same

as the acceleration of the maximum ground level. In this study, earthquake magnitudes were assumed to be 7.7 on the Richter scale, and the acceleration of the maximum ground level was within the range of 0.35 g / g. The evaluation of the liquefaction potential in Tabriz Metro 2nd Line will be based on the two methods of standard penetration resistance (SPT) and shear wave velocity ( $V_s$ ) by applying an empirical relationship between them in soil cementing and non-cementation, as well as post-liquefaction. Became the total number of studied boreholes was 53, of which all 53 were speculated to 20 meters' depth. The depth of each layer was different, and the total number of layers was 464, the layers based on the material of soil are as follows. (Table1)

**Table 1.** The number of layers based on the material of each layer

Layer material	GC	GP	GM	GW-GM	SP-SM	SW	SP	SC	SM	MH	ML	CH	CL
Layers number based on material	4	4	10	2	4	1	3	21	106	11	188	15	94

The nature of each layer and the groundwater level are determined in each gamma loop. For each soil layer, overall stress and effective tension are determined without tariff. Then the permeability standard ( $N_{spt}$ ) for each soil layer is specified in all boreholes. In assessing the soil liquefaction potential, based on the standard penetration resistance test method (SPT), At first, the periodicity shear stress ratio (CSR) of the soil is estimated. In order to estimate the ratio of the soil periodicity resistance (CRR), the SPT number was first corrected and the overpressure was  $P_a = 100$  kpa, the energy ratio CE, which was daunt hammer, was considered 0.75, the diameter of the borehole was 150 mm, the CB was equal to 1, the length The rod was smaller than 4 meters and CR is equal to 0.075 and the sampling method is standard sampling, which is consider Cs equal to 1. Using above numbers and coefficients,  $(N1)_{60}$  is estimated. The safety factor less than 1 indicating the probability of occurrence of liquefaction at the desired depth. Where the safety factor is greater than or equal to 1, the liquefaction potential index is zero that mean, the risk of liquefaction is very low. The PL value is between zero and 100. After calculating PL for each layer, the sum of PLs is also calculated at the end of each borehole. Evaluation of susceptible liquefied soils (sand and mud) using a shear wave velocity in comparison with the SPT method is a new method; therefore, studies in this area are limited. In the shear wave velocity method, instead of using the SPT number, the shear wave velocity ( $V_s$ ) is used to evaluate the liquefaction resistance. It should be noted that in the 11 boreholes numbers, 52,46,40,38,35,23,22,15,12,10,2 tests were performed in a downhole, and in each borehole,  $V_s$  obtained equivalent

of the SPT number that these data are entries to the Data Fit software and empirical relationships have been established between them. The same relation is used to calculate all borehole velocities. It should be noted that the calculations performed for soils in two types of cementitious and non-cementitious materials have been applied as a coefficient into CRR relation. In the definition of cementation, if the age of the soil mass is more than 10,000 years, the value of the parameter C varies from 0.6 to 0.8, which is estimated at 0.7 in this calculation. Also, if the soil is non-cementitious or its age is less than 10,000 years, the value of C considered 1. Periodicity of shear resistance of the modified soil  $CRR_j$

has two CRR and  $k_\sigma$  parameters. Evaluation of settlement value after liquefaction by SPT done for both dry and saturated layers. Settlement of dry Soil happened very quickly and completed before the end of the earthquake. Settlement of saturated soil requires more time, which can continue after the earthquake. For soils that have been completely motivated, the main settlement occurs after Seismic shocks. Soil calculations have been done in both cementation and non- cementation methods. In evaluating the amount of settlement after liquefaction has done by the SPT for both dry and saturated layers, and finally for each borehole log, after calculating of settlement amount of soil layers in the upper and lower parts of the groundwater level, the total settlement is determined by summing the total settlement in a dry and saturated state.

### 3. RESULTS AND DISCUSSION

[Table \(2\)](#) represents the total number of boreholes and the number of layers studied. Based on the SPT test, 66.7%

of the layers were liquefying and 33.3% of the layers were non- liquefied.

**Table 2.** Number of boreholes, liquefied and non- liquefied layers in the SPT test

Total boreholes	Total layers in boreholes	Total liquefied layers in the SPT test	Total non- liquefied layers in the SPT test
53	464	310	155
%		66.7	33.3

[Table \(3\)](#) shows the number of evaluated layers using shear wave velocity test ( $V_s$ ) in non-cementitious mode,

of which 57.5% of the layers were evaluated liquefied and 42.5% of the layers were determined non- liquefied.

**Table 3.** The number of and non- liquefied layers in the Vs test in non- cementitious mode.

Total layers in Vs	Liquefied layers in Vs	Non- liquefied layers in Vs
464	267	197
%	57.5	42.5

[Table \(4\)](#) shows the number of evaluated layers using the shear wave velocity (Vs) test in cementitious mode,

of which 76.7% of the layers were evaluated liquefied and 23.3% of the layers were determined non-liquefied.

**Table 4.** The number of and non- liquefied layers in the Vs test in cementitious mode

Total layers in Vs	Liquefied layers in Vs	Non- liquefied layers in Vs
464	356	108
%	76.7	23.3

The results obtained from the evaluation of 464 soil layers using the shear wave velocity method with the application of experimental relationship in non-cementitious and cementitious states indicate that the shear wave velocity values determined on the basis of the standard SPT penetration test number are low and

32.9 % of layers is non- liquefied and 67.1% of the layers are determined in liquefied manner. [Table \(5\)](#) shows the values of the estimated liquefaction potential index for 464 layers based on the 258 SPT standard penetration test. The results show the layers in the studied range have a moderate liquefaction incidence rate.

**Table 5.** potential liquefaction index based on SPT test

potential liquefaction index	PL=0	$5 \leq 0 < PL$	$15 \leq PL < 5$	$15 > PL$
Total layers	155	258	43	8
%	33.41	55.6	9.27	1.72

[Table \(6\)](#) shows the values of the calculated potential liquefaction index for 464 layers based on the shear wave velocity (Vs) in the cementitious state. The results

show that 201 layers in the studied range have a moderate liquefaction incidence.

**Table 6.** potential liquefaction index based on Vs test in cementitious state

potential liquefaction index	PL=0	$5 \leq 0 < PL$	$15 \leq P < 5$	$15 > PL$
Total layers	108	201	108	47
%	23.8	43.22	23.28	10.12

[Table \(7\)](#) shows the values of the calculated potential liquefaction index for 464 layers based on the shear wave velocity (Vs) in the non-cementitious state. The

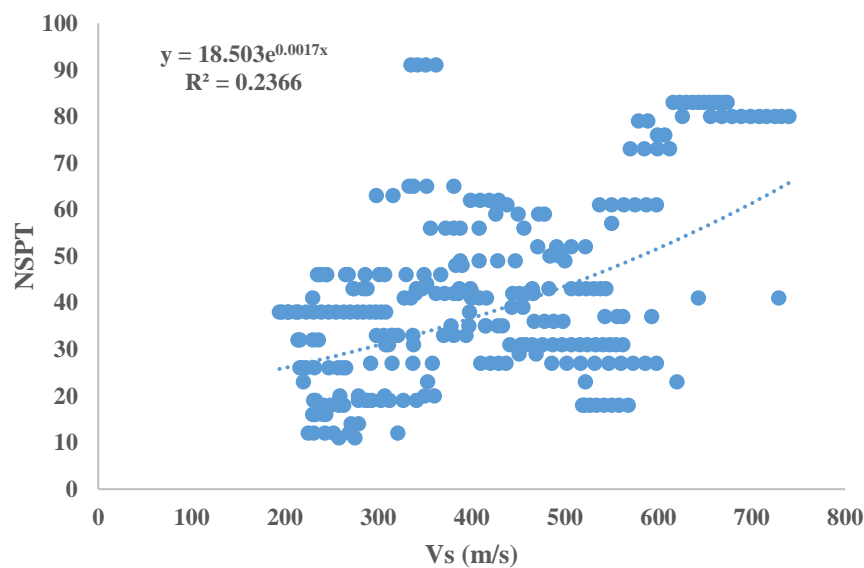
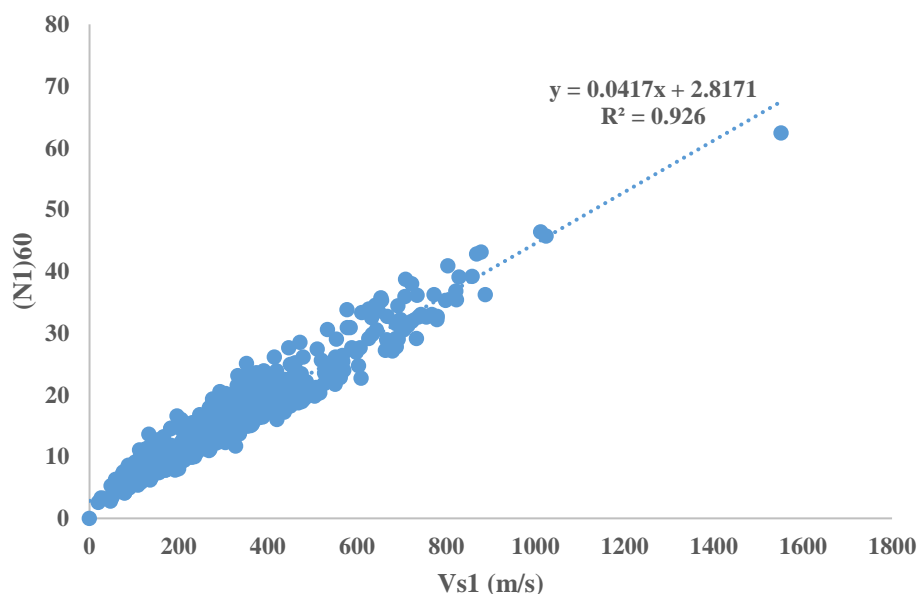
results show that 147 layers in the studied range have a moderate liquefaction incidence.

**Table 7.** potential liquefaction index based on Vs test in non-cementitious state

potential liquefaction index	PL=0	$5 \leq 0 < PL$	$15 \leq P < 5$	$15 > PL$
Total layers	197	147	90	30
%	42.46	31.68	19.4	6.46

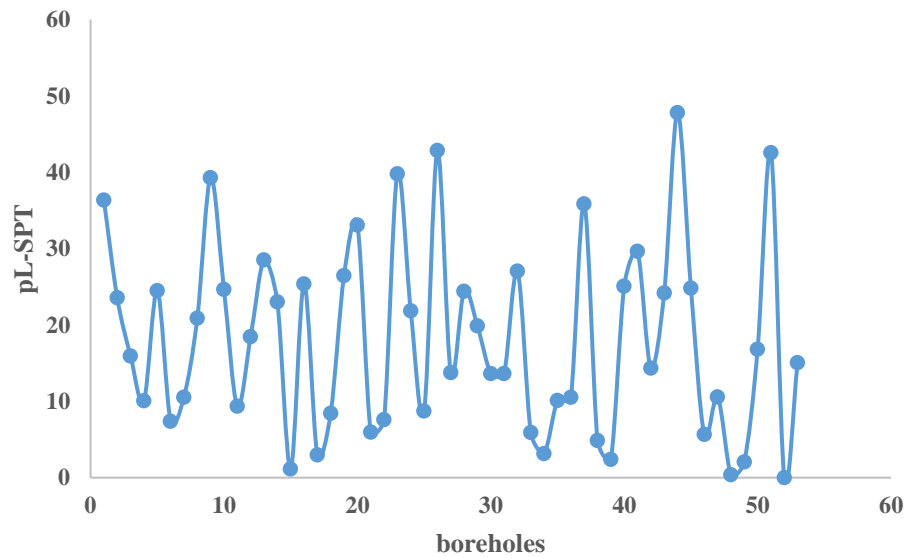
The results of the analyses show that there is no suitable correlation between the methods of liquefaction potential estimation using SPT and shear wave velocity (Vs), and the intensity of liquefaction in the studied range is The basis of the SPT method is less than Vs. [Figure \(1\)](#) shows the relationship between the shear wave velocity and the

standard penetration number for the 11 boreholes in which the downhole test was carried out by Excel software, which, because of its low precision, was shown again in [Figure \(2\)](#) this relationship was done between the modified shear wave velocity and modified standard penetration number, which has a very high accuracy

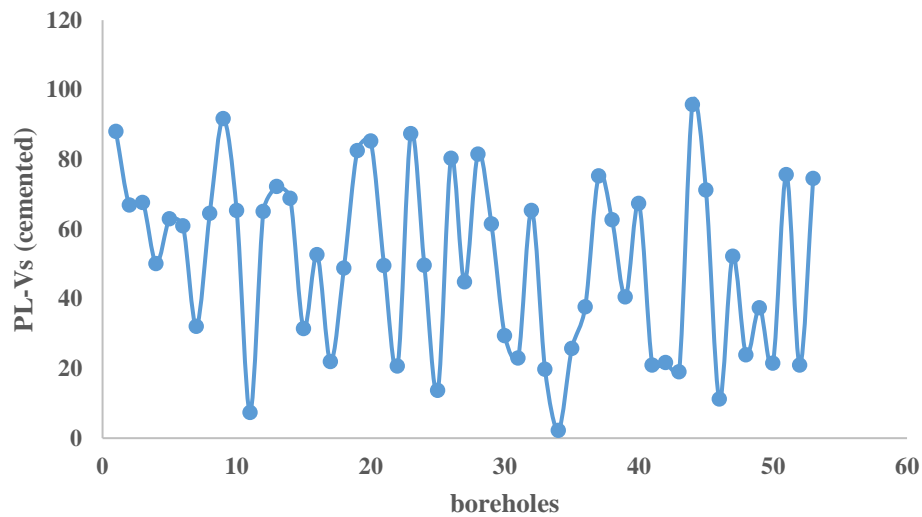
**Figure 1.** The relationship between shear wave velocity and SPT number by Excel software**Figure 2.** The relationship between modified shear wave velocity and modified SPT number by Data Fit software

[Figures \(3\), \(4\)](#) and [\(5\)](#) show changes of the SPT liquefaction potential index and shear wave velocity

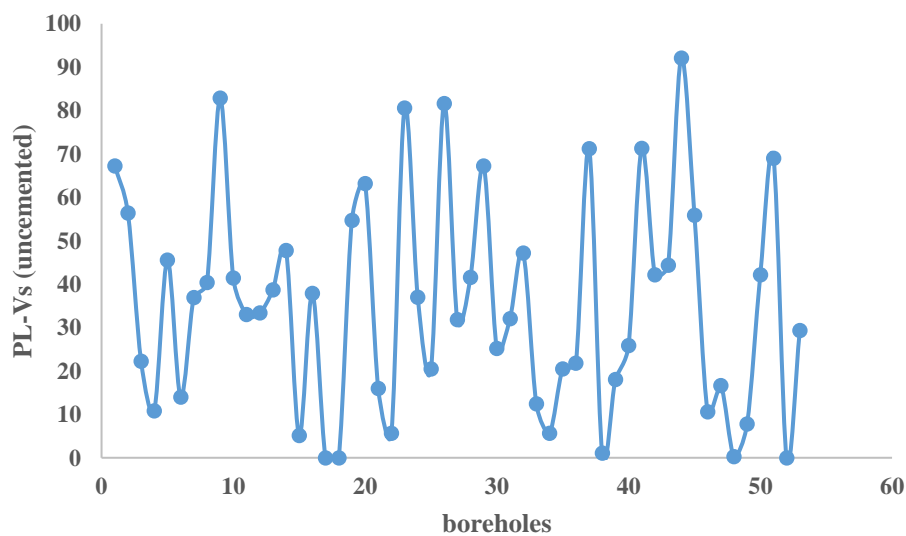
(cementitious and non- cementitious modes) against the number of boreholes.



**Figure 3.** Changes of the SPT liquefaction potential index versus the number of boreholes



**Figure 4.** Changes of the shear wave velocity of liquefaction potential index in cementitious state versus the number of boreholes



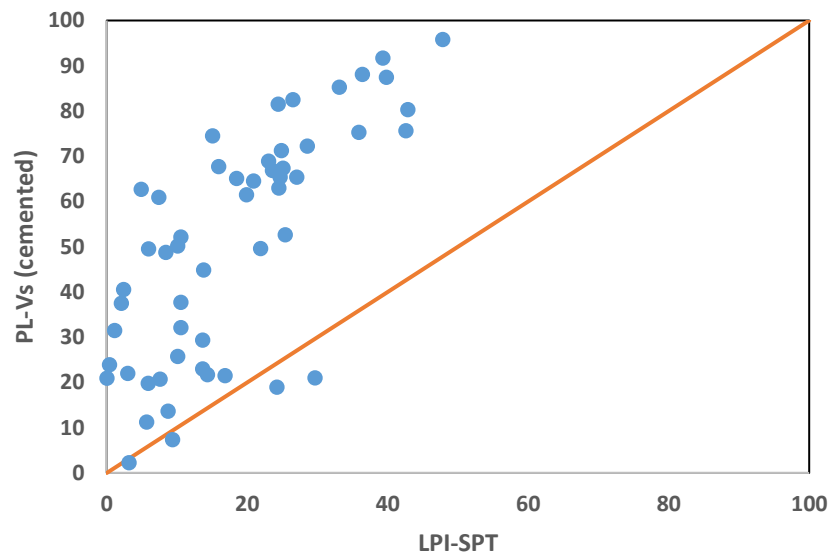
**Figure 5.** Changes of the shear wave velocity of liquefaction potential index in non-cementitious state versus the number of boreholes

Figures (6) and (7) show, respectively, the changes of SPT liquefaction potential index versus the shear wave

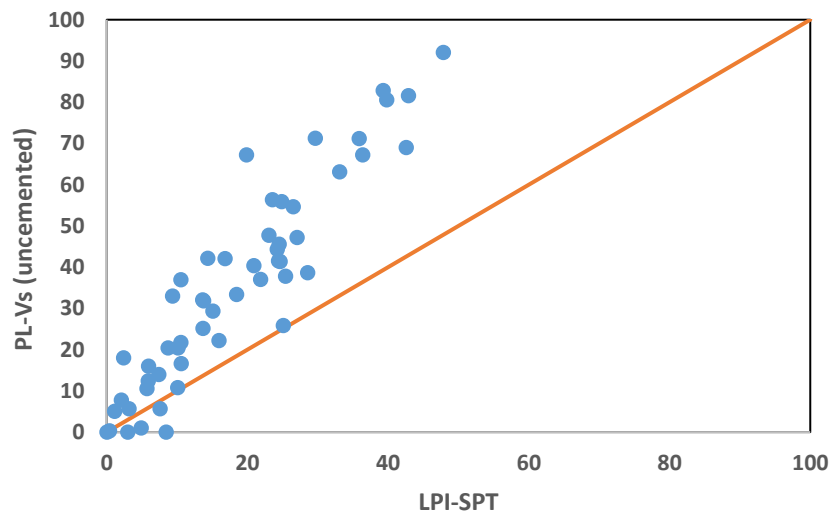
velocity of the cementitious and non-cementitious state for the 11 boreholes that downhole test done inside

within and [Figures \(8\) and \(9\)](#). Accordingly, the changes of SPT liquefaction potential index versus the

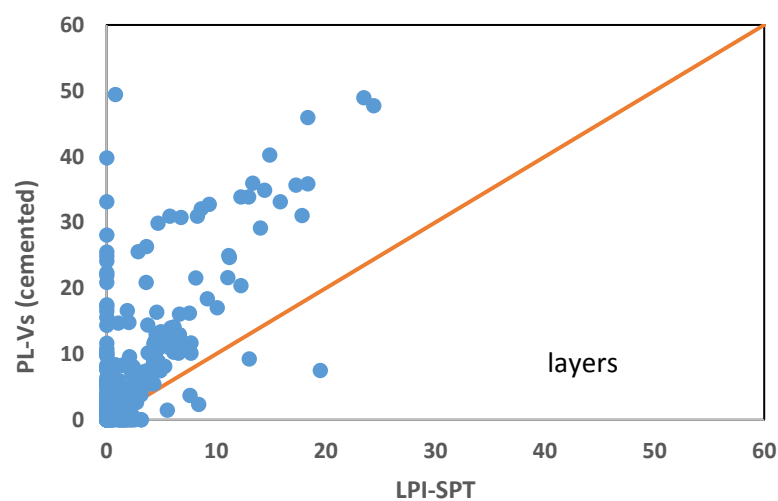
shear wave velocity on the cementitious and non-cementitious state shown for all boreholes.



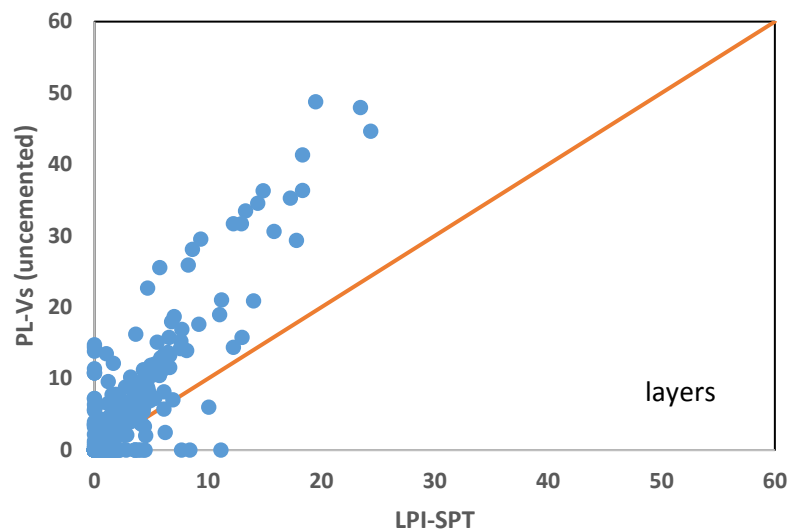
**Figure 6.** Changes of the SPT liquefaction potential index versus the shear wave velocity in cementitious state



**Figure 7.** Changes of the SPT liquefaction potential index versus the shear wave velocity in non-cementitious state



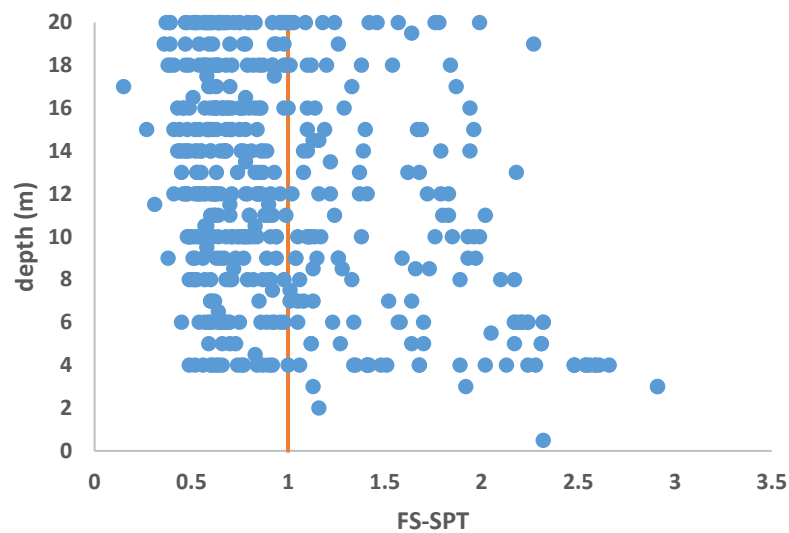
**Figure 8.** Changes of modified SPT liquefaction potential index versus modified shear wave velocity in cementitious state



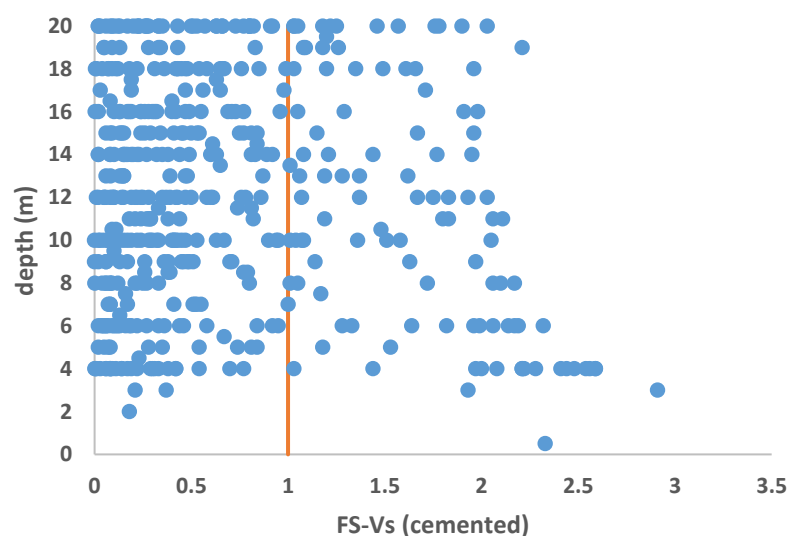
**Figure 9.** Changes of modified SPT liquefaction potential index versus modified shear wave velocity in non-cementitious state

Figures (10), (11) and (12) show the changes in safety factor versus the SPT liquefaction and the shear wave

velocity (cementitious and non-cementitious state) versus the depth.

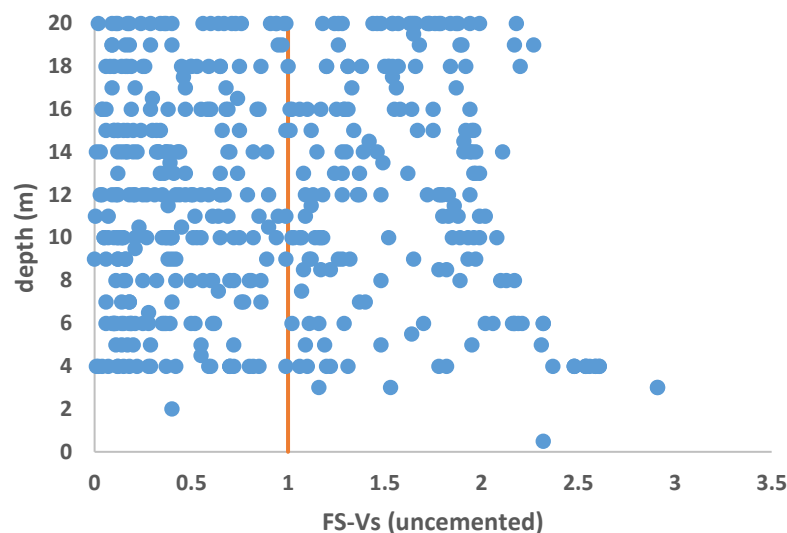


**Figure 10.** Changes of safety factor versus SPT versus depth



**Figure 11.** Changes of safety factor versus liquefaction shear wave velocity in cementitious state versus depth

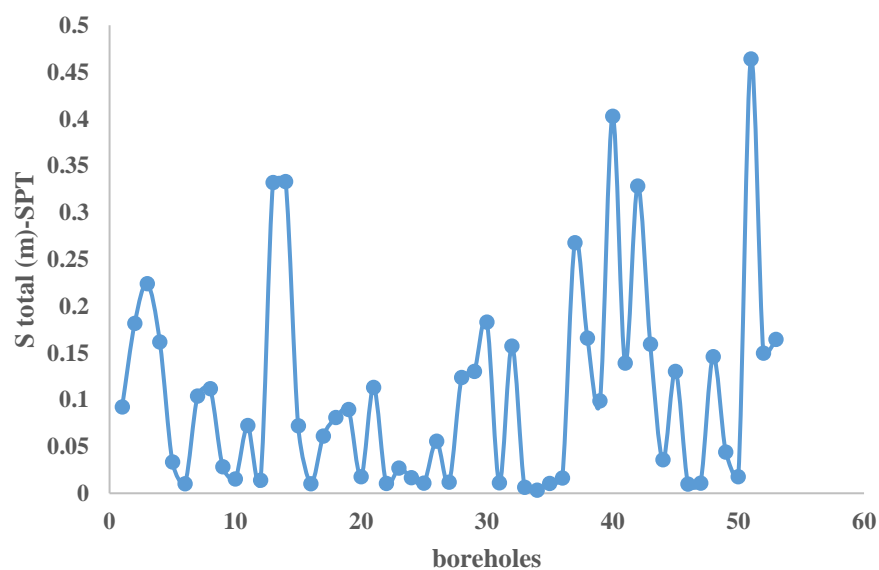




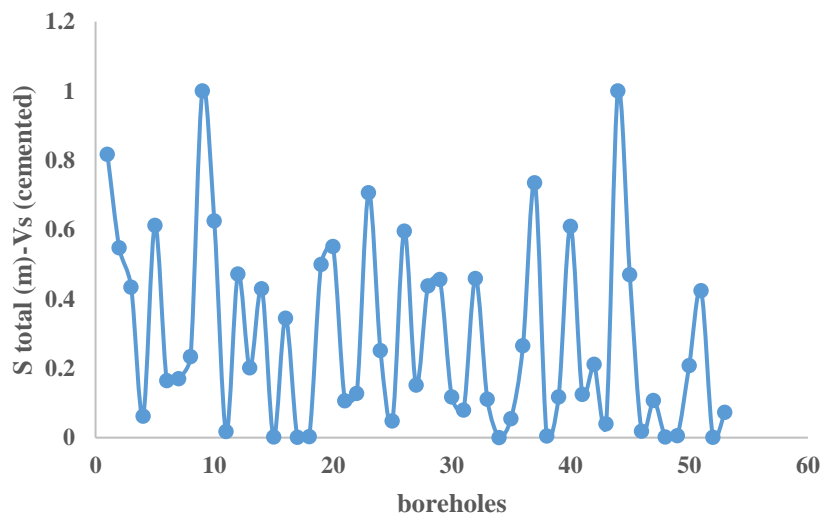
**Figure 12.** Changes of safety factor versus liquefaction shear wave velocity in non- cementitious state versus depth

According to [Figure \(11\)](#) to [\(12\)](#), it can be seen that the maximum value of the liquefaction potential index is related to the shear wave velocity in the cementitious state. After that, the shear wave velocity in non-cementitious state and finally, the lowest amount of the relevant liquefaction potential index is related to the SPT method, which means that the SPT method has the

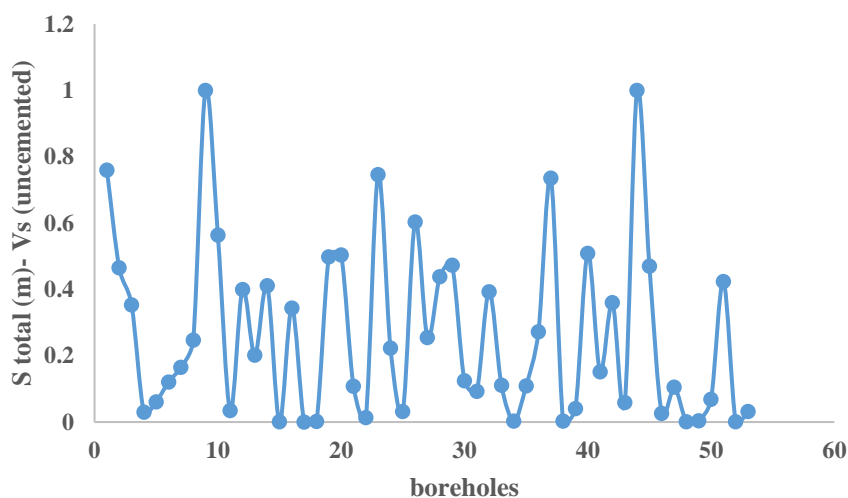
highest safety factor (FS) versus liquefaction, and the lowest safety factor belongs to the shear wave velocity method in cementitious state. [Figures \(13\), \(14\)](#) and [\(15\)](#) show the total settlement changes of SPT and shear wave velocity (cementitious and non-cementitious state) against the number of boreholes.



**Figure 13.** Changes of SPT total settlement versus the boreholes numbers



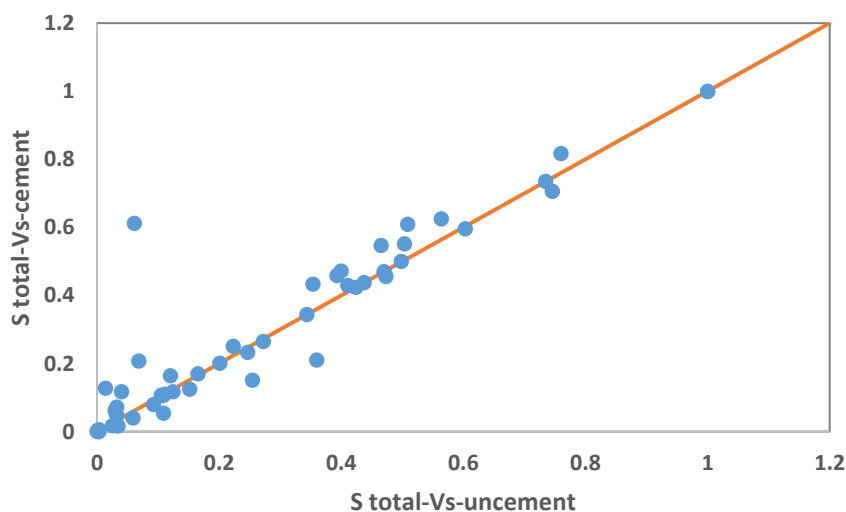
**Figure 14.** Changes of total settlement of shear wave velocity in cementitious state versus the boreholes numbers



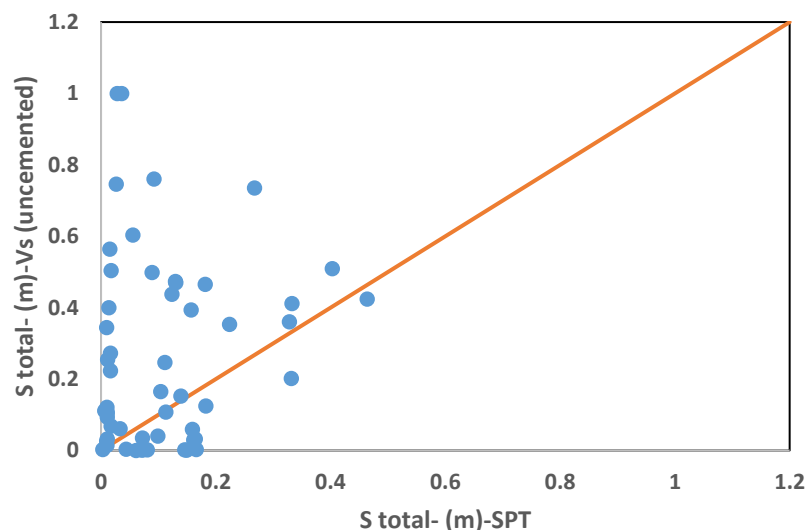
**Figure 15.** Changes of total settlement of shear wave velocity in non-cementitious state versus the boreholes numbers

[Figs \(16\), \(17\)](#) and [\(18\)](#), respectively, represents the change of total settlement of cementitious shear wave velocity versus the total settlement of the non-cementitious shear wave velocity, changes of total

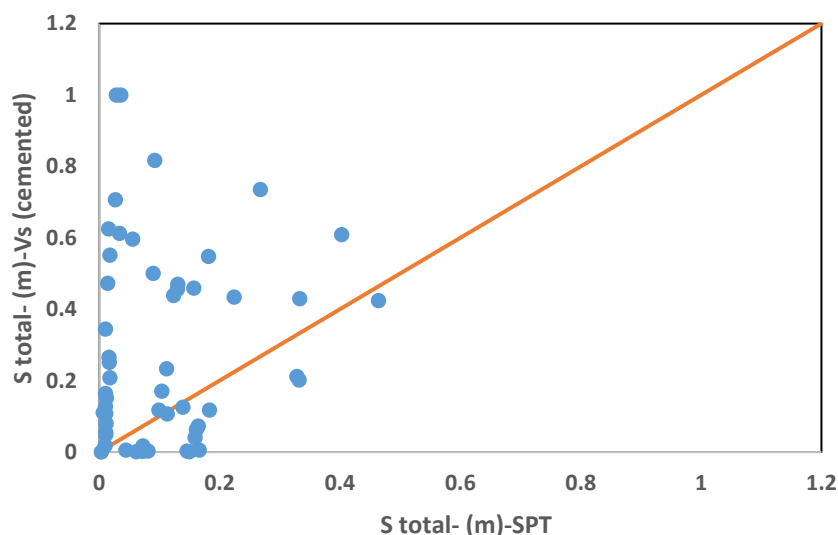
settlement of non-cementitious shear wave velocity versus total SPT settlement and the changes of total settlement of cementitious shear wave velocity versus total SPT settlement.



**Figure 16.** Change of total settlement of cementitious shear wave velocity versus the total settlement of the non- cementitious shear wave velocity



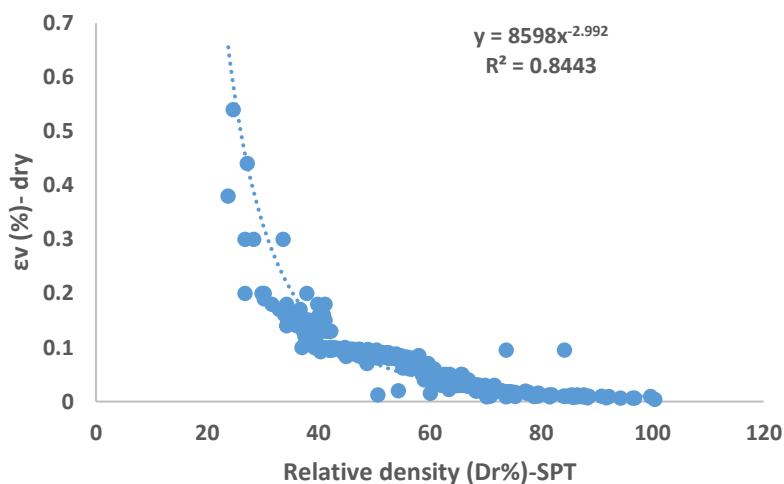
**Figure 17.** Changes of total settlement of non-cementitious shear wave velocity versus total SPT settlement



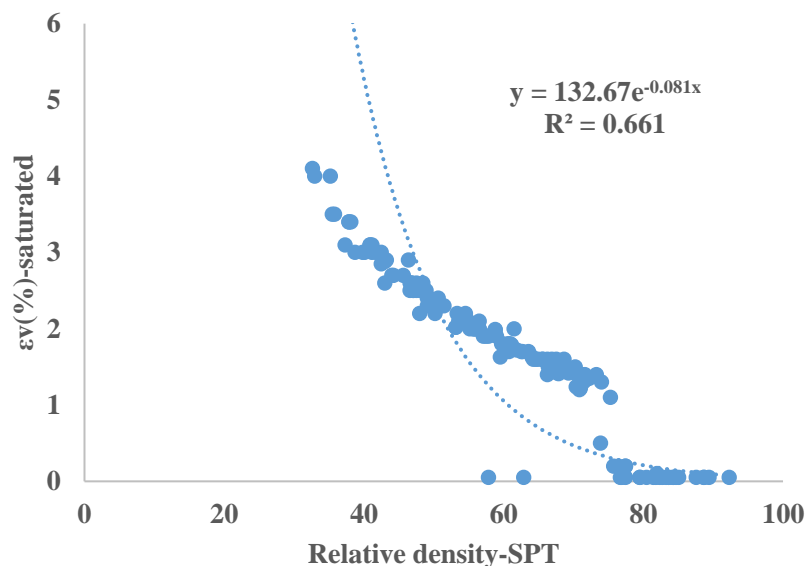
**Figure 18.** Changes of total settlement of cementitious shear wave velocity versus total SPT settlement

amount of settlement is related to the SPT method. [Figures \(19\)](#) and [\(20\)](#) show changes in the SPT volumetric strain versus the relative density in dry and saturated states.

According to [Figure \(17\)](#) to [\(18\)](#), it can be seen that the maximum settlement rate is related to the shear wave velocity in cementitious state, after that the shear wave velocity is in non- cementitious state and the least



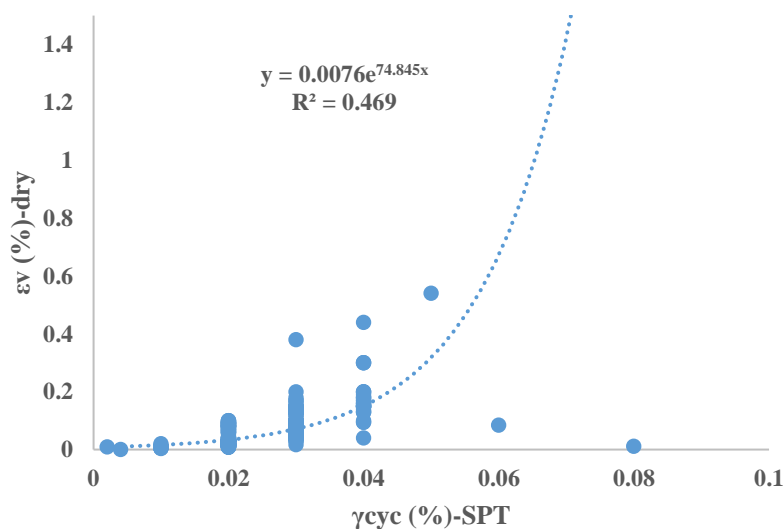
**Figures 19.** Changes in the SPT volumetric strain versus to the relative density in dry state



**Figures 20.** Changes in the SPT volumetric strain versus to the relative density in saturated state

According to [Figures \(19\)](#) and [\(20\)](#), which show the changes of the SPT volumetric strain versus to the relative density in dry and saturated states, it can be seen that the volumetric strain has a vice versa relationship with the density, that means, by increasing

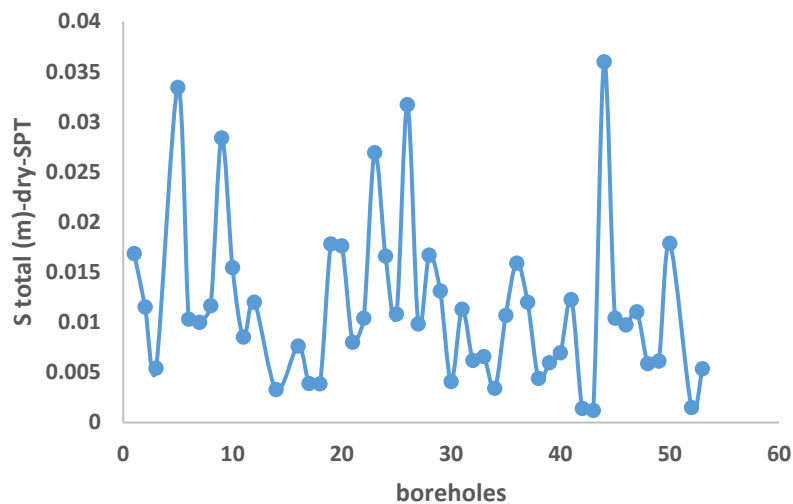
the relative density, Volumetric strain will decrease. Relative density changes by volumetric strain in the SPT method are more consistent in dry state compared to saturated state. [Figure \(21\)](#) shows the change of SPT volumetric strain versus the shear strain in dry state.



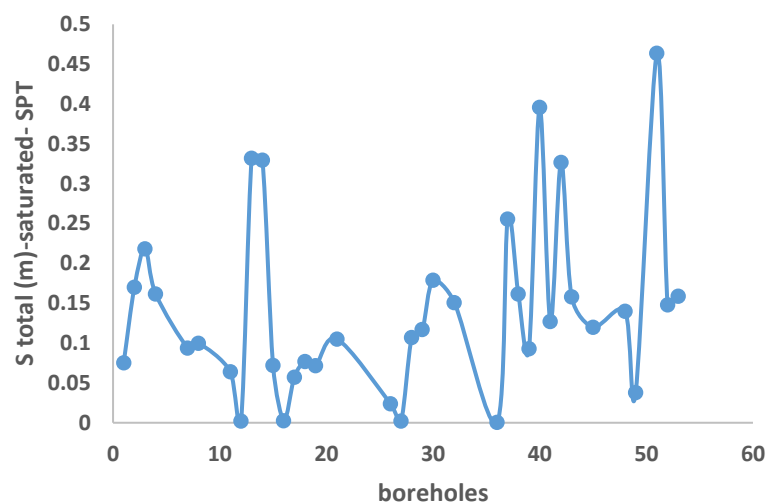
**Figure 21.** Change of SPT volumetric strain versus the shear strain in dry state

Regarding to [Figure \(21\)](#), which shows the changes of SPT volumetric strain versus to shear strain in dry state, it can be seen that the volumetric strain and the shear strain are directly related, that means, with increasing

the shear strain, the volumetric strain also increases. [Figures \(22\)](#) and [\(23\)](#) show, respectively, the total settlement changes of dry and saturated layers versus the number of boreholes.



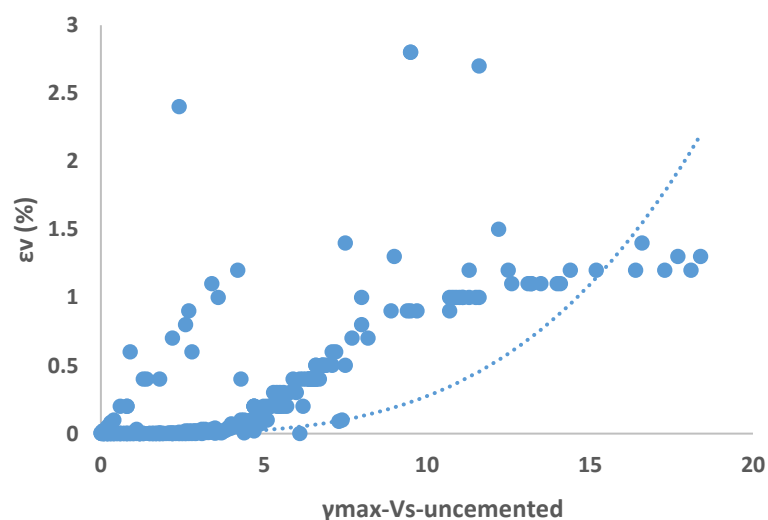
**Figures 22.** Total settlement changes of dry layers versus to the number of boreholes



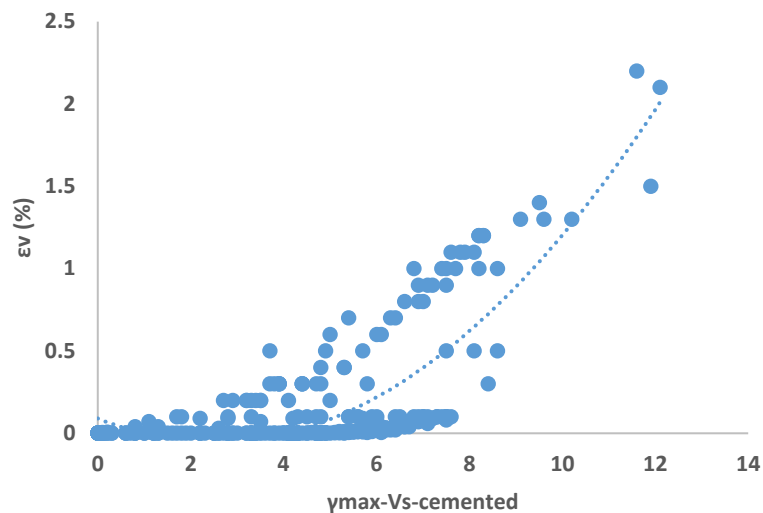
**Figures 23.** Total settlement changes of saturated layers versus to the number of boreholes

According to [Figures \(22\)](#) and [\(23\)](#), it can be seen that in the SPT method, the settlement of dry soil is very small relative to the saturated soil. The settlement of dry soil is completed rapidly, but the settlement of saturated soil may be continued after the end of

earthquake. [Figures \(24\)](#) and [\(25\)](#) represent, respectively, volumetric strain changes of shear wave velocity in cementitious and non- cementitious states versus the maximum volumetric strain.



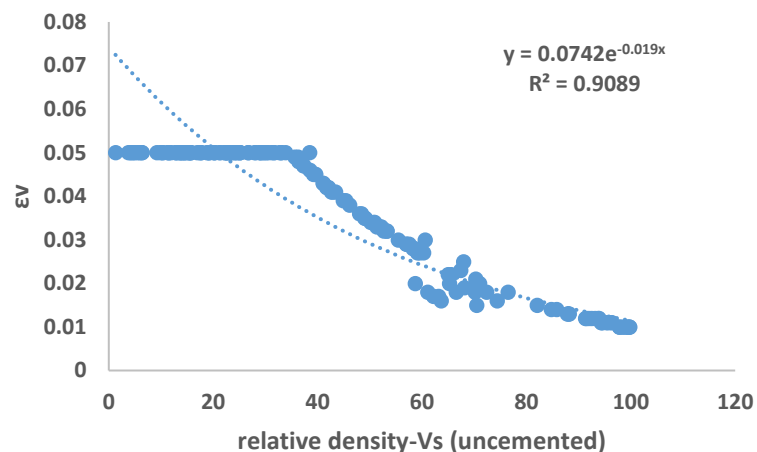
**Figures 24.** Volumetric strain changes of non-cementitious shear wave velocity versus the maximum volumetric strain



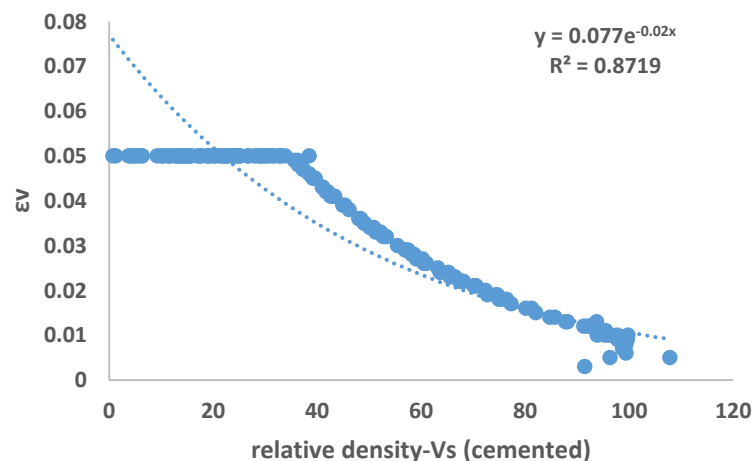
**Figures 25.** Volumetric strain settlement changes of cementitious shear wave velocity versus the maximum volumetric strain.

According to [Figures \(24\)](#) and [\(25\)](#), which show, respectively, volumetric strain changes of shear wave velocity in cementitious and non- cementitious states versus the maximum volumetric strain, it can be seen that the volumetric strain and shear strain are in direct correlation. That means, with the increase of the shear strain, the volume strain also increases. The volumetric

strain changes with the shear strain in the cementitious state are more consistent with non-cementitious state. [Figures \(26\)](#) and [\(27\)](#) represent, respectively, volumetric strain changes of shear wave velocity in cementitious and non- cementitious states versus the relative density.



**Figures 26.** Volumetric strain changes of non- cementitious shear wave velocity versus the relative density



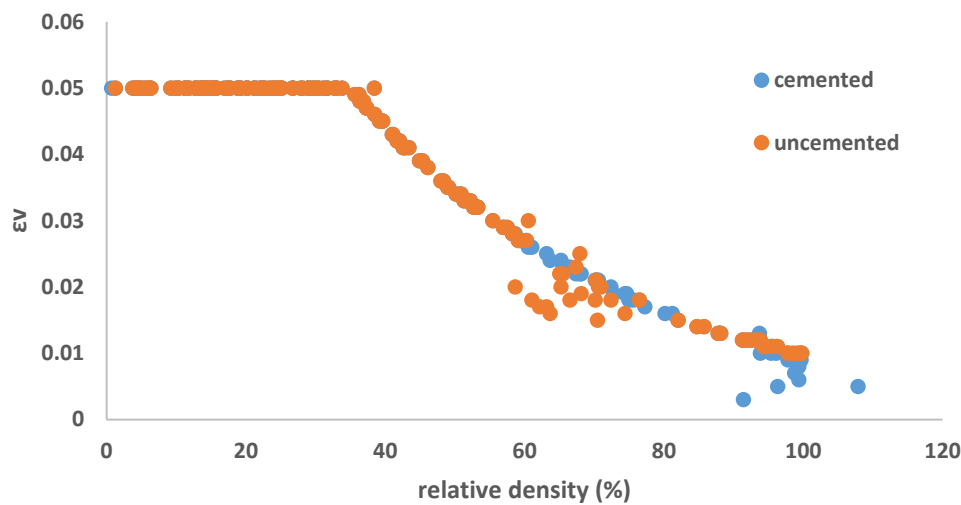
**Figures 27.** Volumetric strain changes of cementitious shear wave velocity versus the relative density

Regarding to the [Figures \(26\)](#) and [\(27\)](#), which show, respectively, volumetric strain changes of cementitious

and non- cementitious shear wave velocity versus the relative density, it can be seen that the volumetric strain

has a vice versa relationship with the relative density. That means, by increasing relative density, the amount of volumetric strain decreases. [Figure \(28\)](#) shows the

matching of volumetric strain changes of cementitious and non- cementitious shear wave velocity versus the relative density.



**Figure 28.** Matching of volumetric strain changes of cementitious and non- cementitious shear wave velocity versus the relative density

#### 4. CONCLUSION

The obtained results from the comparison of the two methods in the studied range are as follows:

- 1- Based on the SPT test, from the total of 464 layers that evaluated regarding the soil material, 66.7% of the layers are liquefied and 33.3% of the layers are determined none liquefied. The result shows that the soil liquefaction potential is in the high range.
- 2- Based on the shear wave velocity test ( $V_s$ ) in non-cementitious state, from the total of 464 layers evaluated regarding the soil material, 57.5% of the layers are liquefied and 42.5% of layers are determined none liquefied. The result shows that the soil liquefaction potential is in a relatively high range.
- 3- Based on the shear wave velocity test ( $V_s$ ) in the cementitious state, from the total of 464 layers assessed regarding the soil material, 76.7% of the layers are liquefied and 23.3% of layers are determined non liquefied. The result indicates that the soil liquefaction potential is in high range.
- 4- According to [Table 6](#), it can be seen that 10.99% of the liquefaction potential index based on the standard penetration test (SPT), it placed in the range of  $15 \leq PL < 30$  and  $PL > 30$ , which means the severity of the liquefaction hazard in the studied range is very low.
- 5- According to [Table 7](#), based on shear wave velocity method ( $V_s$ ) assuming non-cementitious soil by applying empirical relationship it can be seen that 25.86 % of the liquefaction potential index placed in the range of  $5 < PL \leq 15$  and  $PL > 15$ , which means the severity of the liquefaction hazard in the studied range is rather high.
- 6- It can be seen that 33.4 % of the liquefaction potential index based on shear wave velocity method ( $V_s$ ) assuming cementitious soil placed in the range of  $5 < PL \leq 15$  and  $PL > 15$ , which means the severity of the liquefaction hazard in the studied range is rather high.
- 7- The most amount of liquefaction potential index is related to the shear wave velocity in cementitious state, after that shear wave velocity in non-cementitious state and finally the lowest amount is related to the SPT method and it means that SPT method has the highest safety factor (FS) versus liquefaction and the lowest amount is related to the shear wave velocity method in cementitious state.
- 8- The most amount of settlement is related to the shear wave velocity in cementitious state. after that shear wave velocity in non- cementitious state and the lowest amount is related to the SPT method.
- 9- Volumetric strain has an inverse relationship with relative density. It means that with increasing relative density the amount of volumetric strain decreases. Relative density, variation with volumetric strain is more consistent with the SPT method in dry state than saturation state.
- 10- In the SPT method, dry soil settlement is very low in relation to the soil saturation. The dry soil settlement is complete immediately, but the settlement of saturation soil may continue after the earthquake.
- 11- Volumetric strain has a direct relationship with shear strain, which means that with increasing shear strain, the volumetric strain also increases. Volumetric strain variations with shear strain in cementitious state are more consistent than non-cementitious state.
- 12- The amount of volumetric strain in cementitious state and non-cementitious state versus relative density in shear wave velocity method are consistent too much.

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The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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