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Mitigation Of Liquefaction Induced Settlements Under Shallow Strip Footings Using Ground Densification

Aamir Gulzar, Saptarshi Kundu [0000-0002-9290-7966] and Ambarish Ghosh

Department of Civil Engineering, Indian Institute of Engineering Science and Technology,
Shibpur, Howrah 711103, India.

saptarshikundu123@gmail.com

Abstract. The objective of the present study is to establish the optimum influence zone of ground densification to be achieved under shallow strip footings resting on soil deposits susceptible to liquefaction. Finite element-based analysis has been conducted in PLAXIS 2D interface to model the seismic behaviour of liquefiable granular soil by adopting the UBCSAND constitutive law. The developed model has been validated by comparing the numerical results with published centrifuge test results. The effectiveness of ground densification in decreasing the seismic liquefaction induced settlement of footings has been subsequently investigated over a range of depth and width of densified zone expressed as a function of the footing geometry, varying magnitude of loading on the footing. The numerically obtained results have been utilized for developing a power regression model to quantify the improved settlement response of strip footings resting on ground remediated by densification. The study indicates that the dimension of the improved zone and magnitude of surcharge are the most significant factors influencing liquefaction-induced settlements. The utility of this study is to aid in decision making in the field regarding the implementation of ground densification as a liquefaction mitigation technique.

Keywords: *Granular Soil; Liquefaction; Shallow Strip Footings; UBCSAND; Settlement; Ground Densification.*

1 Introduction

Liquefaction is a phenomenon wherein the shear strength of soils become negligible due to extensive ground shaking caused by any rapid loading similar to an earthquake. Development of high pore pressures in soils lead to decreased effective stresses, causing the soil to flow like a fluid. Liquefaction is one of the most disastrous earthquake-induced natural hazards that can affect the structural elements, foundations, and essential life-line utilities like gas pipelines, water tanks, etc. Therefore, it is of utmost importance to geotechnical engineers as it is directly dependent on the type of soil and hydraulic conditions prevailing at the site. Liquefaction can occur by two mechanisms, namely (a) Flow liquefaction (b) Cyclic liquefaction. The Stava mudflow of 19 July 1985 is one of the best examples of flow liquefaction [1], whereas the 1964 Niigata earthquake is a classic example of cyclic liquefaction wherein the destruction was primarily limited to the structures founded on loose, saturated soils [2]. Several mitigation techniques have been proposed by researchers for mitigation of liquefaction induced settlements, out of which the traditional measures include dynamic compaction, vibro-compaction, deep blasting technique, drains, decreasing the groundwater table level, deep soil mixing columns, grouting methods etc. The related studies reported in the literature have mainly focused on the effects of mitigation while maintaining the overburden constant [3, 4], which can have a significant effect on liquefaction induced ground deformations.

The liquefaction mitigation measures can be broadly divided into four categories: (a) Enhancement of drainage (b) Lowering of Groundwater table (c) Densification (d) Reinforcement methods [5]. The insertion of prefabricated vertical drains (PVDs) can facilitate radial drainage, thereby increasing the rate of dissipation of excess pore water pressure and reducing the chances of liquefaction. Ground reinforcement based methods including deep soil mixing (DSM) columns, structural walls, sheet pile for underground structure, the addition of flexible joint to absorb ground displacement, sheet piling of an embankment etc. have also shown promising results in reducing the liquefaction induced settlements. Recent addition to mitigation techniques are desaturation methods, wherein saturation of soil is decreased to enhance liquefaction resistance of soils. Another recent addition to the mitigation techniques has been partially induced saturation. To this effect**,** biogas was added to saturated sands and it was observed that excess pore water pressures are significantly reduced with the decrease in the saturation level of sands [6] .

Another widely used method of liquefaction mitigation involves the densification of soils, which is the potential discussion topic for the present research. Since ancient times, densification has been used to enhance the strength and deformation characteristics of soils. The shear strength of soils plays a pivotal role in negating the effect of liquefaction as they counter the excessive settlements. The ease of field implementation, coupled with the wide variety of methods available to densify soils render it as one of the best options available to enhance the liquefaction resistance of soils. Ground remediation conducted in a potentially liquefiable site located at Chang-Hwa Coastal Industrial Park in Changhua County, Taiwan revealed that as an aftermath of dynamic compaction-based densification, the liquefaction susceptibility was reduced by approximately 60% for more than 80% of the study area [7]. The effectiveness of vibrocompaction-based densification in increasing the soil strength and for reducing the liquefaction potential of an earthen dam foundation was documented in the north of Tunisia at Sidi El Barrak dam, by conducting SPT and CPT before and after employing vibrocompaction [8]. A recent numerical study has revealed that well-graded sands with lesser fines sands experienced complete eradication of liquefaction potential after implementation of Vibroflotation [9].

From the above studies, it is clear that densification methods have proven to be very effective as a liquefaction mitigation measure. However, the depth up to which soil enhancement using densification should be carried out depends heavily on engineering judgment and site conditions. Drawing parallel to the above, the present study aims at establishing the optimum influence zone of ground densification to be achieved under shallow strip footings resting on soil deposits susceptible to liquefaction. Finite element-based analysis has been conducted in PLAXIS 2D [10] interface to model the seismic behaviour of liquefiable granular soil by adopting the UBCSAND constitutive law. The effectiveness of ground densification in decreasing the seismic liquefaction induced settlement of footings has been subsequently investigated over a range of depth and width of densified zone expressed as a function of the footing geometry and varying magnitude of loading on the footing. The numerically obtained results have been utilized for developing a power regression model and subsequently, a design equation to quantify the improved settlement response of strip footings resting on ground remediated by densification.

2 Problem Statement and Validation of the Developed Model

Two-dimensional finite element software, PLAXIS, has been used in the present study to model seismic response of soils. A centrifuge study conducted at Rensselaer

Polytechnic Institute, Troy has been considered for validation purpose [11]. Plane strain condition has been employed in the present study to model embankment resting on liquefiable layer. PLAXIS inbuilt constitutive law, UBCSAND has been used to model the foundation soil, which is a Nevada sand layer of 6-m depth having 40% relative density. A 4.5-m high trapezoidal surcharge of base width 20.3-m and top width 5.3-m is applied for simulating the embankment, modelled using Mohr-Coulomb constitutive law, which best replicates the properties of a clayey soil. The material properties of the liquefiable layer is summarized in Table 3, properties of the clayey embankment in Table 2 [11], while Figure 1 presents the numerical model used in the present study. The material properties of liquefiable layer were obtained from various correlations available in the literature relating various parameters of UBCSAND model with the relative density (*RD*) and corrected SPT blow count $(N_1)_{60}$. Some of these correlations are given in Table 1 [12,13,14,15].

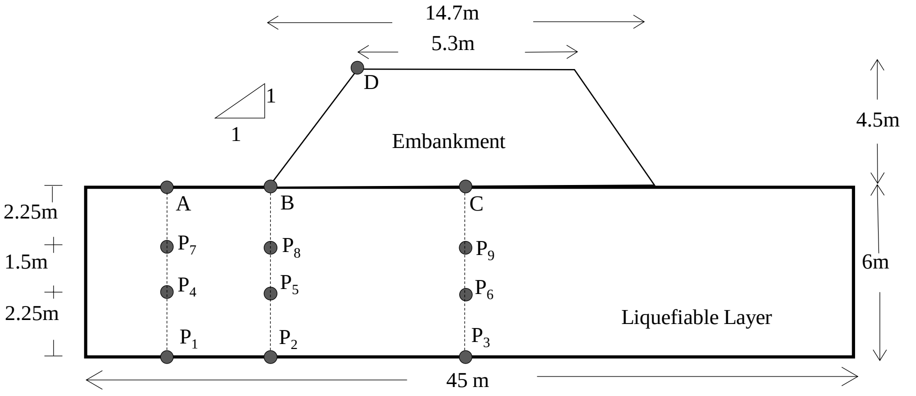

Fig. 1. Dimensions of numerical model for validation with centrifuge tests [11]

Table 1. Correlations used for UBCSAND parameters

Parameters	Correlation	Reference
Corrected SPT blow count	$(N_1)_{60} = 41\times RD^2$	[13]
Peak friction angle	$\phi_p = [15.4\times(N_1)_{60}]^{0.5} + 20$	[14]
Constant volume friction angle	$\phi_{cv} = \phi_p - (N_1)_{60}/10\text{-max } [0,\{(N_1)_{60}-15\}/5]$	[14]
Elastic shear modulus number	$K^e_G = 21.7\times20\times[(N_1)_{60}]^2$	[15]
Elastic bulk modulus number	$K^e_B = 0.7\times K^e_G$	[15]
Plastic shear modulus number	$K^p_G = K^e_G\times[(N_1)_{60}]^2\times0.003+100$	[15]
Failure ratio	$R_f = 1.1\times[(N_1)_{60}]^{-0.15}$	[15]

Table 2. Material properties of the clayey embankment

Properties	Symbol	Units	Value
Dry and Saturated Unit Weight	$\gamma_{dry}, \gamma_{sat}$	kN/m^3	19, 21
Initial Void Ratio	$e_{initial}$	-	0.5
Cohesion	c	kN/m^2	22
Internal Angle of Friction	ϕ	°	31
Modulus of Elasticity	E	kN/m^2	20,000
Poisson's Ratio	μ	-	0.3
Permeability	$k_x = k_y = k_z$	m/day	0.6

Table 3. Material properties of the liquefiable layer

Material property	Notation	Units	Liquefiable layer (RD = 40%)
Corrected SPT value	$(N_1)_{60}$	-	7
Elastic shear modulus number	K^e_G	-	788.16
Elastic bulk modulus number	K^e_B	-	551.71
Plastic shear modulus number	K^p_G	-	185.12
Failure ratio	R_f	-	0.84
Peak friction angle	ϕ_p	(°)	29.6
Constant Volume friction angle	ϕ_f	(°)	29
Initial Void ratio	e	-	0.74
Saturated unit weight	γ_{sat}	kN/m^3	19.24
Elastic shear modulus number	m_e	-	0.5
Elastic bulk modulus number	n_e	-	0.5
Plastic shear modulus number	n_p	-	0.4
Densification factor	f_{dens}	-	1
Post liquefaction factor	f_{post}	-	1

The numerical model simulating the centrifuge experiment was subjected to a cyclic loading of 10 cycles having a frequency of 1.6 Hz with maximum amplitude of of 0.09g, as presented in Figure 2. Viscous boundaries are employed during the dynamic phase in order to prevent reflection of stresses back in to the model, which could otherwise lead to erroneous results. In order to account for the effect of meshing on the accuracy of the results, a mesh convergence study was carried out and the optimum mesh was arrived at, which was found to converge with the inbuilt fine-mesh system of PLAXIS. Figure 3 represents the 15-noded elements having element dimensions of 2.051-m and relative element size of 0.667 used in this study.

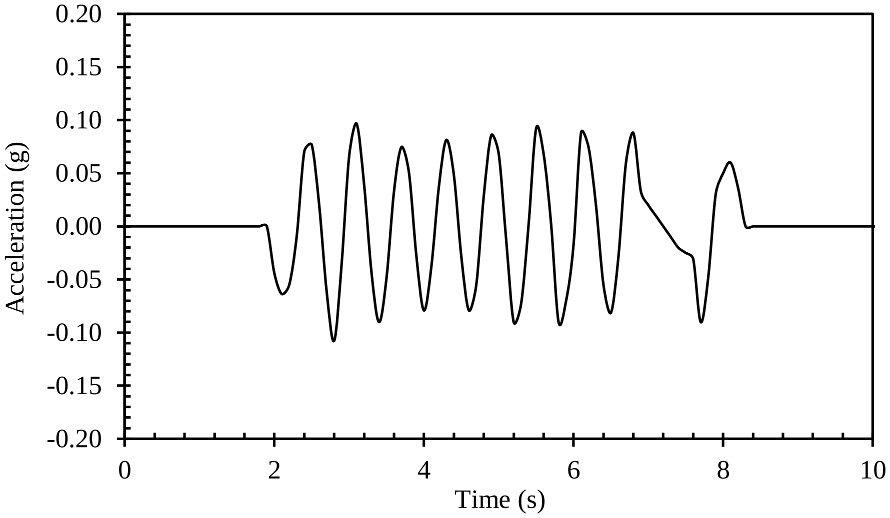

Fig. 2. Cyclic loading provided at the base of the numerical model

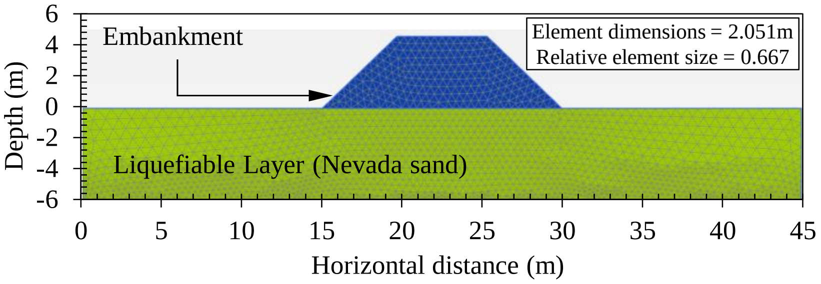

Fig. 3. Finite element mesh used in the numerical model

The excess pore water pressure was computed at strategic points and the results were compared at homologous points with the centrifuge model (Point P5 and Point P8), as depicted in Figure 4 and Figure 5, while the settlement magnitudes monitored at Point D are presented in and Figure 6. It was observed that the settlement values as well as the time at which peak excess pore water pressure was observed at a particular point in the dam section corroborated numerically and experimentally. A minor divergence was however observed in the rate of dissipation of excess pore water pressure in the numerical model as compared to the centrifuge model.

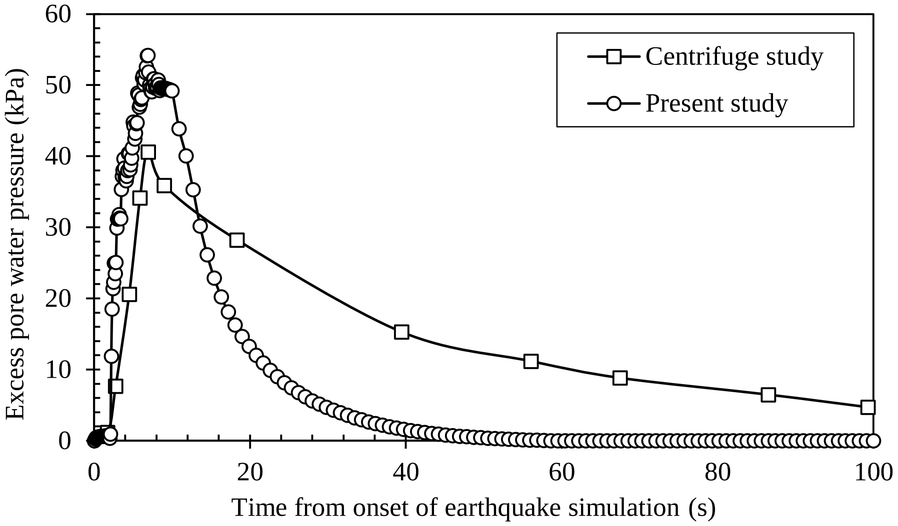

Fig. 4. Comparison of excess pwp between centrifuge and numerical model: Point P5 [11]

3 Numerical Modelling of Liquefaction Induced Settlement post Ground Densification

After the validation of the developed numerical model, the effectiveness of ground densification in decreasing the seismic liquefaction induced settlement of footings has been subsequently investigated by incorporation of a uniform densified layer of relative density 85%, as presented in Figure 7. The material properties used for the densified layer are presented in Table 4 [12,13,14,15]. The same cyclic loading was applied in this case which was used during validation study.

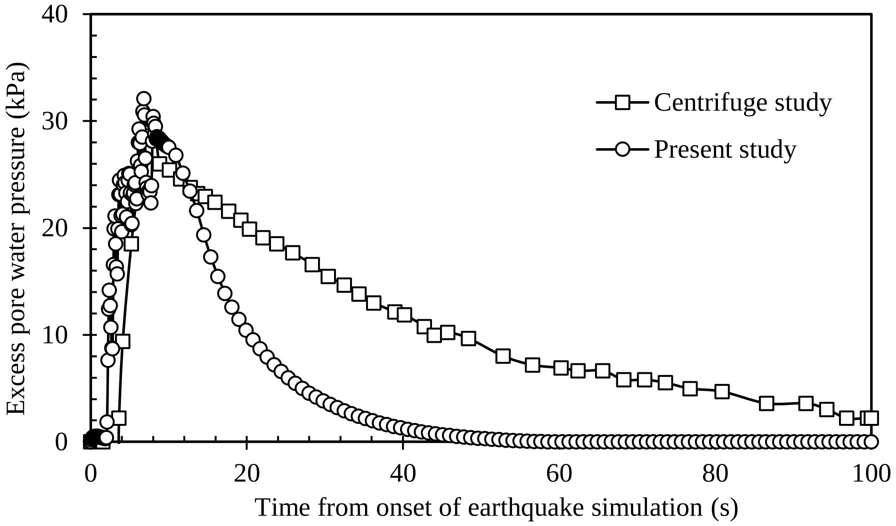

Fig. 5. Comparison of excess pwp between centrifuge and numerical model: Point P8 [11]

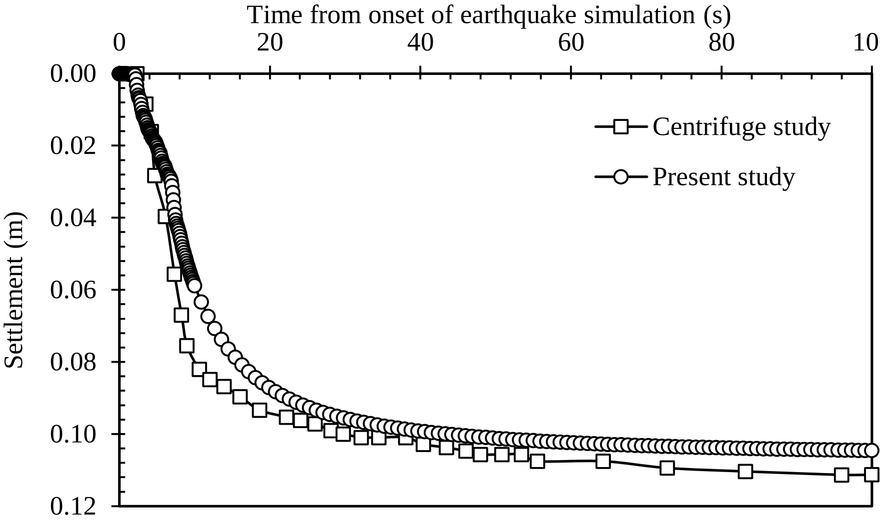

Fig. 6. Comparison of settlement values between centrifuge and numerical model: Point D [11]

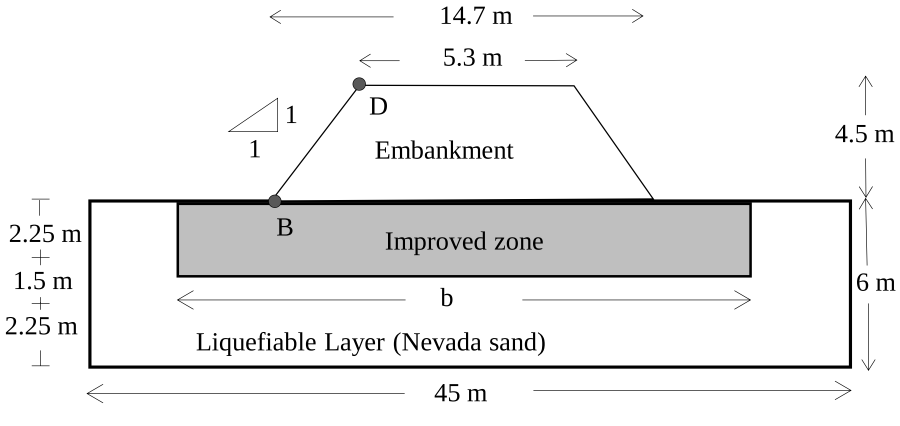

Fig. 7. Modified geometry considering the incorporation of an improved zone

Table 4. Material properties of the densified layer

Material property	Notation	Units	Densified layer (RD = 85%)
Corrected SPT value	$(N_1)_{60}$	-	30
Elastic shear modulus number	K^e_G	-	1331.89
Elastic bulk modulus number	K^e_B	-	932.32
Plastic shear modulus number	K^p_G	-	3460.35
Failure ratio	R_f	-	0.66
Peak friction angle	ϕ_p	(°)	41.1
Constant Volume friction angle	ϕ_f	(°)	35.3
Initial Void ratio	e	-	0.57
Saturated unit weight	γ_{sat}	kN/m^3	20.26
Elastic shear modulus number	m_e	-	0.5
Elastic bulk modulus number	n_e	-	0.5
Plastic shear modulus number	n_p	-	0.4
Densification factor	f_{dens}	-	1
Post liquefaction factor	f_{post}	-	1

In the next case, the width (*b*) and depth (*d*) of the densified layer (Figure 7) are varied for different cases, and the resultant effect has been investigated on the settlement of foundation soil. The width of densified area has been varied from 15-m to 18 m and the depth of densified area has been varied from 1 m to 3 m. Figure 8 and Figure 9 depict the variation of settlements with change in the depth and the width of the improved zone, respectively. It can be observed that with an increase in the depth of the densified layer, the settlement magnitudes decrease. However, there is negligible variation in settlement with change in the width of the densified layer. Additionally, varying magnitude of loading has been considered on the footing by varying the height of the imposed loading (*h*). The magnitude of surcharge considered in the analysis are 20 kPa, 50 kPa and 100 kPa. Figure 10 presents the variation of liquefaction induced settlement with change in surcharge magnitude. It is evident from Figure 10 that an increase in surcharge loading can significantly increase the liquefaction induced ground deformations and the consequences thereupon can be detrimental.

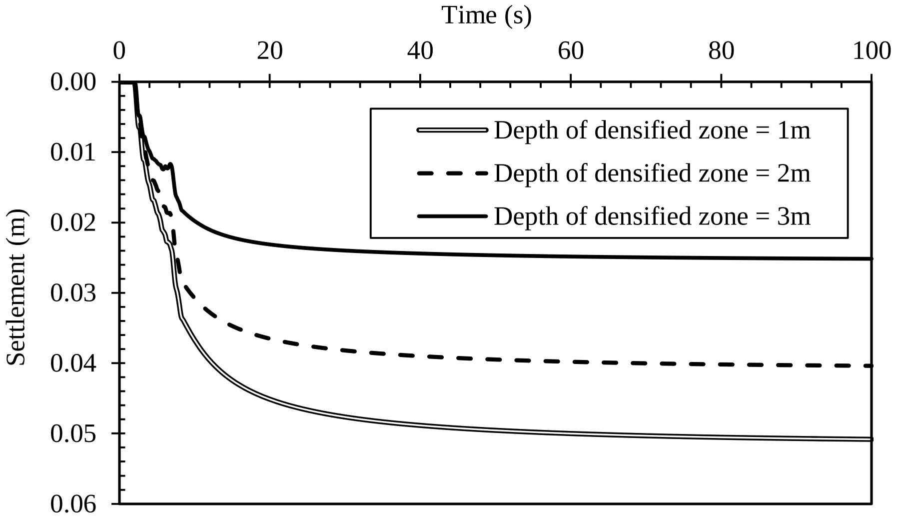

Fig. 8. Variation of settlements with change in the depth of the improved zone

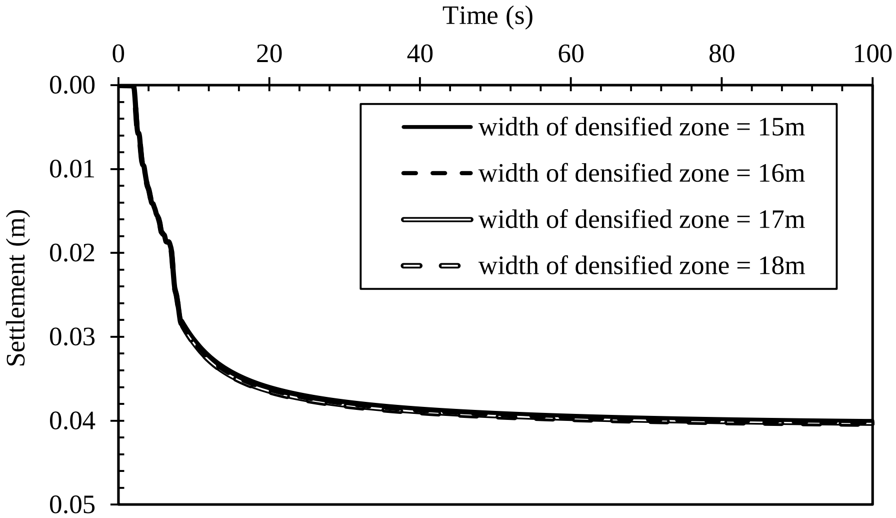

Fig. 9. Variation of settlements with change in the width of the improved zone

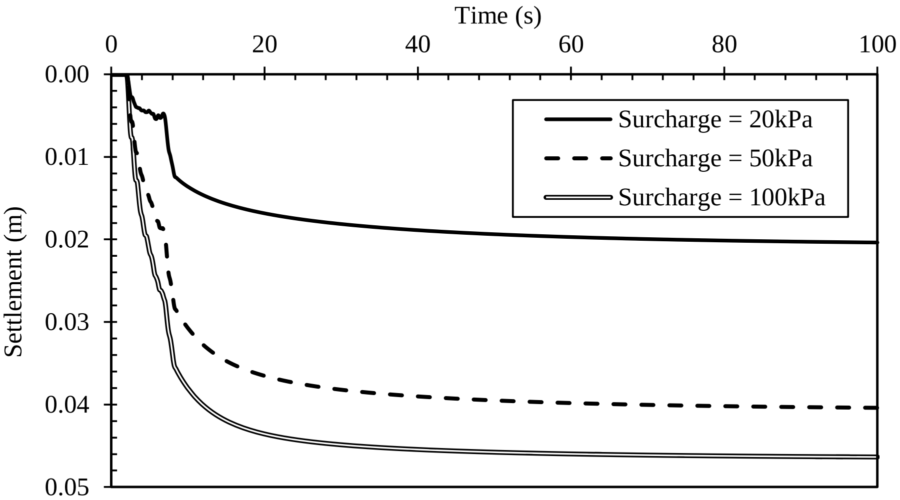

Fig. 10. Variation of settlements with surcharge load

4 Regression Analysis

Based on the data obtained from numerical study, regression model has been developed to predict the effect of surcharge loading on the liquefaction induced peak settlements (at point B in Figure 7) in embankment foundations. The effect of width and depth of compaction has also been incorporated in this analysis. The independent variables include depth of compaction (*d*), width of compaction (*b*), and surcharge load (*P*) and their effect is observed on liquefaction induced peak settlement (Δ). Multiple regression analysis is performed using the log-linear model. The hypothesis for the non-linear model is:

$$\Delta = x_0 \, (d)^{a1} \, (b)^{a2} \, (P)^{a3}$$

where Δ is the liquefaction induced peak settlement, d is depth of compaction, b is width of compaction, P is surcharge load, x_0, a_1, a_2, and a_3 are the constants. The non-linear model is transformed to linear model as follows:

$$\log(\Delta) = \log(x_0) + a_1[\log(d)] + a_2[\log(b)] + a_3[\log(P)] = X_0 + a_1D_l + a_2B_l + a_3P_l$$

where $X_0 = \log(x_0)$, $D_l = \log(d)$, $B_l = \log(b)$ and $P_l = \log(P)$. The equation obtained after regression analysis is:

$$\Delta = 0.00677P^{0.60} / d^{0.73}\, b^{0.11}$$

Where Δ is peak settlement in meters, d is depth of compaction in metres, b is width of compaction in metres and P is the surcharge load in kPa. Figure 11 presents the comparison between the settlement predicted from proposed formula and settlement obtained from numerical analysis (m), which are observed to be in good agreement, as they lie in the vicinity of the line having an inclination of 1V:1H. Moreover, the regression coefficient (r^2 value) obtained in this study is 0.87, indicating good acceptability of the fitted data.

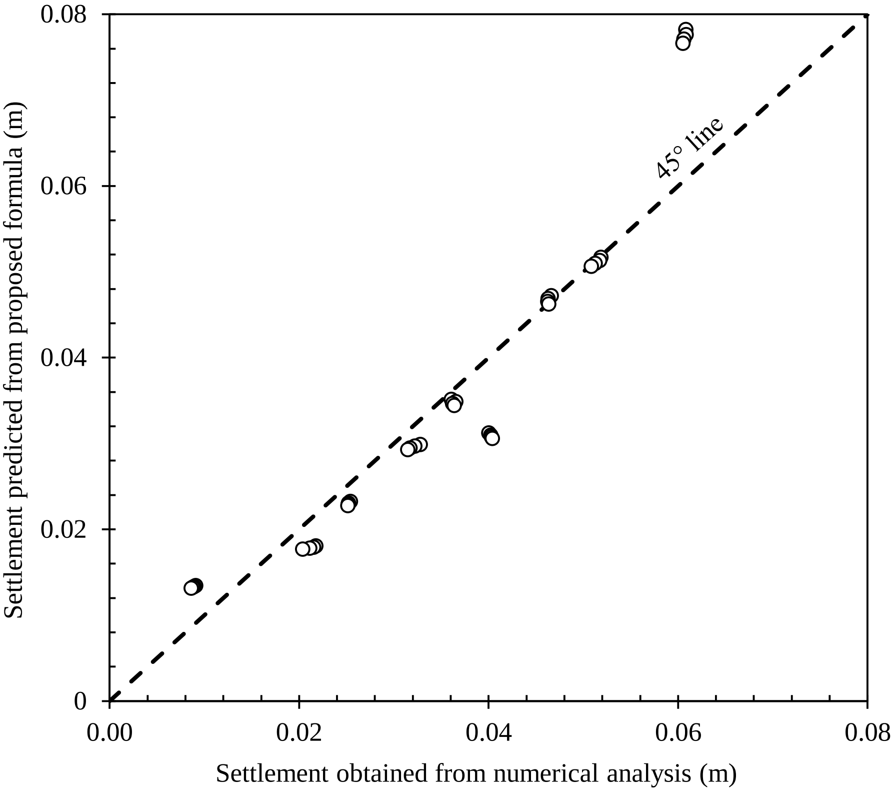

Fig. 11. Results of Regression Analysis

5 Summary and Conclusions

In this study, the effectiveness of ground densification on liquefaction induced settlements in embankment foundations has been studied. Two-dimensional finite element software, PLAXIS 2D, has been used to model liquefaction behaviour of soils. PLAXIS inbuilt constitutive law UBC sand model, has been used to model the foundation soil. A centrifuge model study has been replicated numerically to validate the developed numerical model. The effectiveness of ground densification in decreasing the seismic liquefaction induced settlement of footings has been subsequently investigated over a range of depth and width of densified zone expressed as a function of the footing geometry and varying magnitude of loading on the footing. The numerically obtained results have been utilized for developing a power regression model to quantify the improved settlement response of strip footings resting on ground remediated by densification. The following major conclusions can be drawn from this study:

- Owing to the incorporation of the densified zone, the liquefaction induced settlements decreased by as much as 90% as compared to the unimproved ground.
- With an increase in the depth of densified layer, the liquefaction induced settlements decreased progressively. On increasing the depth of compaction from 1 m to 4 m, the settlements decreased from 32.8 mm to 9.1 mm.
- An increase in the width of the densified layer was observed to have negligible impact on liquefaction induced settlements.
- With increase in surcharge loading, the foundation settlements were observed to increase. Upon increasing the surcharge load from 20 kPa to 100 kPa, the settlements increased from 32.8 mm to 60.8 mm.

The above study thus indicated that the dimension of the improved zone and magnitude of surcharge are the most significant factors influencing liquefaction-induced settlements. The utility of this study is to aid in decision making in the field regarding the implementation of ground densification as a liquefaction mitigation technique. The study can be further extended by considering the influence of non-uniformity of densified zones as well as the geometry of overlying surcharge, including its height, width and inclination.

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