Journal of Science and Technology in Civil Engineering, NUCE 2020. 14 (3): 53–66

POINT FOUNDATION (PF) METHOD: PRINCIPLES AND RECENT RESEARCH FINDINGS

Myoung Su Jo[a], Ki Tae Lee[a], Ho Deok Kang[b], Hong Bum Cho[b], Tien Dung Nguyen[c,*]

[a] *R&D Center, EXT Co. Ltd, Seoul, Korea*
[b] *R&D Center, Lotte E&C, Seoul, Korea*
[c] *Master Program in Infrastruction Engineering, VNU Vietnam Japan Univeristy, Luu Huu Phuoc street, Nam Tu Liem district, Hanoi, Vietnam*

Article history:
Received 20/07/2020, Revised 17/08/2020, Accepted 18/08/2020

Abstract

Conventionally, cement deep mixing (CDM) columns are designed to have constant diameters over the improved depth as this facilitates the construction procedures. However, this design pattern may be inefficient in cases of spread footings or shallow foundations. This paper first briefly introduces principles, construction procedures and quality control techniques of an innovative CDM method that can create head-enlarged column, named as Point Foundation (PF). The method is practically implemented with a specific binder that is environment-friendly and more effective in strength enhancing compared with the common binder as cement. Static load tests on three instrumented PF columns indicate that the variation trend of induced vertical stress profile along the columns in general is similar to that under the centre of shallow footings on elastic soil medium. However, the stress profile in the (semi-rigid) PF columns is larger than that in elastic soil but less than that in (rigid) PHC pile. This confirms the load transfer mechanism along semi-rigid columns like CDM/PF. Test results also indicate that at the depth of one to two times head diameters the induced stress remains just 20% the applied pressure. Findings on the trend of the induced vertical stress in the columns suggests that the settlement of common shallow footings on CDM/PF column-reinforced grounds should be evaluated using 3D condition taking into account the fact that the induced stress decreases with depth.

Keywords: ground improvement; Point Foundation (PF); tapered cross section; load transfer mechanism; load-settlement behavior.

https://doi.org/10.31814/stce.nuce2020-14(3)-05

1. Introduction

The cement deep mixing (CDM) method is one of the most popular methods in ground improvement works. Details on the method such as construction procedures, necessary equipment and recommendations are described in many references or manuals [1–4]. The effectiveness and application of CDMs in Vietnam have also been researched and reported [5]. Conventionally, CDM columns are designed to have constant diameters over the improved depth as this facilitates the construction procedures. However, this design pattern is found inefficient in cases of spread footings or shallow foundations as the upper soil layers are naturally weaker than the deeper ones but are subjected to larger amount of induced stress from the superstructures (Fig. 1).

*Corresponding author. *E-mail address:* nt.dung@vju.ac.vn (Nguyen, T. D.)

To improve such drawbacks of the conventional CDM columns, head-enlarged CDM column, named as Point Foundation (PF), has been recently introduced and implemented by EXT Co. Ltd. from S. Korea. In principle, as shown in Fig. 1, a PF column typically has three sections: the bigger head, the transitional cone, and the smaller tail. The larger head section of PF columns provides a better reinforced stiffness in the upper weaker layers than the conventional CDM columns. Thus, proper designed dimensions of the columns would provide more proper stiffness profile with depth, resulting in larger bearing capacity or smaller settlement. Typical PF columns excavated in the field are shown in Fig. 2.

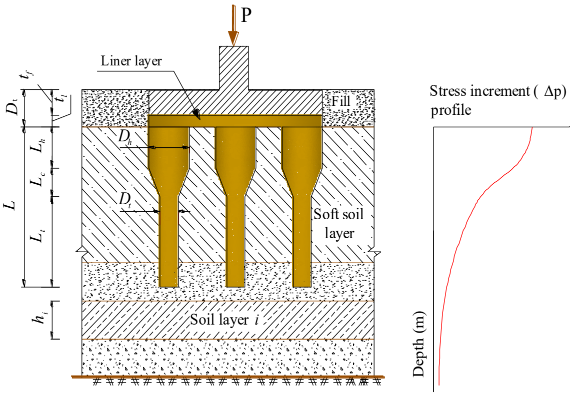


Figure 1. Concept of PF method in ground improvement

Figure 2. An example of PF columns exposed in the field

Since its first introduction to the market (2012), the PF method has been extensively applied to more than 250 projects of car parking areas, industrial buildings, and shallow foundations of transportation structures in Korea. The method has also been applied to two industrial projects in Vietnam: Haein Vina Factory, Ba Thien II Industrial Zone, Binh Xuyen District, Vinh Phuc Province and Samse Vina Factory, Cau Yien Industrial Zone, Ninh Binh City.

The principle of the PF columns in producing more proper reinforced stiffness profiles with depth is clear as mentioned above, however the actual load transfer mechanism of a single PF column and that of groups of PF columns under foundation applied pressure are mostly unfolded. Thus, EXT's engineers have conducted a number of experimental load tests on instrumented PF columns to investigate the actual load transfer mechanism of the columns and consequently to help design engineers more optimal design in bearing capacity and settlement of shallow foundation. This paper first briefly introduces principles of the PF method and advantages of the associated binder. The paper then presents some recent research findings on load transfer behavior obtained from instrumented PF columns in Korea. Finally, a brief discussion on methods for evaluating settlement of shallow footings on grounds reinforced by CDM/PF columns is provided.

2. The PF method

2.1. Principles

The PF method is essentially an innovative CDM method that is capable of installing head-enlarged columns of different head-to-tail diameter ratio (as well as head-to-tail length ratio). This innovative column shape helps optimize the stiffness profile with depth in the improved zone, leading to smaller settlement of the footings. For this the method has been patented not only in Korea but also in the US, China and Vietnam. Depending on the depth required to be improved and therefore required equipment, the PF construction method is divided into three categories: (i) PF-S for surface improvement with depth up to 3.0 m; (ii) PF-M for mid-depth improvement typically with depths of 3.0 to around 14.0 m; and (iii) PF-D for deep-depth improvement with depths of 14 to up to 40.0 m. For PF-S construction (Fig. 3(a)), an excavator and a roller are sufficient for the work. For the PF-M construction, an excavator is often used as the base machine (Fig. 3(b)), whereas for the PF-D construction a larger boring machine, which is often used in the deep mixing, should be used (Fig. 3(c)). The mixing shaft consists of three sections assembled: the head, the tail, and the bit. The length of blades for the tail section is constant whereas that for the head section varies in the form of a truncated cone. In actual projects, the length of the tail section is adjusted to be equal to that of the PF tail and the screw-down of the mixing shaft until the design depth would form the head section to have a required length. The grout is injected (through some nozzles at the bit position of the shaft) and controlled through the whole mixing process until design volume of grout as well as the homogeneous condition of the mixed soil are reached.

(a) PF-S

(b) PF-M

(c) PF-D

Figure 3. PF construction methods in practice

Similar to the CDM method, the PF method can be applied to reinforce grounds under roads, industrial buildings, storage yards, and especially can be used as pile foundation for lightweight transportation structures and low-rise buildings with a maximum applied pressure up to 400 kPa.

2.2. Construction procedures and quality control

In general, construction procedures for a PF column are similar to that for a conventional CDM column. The procedures might simply be sketched as shown in Fig. 4 and are briefed as follows: (1) Move the devices into position, locate the center of the column, check the verticality of the agitation rod. At the same time, the mixed grout should be ready to inject into the ground (Fig. 4(a)); (2) simultaneously stir the soil and pump the binder to design depth at a typical speed of 2.0 m/minute (Fig. 4(b)); (3) when the drill bit reaches the design depth, move the agitation rod up and down two to three times (Fig. 4(c)) until the required homogeneity is achieved; (4) Stir and retract the agitation rod until completed (Figs. 4(d) and 4(e)).

The required stiffness of the PF columns must first be secured by pre-mixing tests in the lab. For this, soil samples taken at designated depths are mixed with the binder at different ratios to determine the minimum binder proportion that satisfies the required strength of the columns. Besides, the quality of PF columns in the field is also strictly controlled by different criteria, in which two important ones are: (1) the verticality of the mixed soil column; (2) the homogenous degree of the mixed soil.

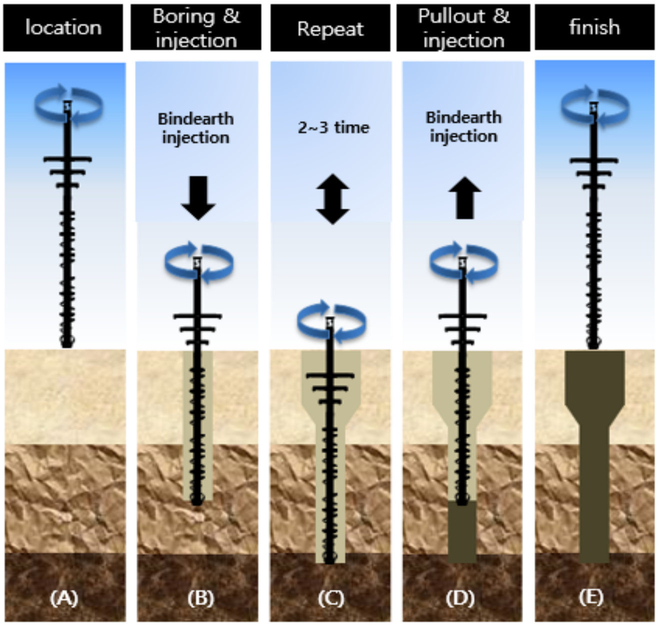


Figure 4. Typical mixing steps for a PF column

The verticality of the PF column is strictly controlled during construction with the support of a tilt sensor attached on top of the agitation rod and wirelessly connected with a digital controller attached near the operator. Thus during the operation, the machine operator can observe and control the verticality of the rod effectively. Practically, the maximum tilt is limited to be less than 1%.

One of distinct features of the PF method is that the homogeneous degree of the mixed soil in

(a) Samplers attached on rod

(b) Samplers in the field

(c) Mixed soil sample obtained

(d) Inserting PVC pipe

(e) Withdrawing PVC pipe

(f) Pieces of samples in the lab

Figure 5. Sampling methods in the field

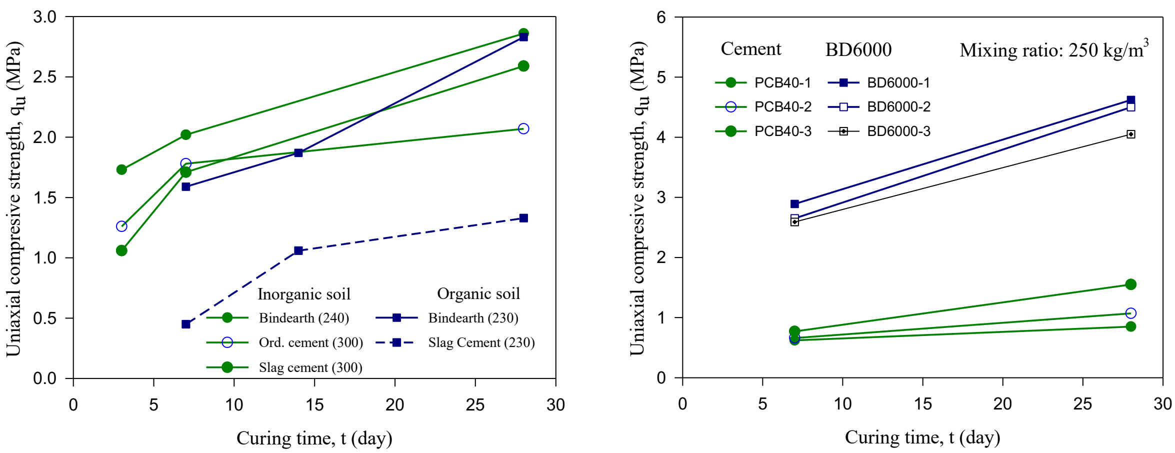
the field can quickly be checked by using a special sampling tube attached on the agitation rod to collect the mixed soil samples at specific depths (Figs. 5(a) and 5(b)). The sampling tube works as an open-ended container. The homogeneous degree of the collected soil samples (Fig. 5(c)) is examined on the surface. If the homogeneous degree is not yet reached, stirring should be executed more until the required degree reaches. Besides using the sampling tubes, PVC pipes of D = 90.0 mm are also often used to collect continuous soft core samples when the agitation is finished (Figs. 5(d) and 5(e)). Besides these two sampling methods, if required, a coring method can also be used to collect continuous samples when the column becomes stiff enough.

3. Binder characteristics

EXT has developed a special binder named Bindearth for the construction of PF method. This special binder has been certificated (by Korea Environmental Industry and Technology Institute) as an environment-friendly additive to soils and groundwater. There are two main types of Bindearth, namely, BD5000 and BD6000, in which the BD6000 is used without using any additional cement whereas the BD5000 is used with some additional cement amount.

Besides the environment-friendly characteristics, experimental data shown that soil samples mixed with the Bindearth often result in higher strength compared with that mixed with ordinary cement using the same mixing ratio. For example, Fig. 6(a) shows a comparison of unconfined compressive strength (q_u) of inorganic soil samples (collected at Songdo site, Incheon City, Korea) mixed with the BD6000, with ordinary cement and with slag-mixed cement and of organic soil samples (organic contents > 5%, collected in Hanoi, Vietnam) mixed with BD6000 and with slag-mixed cement. As shown, for the inorganic soil, the strength value of samples mixed with ordinary cement or slag-mixed cement using a mixing ratio of 300 kg/m^3 was still lower that of samples mixed BD6000 using a mixing ratio of 240 kg/m^3. For the organic soil, using the same mixing ratio of 230 kg/m^3, the strength of samples mixed with BD6000 was significantly larger than that of samples mixed with slag-mixed cement.

Fig. 6(b) shows another comparison for soil samples mixed with the BD6000 and with the ordinary



(a) Soil samples from Incheon and Hanoi

(b) Soil samples from Vinh Phuc

Figure 6. Comparison of strength of Bindearth- and cement-mixed soil samples

cement (PCB40) using the same mixing ratio of 250 kg/m^3. The clayey sand samples were excavated at 3.5 m depth from PF construction site of the Haein Vina Factory (Binh Xuyen District, Vinh Phuc Province). The laboratory test on mixed soil samples were described in detail in Nguyen et al. [6]. It is clear from the figure that the q_u value from specimens using BD6000 is typically 3 to 4 times larger than that from the specimens using PCB40 at the same age (7 days and 28 days).

4. Static load test on instrumented PF columns

4.1. Instrumented PF columns

It is clear that the CDM/PF columns are semi-rigid elements compared with common reinforced concrete piles, whose load transfer mechanism has been investigated and reported extensively in the literature. However, the load transfer mechanism in the deep mixing columns is rarely investigated in practice and the mechanism is still unclear to many engineers. In a series of researches, EXT engineers have conducted several full-scale static load tests on instrumented single PF columns. The key purposes of the load test are: (i) to verify the design bearing capacity of the columns; (ii) to investigate the trend and magnitude of vertical stress distributed along the columns, or in other words, the load transfer mechanism. Understanding the latter clearly is significantly important in verifying proper evaluation methods for bearing capacity and settlement of foundations on ground reinforced by PF columns.

(a) Configuration of a test PF column

(b) Strain gauges pre-attached to a PVC pipe

(c) Inserting strain gauges into the PF column

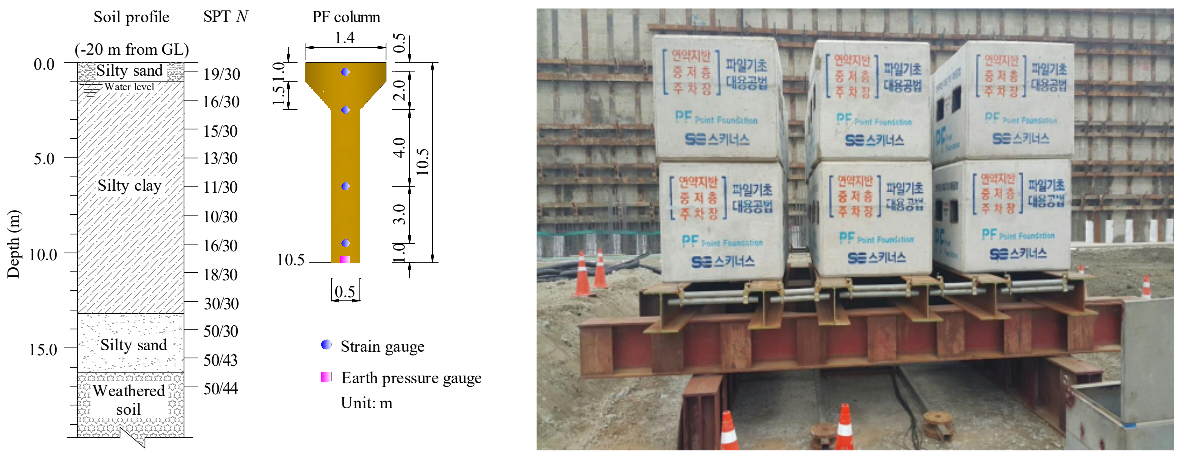
Figure 7. Construction of an instrumented PF column

Fig. 7(a) shows a typical configuration of an instrumented PF column at the construction site. Typically, strain gauges of KM-100B type are attached along a small PVC pipe at designated intervals (Fig. 7(b)) and then the sensor system is inserted into the PF body right after the completion of the agitation work (Fig. 7(c)). The instrumented columns were then left for curing. After at least 14 days, when the strength of the column gains sufficiently, static load test is then applied on the column. The following two sections describe the static load tests on three instrumented PF columns and one instrumented PHC pile at three construction sites in Korea.

4.2. Songdo site

The PF method was applied to reinforce grounds under low-rise office buildings and car parking lots in Songdo Urban Area, Incheon city, S Korea in April 2016. For this project, a total number of 2,500 PF columns, with a total length of 24,453 m, were constructed at the site. The PF columns were installed in groups under shallow footings, which were designed to have a design capacity of $q = 300$ kPa.

The soil profile and configuration of the instrumented column is shown in Fig. 8(a). Note that the depth in the profile started from the bottom of an excavation, which was −20.0 m below the original ground level (GL). The diameters of the head and the tail were 1.4 m and 0.5 m, respectively. The total length of the column was 10.5 m, in which the lengths of head, cone and tail were 1.0 m, 1.5 m, and 8.0 m, respectively. The column was formed by using the BD6000 with a mixing ratio = 220 kg/m^3 (as used for the mass columns). Four strain gauges and one earth pressure gauge were installed along the column and at the toe as shown in the figure. After 14 days of curing, the full-scale static load test was carried out on the instrumented column as shown in Fig. 8(b). For the test, a steel bearing plate of $B \times B$ = 1.0 m × 1.0 m was placed on the column head. In total, there were 8 incremental loading steps, starting from q = 75 kPa to the maximum value of q = 600 kPa. The maximum value of q = 600 kPa was selected to be equal to two times the design bearing capacity value.

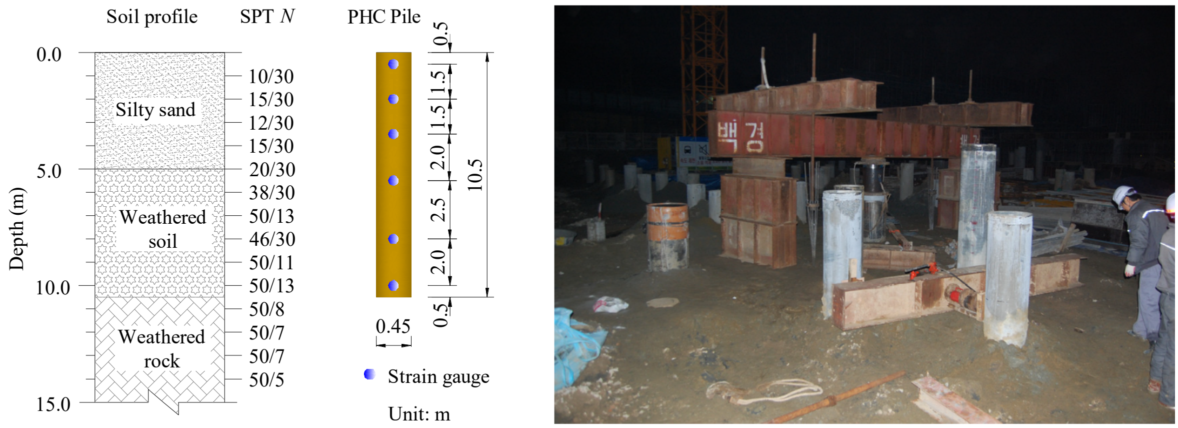


(a) Soil profile and the PF column

(b) Static load test at the site

Figure 8. Instrumented PF column at Songdo site

After the completion of the load test at Songdo site, EXT carried out a PHC piling contract at Gunpo city (Kyeonggi Province) which is approximately 30 km from the Songdo test site. Although the locations (and therefore the soil profiles) were different, the company decided to perform the static load test on an instrumented PHC pile at Gunpo site to compare the load transfer trend obtained from the PHC pile and PF column at Songdo site. An instrumented segment of PHC pile of 10.5 m long with outer and inner diameters of 0.45 m and 0.31 m, respectively, was manufactured for the test. As shown in Fig. 9(a), a total of six pairs of vibrating wire strain gauges were installed along the rebar cage of the pile before it was cast in the factory. The open-ended pile segment was then jacked into the ground at the site with the support of pre-boring method. After 14 days following the installation, the static load test was carried out on the pile as shown in Fig. 9(b). A total of 8 incremental loading steps were applied ranging from $Q = 300$ kN to the maximum value of $Q = 2400$ kN (two times the design resistance value).

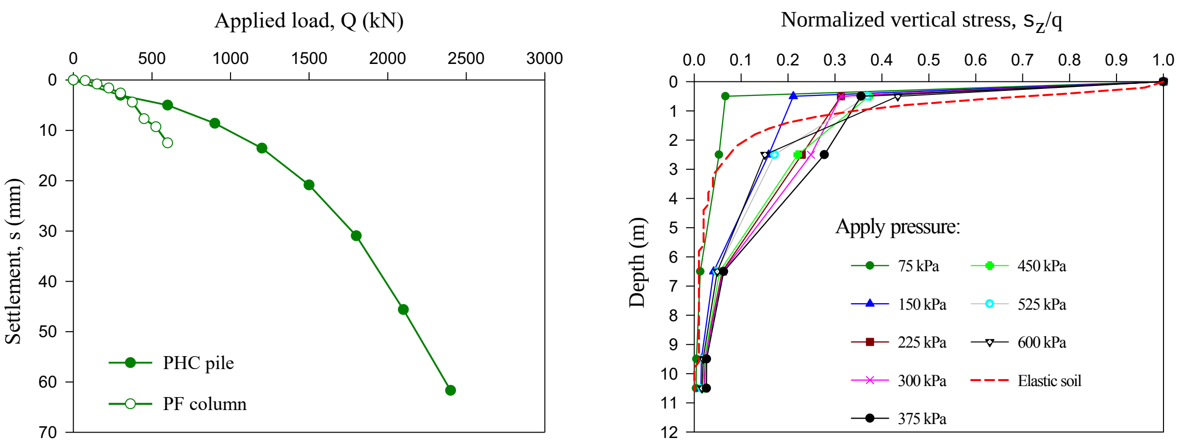


(a) Soil profile and the PHC pile

(b) Static load test at the site

Figure 9. Instrumented PHC pile at Gunpo site

Fig. 10(a) shows the load-settlement curves obtained from the tests on the instrumented PF column and PHC pile. As shown, at $Q = 600$ kN (equivalent to $q = 600$ kPa), the maximum settlement of the PF column $s_{\max} = 12.46$ mm was just half an inch (25.4 mm), the maximum allowable settlement applied to architectural structures in Korea. At the maximum applied load of 2400 kN, the PHC pile head experienced significant displacement. Fig. 10(b) shows the normalized induced stress profiles along the PF column, where q = applied pressure at $z = 0$, σ_z = induced stress (kPa) at each strain gauge level. The induced stress value ($\sigma = \varepsilon E$) was calculated using an average elastic modulus of column material $E = 507.0$ MPa (analyzed from UC test results). As shown, the normalized stress values at $z = 0.5$ m (or $z/B = 0.5$) varied from 0.43 to 0.07, indicating that the induced vertical stress at the depth remained 43% to 7% the applied pressure value at the column head. At $z = 2.5$ m



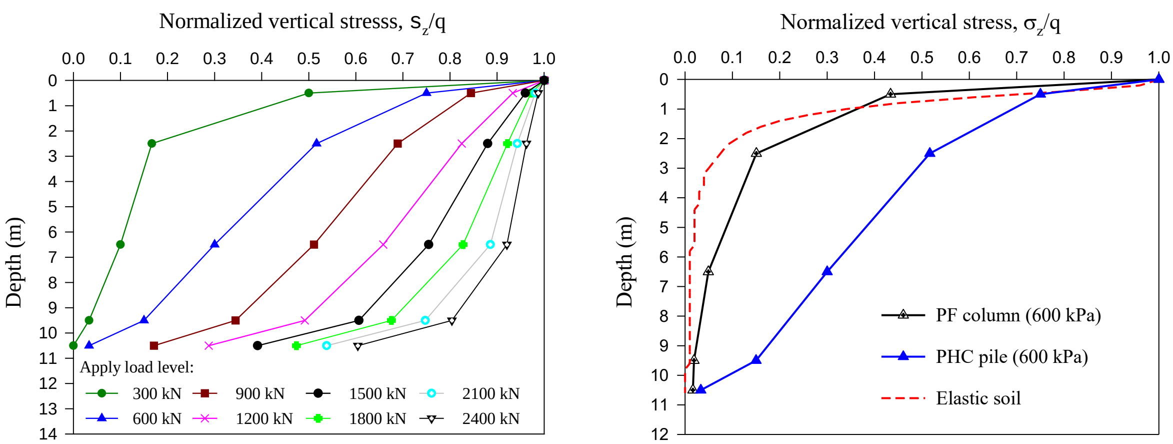
(a) Load-settlement curves

(b) Normalized vertical stress profiles

Figure 10. Static load test results on instrumented PF column at Songdo site

(or $z/B = 2.5$) the induced vertical stress remained 23% to 5% the applied pressure. The significant variation of the normalized stress values at $z = 0.5$ m and 2.5 m, especially with the applied pressures of 75 and 150 kPa, might mainly be attributed to the heterogeneity of column material and possibly to poor function of the strain gauges at these levels.

Fig. 10(b) also shows the normalized vertical stress profile under the center of an assumed square footing of 1.0 m × 1.0 m (the size of the bearing plate) placed on the surface of the theoretical half-space elastic medium. The solution of vertical stress increment ($\Delta\sigma_z$) under such footing conditions can readily be found in many reference books [7]. The stress profiles are plotted together to see how the induced stress in the column varies compared with that in the elastic medium, which is often adopted in elastic settlement analyses. It is interesting to note that, up to the depth of around $z = 1.5$ m (or $z = 1.5B$) the induced stress in the column was less than that in the elastic medium, and then the trend inverted when $z > 1.5B$. This behavior is attributed to the larger stiffness of the PF column compared with that of the soil.



(a) Normalized stress transfer curves

(b) Comparison of stress transfer curves

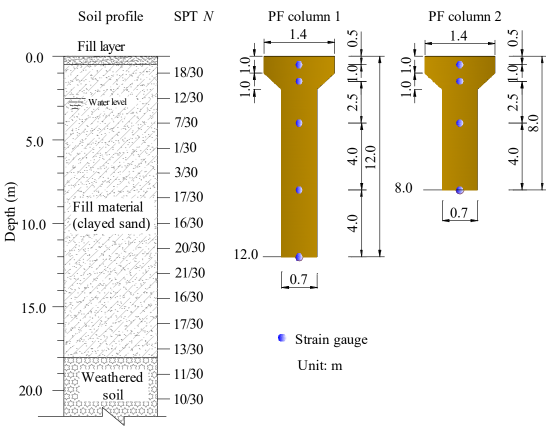
Figure 11. Static load test results on instrumented PHC at Gunpo site

Fig. 11(a) shows the normalized stress profiles along the PHC pile, in which the stress value ($\sigma = \varepsilon E$) was calculated using an average elastic modulus of pile material $E = 25.0$ GPa. The curves indicate typical load transfer mechanism in a pile: when the applied load is small, most of the load is resisted by shaft resistance (i.e., mobilized toe resistance is insignificant) and when the load increases further the shaft resistance becomes fully mobilized gradually with the increases in the mobilized toe resistance. Fig. 11(b) shows a comparison of stress transfer profiles obtained from the elastic soil medium, PF column (Songdo site) and PHC pile (Gunpo site) at the same applied pressure $q = 600$ kPa on the surface/head. As shown, at a certain depth below the head, the induced stress in the soil is less than that in the PF column (the semi-rigid one) which in turn is smaller than that in the PHC pile (the rigid one). It may be concluded that at the same applied pressure on the head, the stiffer column/pile would in general transfer a larger stress down the head. Note that since the two sites have different geological profiles, the comparison herein could indicate the trend only, not the absolute values.

4.3. Gunsan site

The PF method was applied to reinforce grounds under factory buildings in Gunsan city, Jeollabuk Province, S. Korea in Oct 2018. For this project, a total number of 3,438 PF columns, with a total length of 37,991 m, were constructed at the site. The PF columns were installed in groups of 4 to 8 under shallow footings, which were designed to have a design capacity of q = 300 kPa.

At this site, two instrumented PF columns of 8.0 m and 12.0 m long were installed as schematically shown in Fig. 12(a). Both the instrumented columns had the same head and tail diameters (1.4 m and 0.7 m, respectively) and the same lengths of head (1.0 m) and cone (1.0 m) sections. Thus, the tail lengths of the two columns were 6.0 and 10.0 m, respectively. The columns were formed by using the BD6000 with a mixing ratio = 230 kg/m^3 (as used for the mass columns). Five strain gauge levels were installed along the longer column whereas only four along the shorter one. Similar to the instrumented column at Songdo site, static load test was applied on the columns (Fig. 12(b)) after 14 days of curing when the strength of the column material soil was sufficiently ensured (by UC test in the lab). The test also used a square steel bearing plate of 1.0 m × 1.0 m on the column head. In total, there were 8 incremental loading steps starting from q = 75 kPa to the maximum value of q = 600 kPa.



(a) Soil profile and the PF columns

(b) Static load test at the site

Figure 12. Instrumented PF column at Gunsan site

Fig. 13 shows the load-settlement curves of the two columns at the site. As shown, both columns resulted in very similar settlement curves with the maximum settlement of around 6.0 mm. The similar settlement values from the column indicates that the settlement value from 8.0 m to 12.0 m of the long column was insignificant. This was because the load transferred to the section of 8.0 to 12.0 of the longer pile was insignificant. It was obvious that the maximum settlement values in these cases were just about one fourth of the allowable value (25.4 mm).

Figs. 14(a) and 14(b) show the normalized induced stress profiles along the depth of the two instrumented columns. The induced stress value ($\sigma = \varepsilon E$) was calculated using an average elastic modulus of column material E = 450.0 MPa. Note that the normalized stress values at the same strain gauge levels varied less compared with that from the Songdo site. This might come from better quality of the column (e.g., better homogeneity) as well as better preformation of the monitoring team. As shown, for both the columns, the normalized stress values at z = 0.5 m (or z/B = 0.5) varied at around 0.40, indicating that the induced vertical stress at the depth remained 40% the value at the column head. At $z = 2.5$ m (or $z/B = 2.5$) the induced vertical stress remained around 20% for the 8.0 m column and 30% for the 12.0 m column. Note from the two figures that the trend of induced stress of the 8.0 m column was slightly different from that of the 12.0 m column, as the values at 4.0 m (of the 8.0 m column) were slightly larger than the values should be. This abnormality might be attributed to poor function of the strain gauge at this depth. Similar to the trend at Songdo site, up to around $1.5B$ the induced vertical stress in the column was less than that in the elastic medium, however the trend changes oppositely when $z/B > 1.5$.

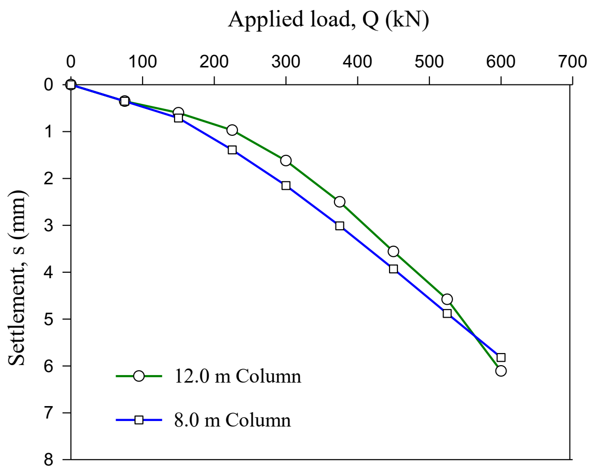
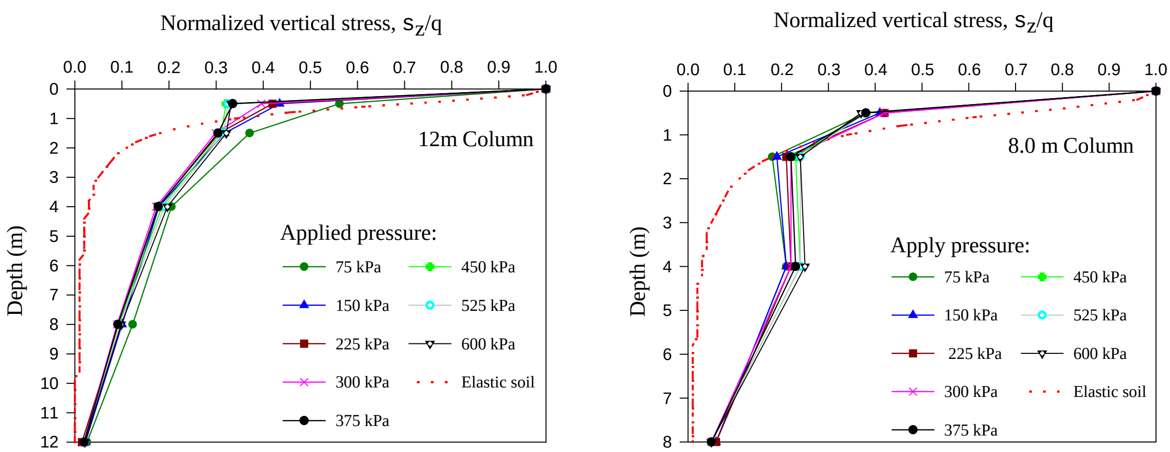


Figure 13. Load-settlement curves of the instrumented PF columns at Gunsan site



(a) 12.0 m column (b) 8.0 m column

Figure 14. Induced vertical stress profiles with depth at Gusan site

5. Discussion on methods for evaluating settlement of shallow footings on column-reinforced ground

In the literature, there haven't been reliable models/methods to calculate settlement of shallow footings on ground reinforced by CDM/PF columns. This is because, unlike the obvious case of

1D model under large embankments, the load transfer mechanism in the columns under the shallow footings are not completely understood or unified. Thus, settlement of shallow footings on reinforced grounds is often approximately evaluated by different methods depending on ground conditions and column length. Han [8] has recently reviewed three methods recommended in the literature: (i) stress reduction method; (ii) piled-raft method; (iii) column penetration method (floating type).

The stress reduction method was derived based on 1D theory, which is actually applicable under very large embankments or foundations only, not to common shallow footings. The piled raft method works based on the condition that piles are rigid elements compared to the surrounding soil. However, CDM/PF columns are semi-rigid elements having different load transfer mechanism compared with that of piles. The column penetration method is essentially based on the concept of composite foundation with assumption of 1D compression within the reinforced block and empirical stress distribution schemes under the loaded footings. It could therefore be stated that all the methods are approximate solutions to actual footings working under 3D conditions.

In Vietnam, a method for estimating settlement of footings on CDM-reinforced grounds is recommended in Vietnam National Standard: TCVN 9403 [4]. Fig. 15 illustrates the concept of the method described in the standard. Similar to the other methods, the total settlement of the footing (S_t) consists of settlement of the reinforced block (S_1) and settlement of the ground underneath the block S_2 (i.e., $S_t = S_1 + S_2$). The settlement S_1 value is evaluated using 1D strain theory.

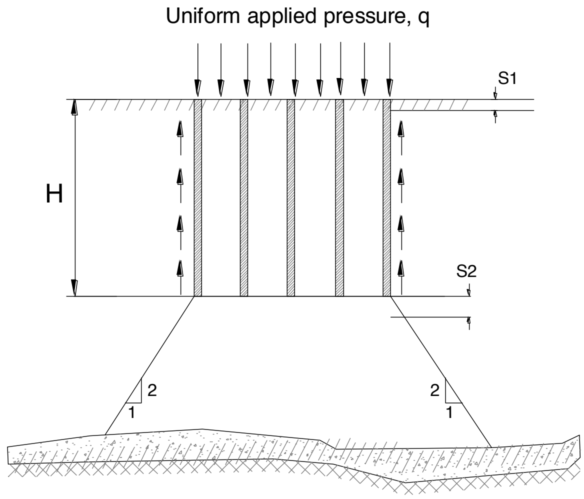


Figure 15. Mechanism of estimating settlement of footing on CDM-reinforced ground (Reproduced after TCVN 9403:2012)

As mentioned but not cited clearly, the settlement evaluation method provided in TCVN 9403: 2012 was adopted from that recommended by Broms [9, 10], which is also described in detail in Bergado et al. [11]. Essentially, the method recommends procedures to estimate settlement of shallow footings on lime/CDM-reinforced grounds, not of infinitely large embankments/fills (to be able to apply 1D strain theory). That is why, as suggested, the stress distribution from the column toes level can approximately be estimated using the 2:1 method. Practically, the 1D strain theory may be applied under large embankments that satisfies some conditions as mentioned in Day [12].

Under limited footing sizes, the induced vertical stress must decrease with depth similar to the trend obtained from the instrumented PF columns discussed above. Thus, the induced stress value at the column toes level recommend in TCVN 9403:2012, that was assumed to be equal to the applied stress value at the footing base (i.e., at column heads), is improper. The settlement evaluation method recommended in the standard should therefore be reconsidered. Since there are still no very reasonable methods to evaluate settlement of shallow footings on CDM/PF-reinforced ground, Nguyen et al. [13] recommended an alternative method using 3D elastic theory, which is basically recommended for evaluating settlement of shallow footings on natural grounds [7].

6. Conclusions

This paper introduces a renovated CDM method named Point Foundation (PF) and presents some recent research findings from this method. First, principles of the method, construction procedures and techniques to control the quality during construction were briefly introduced. The results from static load tests on three instrumented PF columns and one instrumented PHC pile were then analysed and discussed. Finally, the paper briefly presents a comparative study on settlement of a shallow footing on ground improved by PF and CDM columns under the same conditions.

Static load tests on three instrumented PF columns indicated that the induced vertical stress in the column decreases with depth. For the test columns, at the depths of around 2.5 to 3.0 m (or 1.5 to 2.0 times the head diameter) the induced stress remained just about 20% the applied pressure at the pile head. Comparison of induced stress distribution profiles in elastic medium, in PF columns and in PHC pile indicated that at the same applied pressure on the head, the stiffer column/pile would in general transfer a larger stress down the head. Thus, the induce stress in (semi-rigid) PF columns is larger than that in soil but is smaller than that in (rigid) PHC pile. Test data in this study show that at the depth less than approximately 1.0 times head diameter, the induced stress value in elastic soil was slightly larger than the value in PF columns, however at larger depth the stress in the columns remained larger than the value in the soil. This indicates an interesting finding of load transfer in semi-rigid columns.

The findings on the trend of the induced vertical stress in the instrumented PF columns suggest that the settlement of the shallow footings should be evaluated under 3D condition taking into account the fact that induced vertical stress decreases with depth. In such an approach, the settlement evaluation method recommended in TCVN 9403:2012 should be reconsidered for more reasonable evaluations.

Acknowledgement

This work is supported by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant 20CTAP-C151788-02).

References

[1] Bruce, M. E. C., Berg, R. R., Collin, J. G., Filz, G. M., Terashi, M., Yang, D. S. (2013). *FHWA design manual: Deep mixing for embankment and foundation support*. US Department of Transportation, Federal Highway Administration (FHWA), Publication No.: FHWA-HRT-13-046.
[2] BS EN 1467 (2005). *Execution of special geotechnical works – Deep Mixing*. British Standards Institution.
[3] Kitazume, M., Terashi, M. (2013). *The deep mixing method.* CRC Press.
[4] TCVN 9403 (2012). *Stabilization of soft soil – the soil cement column method.* Vietnam National Standard.

[5] Hung, N. S., Thach, V. H. (2019). Shallow reinforcement of filling sand layer above soft soil using soil-cement columns method. *Journal of Science and Technology in Civil Engineering (STCE) - NUCE*, 13 (4V):159–168. (in Vietnamese).

[6] Nguyen, A. N., Nguyen, T. D., Yim, C. S., Lee, M. S. (2020). Point foundation (PF) method for foundations and embankments. In *the 4th International Conference on Geotechnics for Sustainable Infrastructure Development*, Springer, Hanoi, Vietnam, 571–578.

[7] CFEM (2006). *Canadian Foundation Engineering Manual*. 4th edition, Canadian Geotechnical Society.

[8] Han, J. (2015). *Principles and practice of ground improvement*. John Wiley & Sons, Inc.

[9] Broms, B. B. (1986). *Stabilization of soft clay with lime and cement columns in Southeast Asia*. Applied Research Project RP10/83, Nanyang Technical Institute, Singapore.

[10] (2002). *Deep soil stabilization – Design and construction of lime and lime/cemen columns*. 1st edition.

[11] Bergado, D. T., Anderson, L. R., Miura, N., Balasubramaniam, A. S. (1996). *Soft ground improvement in lowland and other environments*. ASCE Press.

[12] Day, R. W. (2010). *Foundation engineering handbook, design and construction with the 2009 international building code*. 2nd edition, ASCE Press.

[13] Nguyen, T. D., Ha, Y. M., Choi, H. K., Nguyen, D. T. (2019). Effectiveness of head-enlarged CDM columns in evaluating settlement of improved grounds. In *The 44th DFI Annual Conference on Deep Foundations*, Chicago, USA, 501–510.