Compaction grouting – A Ground Improvement Technique Against Liquefaction

Neha Shrivastava
Department of Civil Engineering
Swami Keshvanand Institute of Technology Management & Gramothan, Jaipur,
Email- neha.geotech@gmail.com

Received 18 January 2017, received in revised form 27 January 2017, accepted 05 February 2017

Abstract: **Compaction grouting (CPG) also known as static compaction is relatively a new ground improvement technique against liquefaction. In this technique, a stiff mortar is injected under high pressure that displaces and compacts the surrounding soil. Since 1990, CPG has been implemented successfully in many projects throughout the world with ground improvement as the major objective. This paper presents a laboratory experimental study to quantify the impact of CPG in liquefaction resistance. Design charts are obtained in terms of the liquefaction resistance parameters of CPG due to its densification, confining and combined densification and confining effects, and for different initial ground conditions.**

Keywords: **compaction grouting, density, earth pressure, ground improvement, liquefaction.**

1. INTRODUCTION

The term liquefaction is defined as 'The state existing when saturated sandy soil loses shearing strength and effective stress are reduced as a result of increased pore water pressure is called liquefaction' [1]. Causes for the rise of pore water pressure include fluctuations of ground water table in addition to the repeated action of shear stresses on saturated sandy soil during earthquakes [2]. The ground where the liquefaction phenomenon occurs is generally composed of loose sandy soil saturated with water. If such ground is subjected to stresses caused by earthquake motion, the pore water rises in the soil, and the effective stresses in the soil are lost, then the strength of soil is eventually lost. For majority of the civil engineering works, such ground need to be treated against liquefaction by means of some suitable ground improvement technique.

2. COMPACTION GROUTING – A GROUND IMPROVEMENT TECHNIQUE

Compaction grouting (CPG) involves the injection of high viscosity mortar–type grout under relatively high pressure which does not permeate into pores but rather displaces and compacts the soil in-place.

2.1 Scope of Application of Compaction Grouting

Compaction grouting can be applied to densify all sandy soils. Since its features include static densification through pressurized injection and the use of compact ground equipment, the method can be applied for liquefaction remediation of existing structures as well as of new structures with constricted work spaces. Specially, the scope of application is: 1) Backfill of existing quay walls; 2) Prevent settlement by remediating liquefiable soils underneath runways which are in service; 3) Underground existing oil storage tanks; 4) Prevent floating and tilting of underground structures by remediating liquefiable soils; 5) Prevent river embankment settlement and failure by remediating liquefiable soils.

3. NATIONAL AND INTERNATIONAL STATUS

The dynamic compaction methods such as sand compaction pile (SCP) cause heavy vibration during execution of work and large displacement in adjacent soil zones in the ground. If there are important structures around an area of ground improvement work, those methods cannot be adopted. Compaction grouting (CPG) may be suitable under such circumferences. Some of the available researches and the case histories especially related to liquefaction remediation are reported in the following sections.

3.1 International Status

Although CPG has been developed in the United States for quite some-time now, the scope of application of this method has expanded substantially as a result of rapid modification of equipment and technique for injecting very stiff grout. Aside from the United States, this technique has also become popular in Europe. This technique has been introduced in Japan in 1989, after which there has been steady increase in the number of cases where the technique has been implemented.

Boulanger et al. (1995) [3] review the available case history data on the treatment of liquefiable soils by compaction grouting to provide observation that are useful in evaluating the effectiveness of future compaction grouting applications. Observations are made on practical aspects such as the effect of construction procedures on treatment effectiveness, the types of soil effectively treated and issues in in-situ testing for quality control. It is concluded that significant increases in penetration resistance were achieved in soils ranging from silty sand to silt. The grout required to produce a specified increase in penetration resistance (near treatment grid centers) have been consistently greater than expected based on simple design calculations that assume a uniform distribution of volumetric strains.

Tamura et al. (1996) [4] emphasis that to achieve that desired ground improvement from compaction grouting, the grout must be injected precisely in accordance with the plan. They carried out experiments to investigate the relationship between the final form the grout and the grouting conditions.

Yamaguchi el al. (2000) [5] applied the compaction grouting to an actual ground and proposes a design and construction method for its application. In their field study, the CPG was found to be effective in increasing the N–value, soil density and the cyclic stress ratio. The design method proposed was based on a principle similar to that for the design method of SCP.

Compaction grouting involves the injection of stiff mortar grout that does not penetrate the ground (Kovacevic et al. 2000) [6]. It is applied to free-draining granular soils. If the soil is not sufficiently permeable for consolidation to occur as it is treated, excess pore pressures may be generated, which will dissipate after treatment. The potential effect of such excess pore pressures on the compaction achieved is considered and is found that the efficiency of treatment may be reduced substantially.

Zen et al. (2003) [7] carried out an experimental study at Tokyo International Airport to determine and compare pre and post–CPG coefficient of lateral earth pressure at rest, K0 and to establish a design method for CPG that takes into account such increased coefficient K0. Standard penetration test (SPT), density log in borehole and self boring pressure meter test (SBP) were carried out to measure depth wise N–values, bulk density and coefficient K0 respectively. A relatively good correlation was observed between the increment in the K0 and the N–value. The K0 values measured after three years from application of CPG were reported as high as those immediately after its application.

Nakazawa et al. 2010 [8], describes the effect of countermeasures for liquefaction by compaction grouting, which was investigated by the experiment of full-scale field liquefaction by controlled blast technique. The experiment was conducted to assess the performance of airport facilities subjected to liquefaction, to investigate damage mechanism, and to estimate the effect of countermeasures for liquefaction by compaction grouting applied to liquefiable sand layer under runway pavement. In this study, before and after grouting and after artificial liquefaction caused by in-situ blasting, self boring pressure-meter tests at the center and the edge of a grouted area were carried out to investigate the coefficient of earth pressure, K, for evaluation of the improved ground because it is generally known that compaction grouting makes K-value increase in and around the grouted area. Additionally, to estimate the continuation of improving effect after liquefaction, K-values after blast were also investigated at same points. As the results of investigation, it was found that post-liquefaction K-value was higher than that of untreated ground before improvement and compaction grouting with cost-reduction design examined in this study, that is, the cost-reduction design is effective.

Nishimura et al. (2011) [9] presents a study to investigate characteristics of the stress changes by simulating compaction grouting processes in a geotechnical centrifuge. The observed increases in the horizontal stresses, evaluated in terms of earth pressure coefficient, K, reflected the influence of grout pile spacing, and were found to be consistent with field measurements except near the surface. The centrifuge tests also allowed the changes in the dominant stress direction within the horizontal planes at the stabilized domain's centre to be evaluated, with the results indicating the dependency of the stress changes upon depth and interactions between neighboring grout piles. The significance of the stress changes in increasing the liquefaction resistance is demonstrated by mapping liquefaction curves against stress states through a series of cyclic hollow cylinder simple shear tests.

3.2 National Status

International Geotechnical Contractor, Keller Ground Engineering India Pvt Ltd. (www.kellerfareast.com), [10] reports densification of loose soils by compaction grouting to facilitate NATM tunnel construction for DMRC, New Delhi. As a part of Phase II, expansion of Metro network, Delhi Metro Rail Corporation (DMRC) is building a metro corridor connecting Central Secretariat and Qutub Minar. New Austrian Tunneling Method (NATM) was adopted to construct the proposed tunnels. The presence of loose filled up sandy soils over a stretch of 100 m near Saket station (BC 19C package) posed problems with effective soil arching which is required for NATM construction.

Compaction Grouting was adopted to enhance the densities of loose sandy soils to form effective arching. The proposed site consists of Sandy Silt fill up to 5m depth, followed by Delhi Silt alluvium layer with bed rock (Quartzite) at a depth of about 26m. The compaction grouting technique is proposed to increase the SPT – N values in the existing loose soils above the tunnel crown level to facilitate the soil arching effect for NATM construction. In general, site execution constitutes of drilling, installation of stinger rods & pumping the grout mix. A truck mounted hydraulic drill rig is used to drill a nominal diameter hole of 90mm to a depth of about 8m through the overburden soils. After completion of drilling process, the grout mix is pumped through the stinger rods, to form a bulb like element in the loose soils, in stages (0.5 m each) from bottom to the top of the working platform. Field trials were carried out to establish suitable grid pattern for main works. Pre and Post treatment tests were carried out to assess the performance of compaction grouting works. The Post SPT results are well above the design requirements.

From the review of the some latest available data, CPG is found to be effective in treatment of liquefiable soil. Although significant increases in penetration resistance were achieved in soil ranging from sand to silt, the mechanism of CPG are not well understood presently which lead to a reduced reliability of treating liquefiable soil by this technique. This research presents a laboratory experimental study of CPG that may lead to reveal the liquefaction resistance of CPG.

4. EXPERIMENTAL STUDY

4.1 Grout Mix

The grout mix of CPG should be prepared in appropriate consistency meeting the requirements of GPG. It should have good pumpability, low segregation and should be of very low mobility. The gradation of the mineral aggregate used in the grout is developed in conjunction with the recommendations of Warner and Brown (1974) [11] and Nichols and Goodings (2000) [12].

Mini slump tests and flow tests are performed on the several mixes of mineral aggregate, cement and water. The composition of the grout mix with slump value of 28.6 mm (Table 1) and flow test value of 179.3 mm (Table 2) which indicate a low degree of workability is considered as grout mix for experimental CPG.

Table 1: Mini Slump Test

I Test	27.9
II Test	29.3
Average	28.6

Note: Test values are in mm.

Table 2: Flow Test

	— Axis	⊥ Axis	Average
I Test	181.3	179.5	180.4
II Test	178.4	177.9	178.2
Note: Test values are in mm.			179.3

4.2 Description of the Apparatus and the Procedure involved

Figure 1 shows the schematic diagram of laboratory CPG apparatus. Injection pipe of CPG apparatus is designed having slits throughout its length. This design would ease grout to come from injection pipe in a regular manner without choking the injection pipe. First of all, a sand ground of constant relative density is constructed by pouring the sand in a free flow fashion for a specified height. Displacement and earth pressure gauges are set at different radial distances during the formation of the ground. After the formation of the model ground a uniform air pressure is applied through a rubber sheet to serve as an overburden pressure and thus to prevent up-heaving of the ground. The grout mortar is injected under high pressure with the help of a speed control injection machine at the top end of the injection pipe. The grout comes from the silts of the injection pipe under high pressure, displaces and thus compacts model ground in a regular shape.

5. LIQUEFACTION RESISTANCE BY COMPACTION GROUTING

Many researchers and engineers around the world have made efforts to understand the mechanism of liquefaction and to establish design codes/standards to overcome the disaster caused by seismic-induced liquefaction.

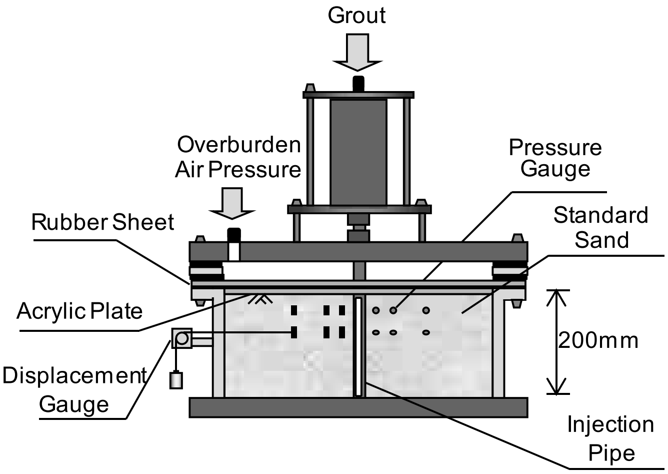


Figure 1: Laboratory Compaction Grouting Apparatus

In compaction grouting (CPG), the methods used in evaluating liquefaction potential have been based on the grain size distribution curve and SPT (Standard penetration test) N-value or laboratory cyclic tri-axial tests. The liquefaction resistance of the CPG treated ground can be predicted as follows:

The factor of safety against liquefaction, F_L, is usually described as

$$F_L = R/L \quad (1)$$

where L is shear stress ratio induced by earthquake has given by various seismic design codes e.g. Specifications for Technical Standards for Port and Harbor Facilities and Commentaries and Highway Bridges (1999) [13] based on design horizontal seismic coefficient.

and R is the cyclic shear strength ratio. It is estimated either from *in situ* tests or from laboratory tests.

The Japanese Highway Bridge Specifications (1996) [14] based on design horizontal seismic coefficient has also given F_L by the following expression:

$$F_L = \frac{R_{\max}}{L_{\max}} = 0.9 \cdot \frac{1}{C} \cdot \frac{1+2K_0}{3} \cdot \frac{R_{20}}{L_{\max}} \quad (2)$$

where R_{20} is the shear stress ratio with which liquefaction occurs after 20 cycles of loading and has been correlated to the relative density D_r of the ground as:

$$R_{20} = 0.0042 D_r \tag{3}$$

From the above expressions, in general, it may be assumed that $R \propto D_r$ and also $R \propto (1 + 2K_o)/3$

Thus combined relation of D_r and K_0 with shear strength ratio, R, is

$$R \propto D_r \times (1 + 2K_o)/3 \tag{4}$$

It is assumed that the liquefaction resistance of the CPG treated ground, R_1 is R_{CPG} times of its pre-CPG value, R,

$$R_1 = R.R_{CPG} \tag{5}$$

where R_{CPG} may be conveniently defined from the Eq. 4 as

$$R_{CPG} = \frac{D_{r_I} \times \{(1 + 2K_o)/3\}_I}{D_{r_o} \times \{(1 + 2K_o)/3\}_o} \tag{6}$$

$$= R_{D_r}.R_K$$

R_{Dr} is increase in liquefaction resistance due to increase in relative density of the original ground and R_K is the same due to increase in coefficient of lateral earth pressure at rest, K_0, of the original ground.

In the following sections, design charts are obtained in term of the liquefaction resistance parameters of CPG due to its densification, R_{Dr}, confining, R_K, and combined densification and confining effects, R_{CPG}, and for different initial ground condition.

6. RESULTS AND DISCUSSION

Experiments were carried out with the conditions as given in Table 3. Grout was injected controlling its volume, V_G, and earth pressures and radial displacements were noted. Six number of experiments, from Ex. No 1 to 6 are considered in this study. Ex. No. 1 to 3 and other 4 & 5 were performed in similar conditions, hence grouped together in this session.

Table 3: Experimental Variables and Liquefaction Resistance Parameters

Experiment No.	1, 2 & 3	4 & 5	6
	Variables		
Relative density of ground Overburden pressure (kPa) Volume of grout, VG (cm3)	60 % 50 500 (1.3%)	40 % 50 500 (1.33 %)	40 % 50 750 (2.0 %)
	Liquefaction resistance parameter, R_{CPG}		
Peak r/bo = 0.16	3.71	5.89	4.96
1.0	1.86	1.30	1.50
Ultimate r/bo = 0.16	3.20	3.47	2.39
1.0	1.70	1.32	1.55

Firstly, density calculations are done based on the readings of the radial displacement gauges, u. Knowing the values of relative density before CPG and after CPG due to its densification effect, density resistance parameter, R_{Dr}, is calculated as mentioned in Eq. 6. Figure 2 depicts the variation of R_{Dr} with normalized radial distance, r/b_o, for all the experiments Ex. No. 1 to 6. R_{Dr} is found atmost 1.53 at the grout–soil interface, $r/b_o = 0.16$. There is rapid fall in value of R_{Dr} with increase in radial distance and for $r/b_o > 0.5$, considerably, there is no densification resistance.

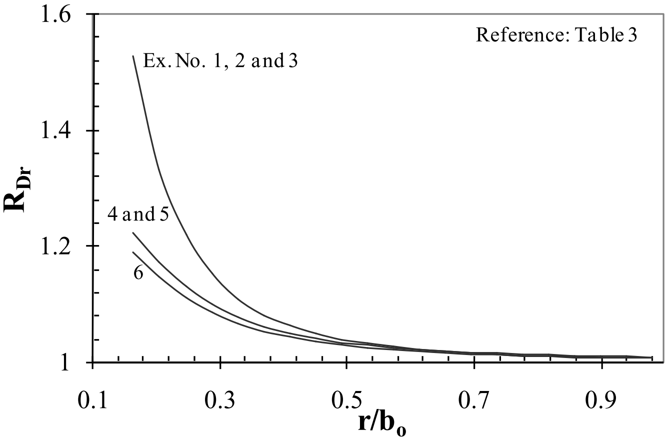
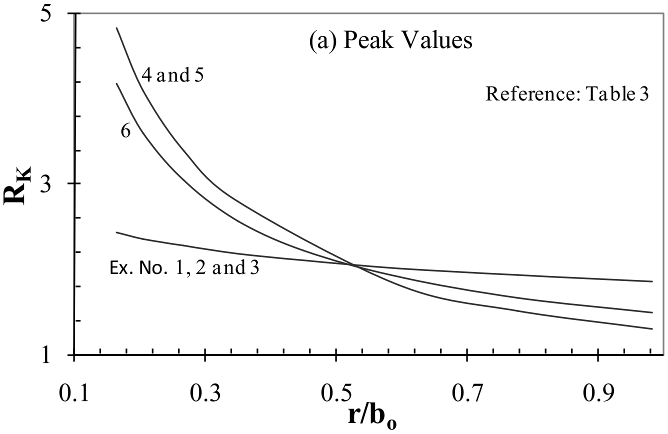


Figure 2: Variation of R_{Dr} with the Radial Distance

Earth pressure gauges were set in lateral and vertical directions. K_0 values were obtained as the ratio of the lateral earth pressure to the vertical earth pressure. R_K is calculated as liquefaction resistance parameter due to increase in relative density of the original ground (Eq. 6). As earth pressure values fall with the passage of time, both peak and ultimate values are considered in calculation of R_K.

In contrast to R_{Dr} (Figure 2), R_K is found to be effective at all the radial distances for all the experiments (Figure 3 a and b). Hence it can be said in case of CPG, study of lateral earth pressures is equally important to that of density effects. Even the ultimate values are greater than 1 in the entire region and for all the experiments.



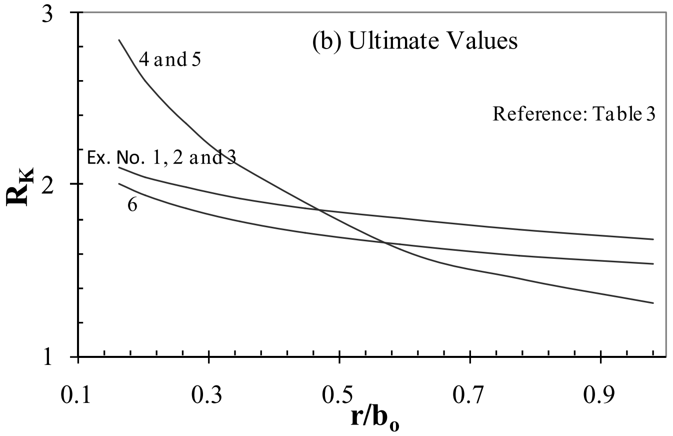
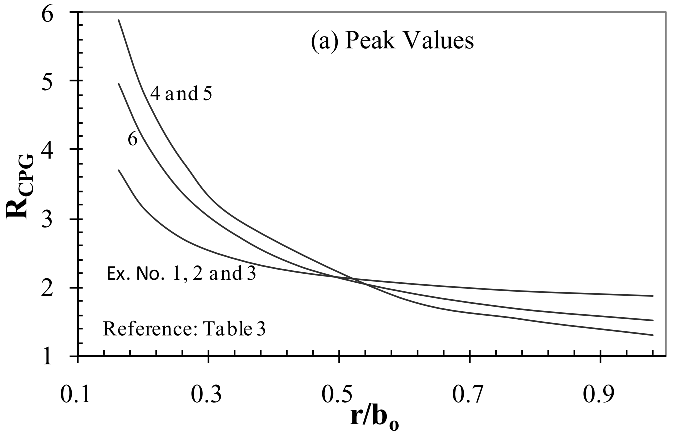


Figure 3: Variation of R_K with the Radial Distance

Liquefaction resistance parameter of CPG due to its combined densification and confining effects is named as R_{CPG} (Eq. 6). R_{CPG} value is found at least 1.5 in its entire region (Figure 4). The trends of the peak values show that the decrement in R_{CPG} from the value at closest location to the farthest location is most for Ex. Nos. 4 and 5 that are with initial % D_r = 40 % and least for Ex. Nos. 1, 2 and 3 that are with % D_r = 60 %. Hence, it can be said the maximum effect of CPG is in the loose soil at the grout – soil interface but these effects decrease with the radial distance, this decrement is relatively less in the medium soil. The peak and the ultimate values of the R_{CPG} at the closest and the farthest locations have been summarized in Table 3.

Among all the experiments, maximum of the R_{CPG} are found 5.89 and 1.86 at the radial distances, r/b_o = 0.16 and 1.0 respectively. In the vicinity of the grout bulbs, r/b_o = 0.16, R_{CPG} values fall by 86 – 48 % with time while at the outer boundaries, r/b_o = 1.0, this fall is in the range 91 – 103 %. Thus in general, it can be said that at the grouting locations at least 50 % of the improvement and at the center of the grid points (farthest locations) at least 90 % improvement may be secured.



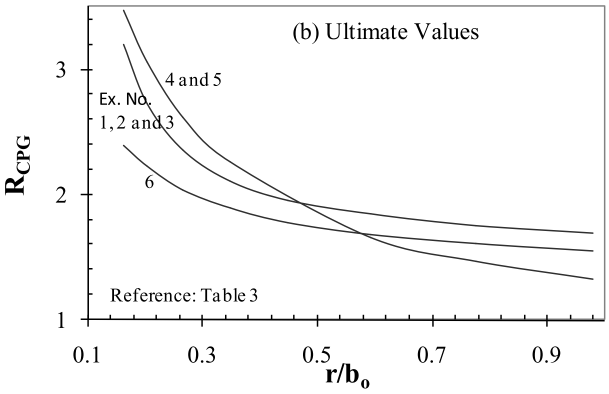


Figure 4: Variation of R_{CPG} with the Radial Distance

7. CONCLUSION

In this paper, liquefaction resistance of CPG as a parameter R_{CPG} has been predicted based on the experimental studies. The present study can be summarized with the following findings:

1. The liquefaction resistance due to increased density of the ground, R_{Dr} is found at most 1.53 at the grout–soil interface and at the normalized radial distances greater than 0.5, it was negligible.
2. The resistance due to increased K_0 was found to be effective at all the radial distances and for all the experiments.
3. R_{CPG} value is found at least 1.5 in its entire region. Among all the experiments, maximum of the R_{CPG} were found 5.89 and 1.86 at the normalized radial distances equal to 0.16 and 1.0 respectively.
4. The maximum effects of the CPG are in the loose soil at the grout – soil interface but these effects decrease with the radial distance and this decrement is relatively less in the medium soil.

In general, at the grouting locations at least 50 % of the improvement (R_{CPG}) and at the center of the grid points (farthest locations) at least 90 % of the improvement may be secured with the passage of time.

REFERENCES

[1] The Japan Society of Soil Mechanics and Foundation Engineering (JSSMFE) (1985). *Dictionary of Soil Mechanics and Foundation Engineering*, pp 140.

[2] Zen, K. & H. Yamazaki (1990). Mechanism of Wave-induced Liquefaction and Densification in Seabed, *JSSMFE Proc*. 30(4): 90-104.

[3] Boulanger, R.W. and Hayden, R.F. (1995). Aspects of compaction grouting of liquefiable soil. *J. of Geotech. Engg.*, ASCE, 121(12), 844-855.

[4] Tamura, M., Shibata H., Jinnai, N., and Kobayashi, K. (1996). Basic test of low mobility grout for compaction grouting. *Grouting and Deep Mixing, Yonekura, Terashi & Shibazaki (eds) 1996 Balkema, Rottedam.* ISBN 90 5410 805 3.

[5] Yamaguchi, S., Kozawa, D., Arata, M., Matsumoto, H., Taki, M. and Kanno, Y. (2000). Design and construction method of compaction grouting as a ground-improving technique against liquefaction. *Coastal Geotechnical Engg. in Practice, Nakase & Tsuchida (eds) 2000 Balkema, Rotterdam,* ISBN 90 5809 151 1.

[6] Kovacevic, N., Potts, D.M. and Vaughan, P.R. (2000). The effect of the development of drained pressure on the efficiency of compaction grouting. *Geotechnique*, 50(6), 683-688.

[7] Zen, K., Ikegami, M., Masaoka, T., Fujii, T. and Taki, M. (2003). Research on the coefficient of earth pressure at rest (K_0) for a CPG improved ground. *Soft Ground Engineering in Coastal Areas, Tsuchida et al. (eds) 2003 Swets & Zeitlinger, Lisse,* ISBN 90 5809 613 0.

[8] Nakazawa, H., Sugano, T., Shinsaka, T., Adachi, M. and Yamada, K. (2010). Investigation of the coefficient of earth pressure for improved ground by compaction grouting in the full-scale field liquefaction experiment. *Fifth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics and Symposium in Honor of Professor I. M. Idriss,* May 24-29, 2010, SanDiego, California.

[9] Nishimura, S., Takehana, K., Morikawa, Y. and Takahashi, H. (2011). Experimental study of stress changes due to compact grouting. *Soils and Foundations*, JGS, 51(6), 1037-1049.

[10] Keller (2009). Densification of loose soils by compaction grouting to facilitate NATM tunnel construction for DMRC, New Delhi http://kellerindia.com/pdf/Grouting/NATM%20tunnel%20construction.pdf?...

[11] Warner, J., and Brown, D. R. (1974). Planning and performing compaction grouting. *J. of Soil Mech. and Found.*, ASCE, 100(6), 653-666.

[12] Nichols, S. C., and Goodings, D. J. (2000). Physical model testing of compaction grouting in cohesionless soil. *J. of Geotech. and Geoevviron. Engrg.*, ASCE, 126(9), 848-851.

[13] Japan Port and Harbor Association (1999). *Technical Standards for Port and Harbor Facilities and Commentaries*. (in Japanese)

[14] Japan Road Association (1996). *Specifications for Highway Bridges: Part V – Earthquake Resistant Design*. (in Japanese)

◆ ◆ ◆