Evaluation of bearing capacity of precast piles with dissimilar post-grouting pressures

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ABSTRACT
A bored precast pile construction method is limited in controlling the diameter and the length of a pile. Nevertheless, this method has many advantages such as convenience of construction, shortening of construction period, and usefulness in management. Furthermore, because a precast pile is manufactured in a production facility it is easy to control the quality of the pile, and it is used widely in foundation structures for apartment building in Korea. Due to soil disturbance at the tip during the installation process of the bored pile, the end bearing capacity of the pile is not fully mobilized in common cases. To mitigate this problem, the Post-Grouting method has been extensively used worldwide. In this study, the effect of Post-Grouting was estimated by performing 3 cases of pile load tests on PHC (Pre-stressed High-strength Concrete) piles. The test piles were constructed both with and without Post-Grouting pressure and the grouting pressure was applied using two dissimilar pressures. By comparing the test results, the increment of the end bearing capacity due to the grouting was estimated quantitatively.

RÉSUMÉ
La méthode d'une construction du tas précoulée est limité pour contrôler le diamètre et la longueur du tas. Néanmois, cette méthode a beaucoup d'avantages comme la convenance de construction, raccourcir la période de construction et l'utilité dans la direction. De plus, car le tas précoulé est fabriqué par une production qui est facile de contrôler la qualité de tas, et il est utilisé largement dans la fondation structure de bâtiments en Corée. Dans les cas communs, c'est à cause du sol dérangement à la pointe, pendant la processus d'instalation du tas précoulé n'était pas entièrement mobilisé. Pour adoucir cette problème, la méthode de "Post-Grouting" est utilisé considérablement dans le monde entier. Dans cette étude, l'effet de "Post-Grouting" est estimé par exécuter les trois cas de tas pour tester le "PHC (Pre-stressed High-strength Concrete)" tas. Les tas pour tester sont construits avec et sans la pression de "Post-Grouting" et la pression de "Grouting" a été appliqué en utilisant deux dissemble pressions. En comparant les résultats du test, l'augmentation du fin capacité est à cause du "Grouting" était estimé quantativement.

1 INTRODUCTION

Because of the civil complaint made about noise and vibration problems occurring on construction sites and due to the increased regulations for noise management, pile foundation construction using driven piles has gradually become more difficult to carry out. To compensate for this difficulty in construction, the application of bored piles and drilled shafts has gradually increased.

When using drilled shafts it is relatively easy to control the diameter and length of the pile compared with precast piles (steel pile and PHC pile). Recently, drilled shafts with a large diameter of over 1.5 m (maximum 3.0 m) have been widely used in the superstructure construction of long span bridges and skyscrapers. However, there is a possibility of deficiency in the existing pile during the concrete placing of drilled shafts, and the construction cost is relatively expensive compared to other methods.

On the other hand, with the precast pile method it was difficult to control the diameter and length of the pile, yet the construction, management and maintenance of the quality of the pile was relatively easy because it was manufactured at the factory before construction. Therefore, this method is also widely used in small scale foundation structures, and usage of the PHC (Pretensioned spun High strength Concrete) pile is generalized in Korea.

Normally, the unit ultimate tip capacity of a bored pile could be in the order of 20 times the unit ultimate side resistance. However, since the tip capacity is fully mobilized at displacements of 10 ~ 15% of the pile diameter, the pile head displacement exceeds the allowable settlement requirements before the tip capacity is fully mobilized. Thus, with a general construction method, the pile tip capacity cannot be used effectively.

In this research, to develop the bearing capacity improvement method for a bored pile by tip grouting, static load tests were performed for two piles grouted with dissimilar pressures and one non-grouted pile, and an improvement effect analysis was carried out.

2 CONSTRUCTION OF THE TEST PILES

2.1 Post-Grouting Method

First, before pile construction, a packer injection pipe was installed at the tip of the pile, and the pile was placed in the right position. Subsequently, a packer was inserted into the injection pipe, and tip grouting using this equipment was performed. In this case, a 500mm (φ=500mm) diameter PHC pile was used, and a 76mm diameter pneumatic packer was employed to carry out the tip grouting.

The procedure to improve the tip capacity of the bored pile is shown in Figure 1. A pile shoe was installed to prevent the inflow of the surrounding soil at the pile tip. Subsequently, to insert the packer for grouting injection, a drill hole was punched and combined with an injection pipe. Finally, after the construction of the processed pile into the ground and the curing of the fixing agent at the pile-soil interface area, the packer was constructed at the tip of the pile. Grouting was then carried out.

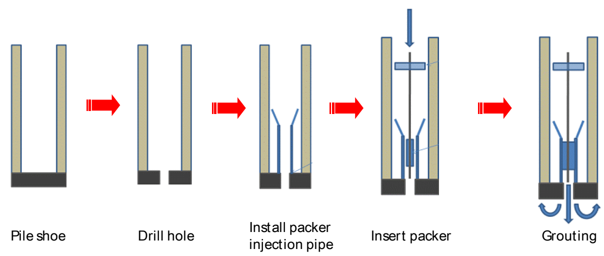

Figure 1. Pile tip grouting procedure

2.2 Site Investigation and Pile Construction

The test piles were constructed at the Honam express railway construction site 3-3, and static load tests were carried out to analyze the bearing capacity improvement by tip grouting. The location of the test piles and site investigation results are shown in Figure 2.

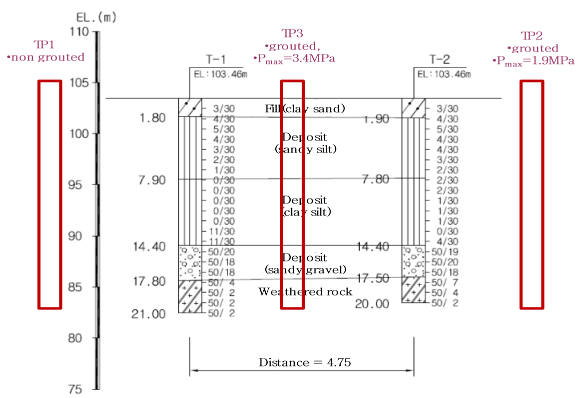

Figure 2. Location of the piles and site investigation results

In Figure 2, sampling and standard penetration tests (SPT) were conducted in two places at the middle of the test piles. Sampling in the soil layer containing weathered rock was performed using the SPT sampler, and standard penetration tests (SPT) were carried out at 1 m intervals in the subground and at the boundary of the soil layers. The test piles were socketed into the weathered rock.

2.3 Grout Injection and Results

The research program consisted of full-scale testing using two grouted piles (TP2, TP3) and one non-grouted pile (TP1) to analyze the bearing capacity improvement of the bored precast pile by tip grouting. According to literature studies and former construction cases, the maximum tip grouting pressure is about 5 MPa. However, in this study, considering the uplift pressure on the side area of the pile, the maximum pressures were determined as 1.9 MPa for TP2, and 3.5 MPa for TP3.

Portland cements, mixed in W/C=83%, were used for grouting the injection material, corresponding to the construction specification of the Korea Land & Housing Corporation. According to this specification, in this mixing condition, the strength of the grouting material is about 20 MPa.

To confirm the uplift pressure occurrence on the perimeter of the pile, an LVDT was installed on the pile head, and the displacement of this section was measured. Consequently, in the case of TP2, upward displacement did not occur, while in the case of TP3, upward deformation was about 0.3 mm. Therefore, there was no reduction effect of the grouting pressure.

The results for TP2 and TP3 are shown in the following Figures. The grouting pressures, instantaneous flow rate, and accumulated flow are presented with time in Figures 3 and 4.

In Figures 3 and 4, the instantaneous flow rate increased regularly with the growth of grouting pressure; this implies that the grout material was injected consistently without loss of injection material. Meanwhile, in the case of TP3, it was difficult to maintain a constant value of the injection pressure; this was due to the use of excessive volume pumping compared with the injection pressure.

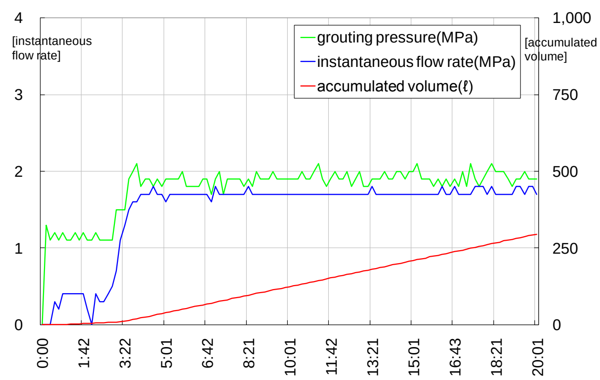

Figure 3. Grouting results for TP2

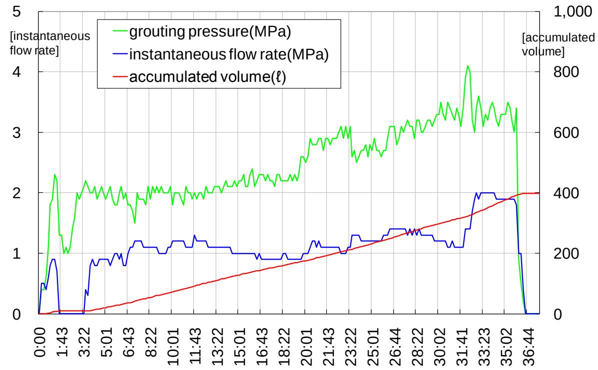

Figure 4. Grouting results for TP3

3 STATIC LOAD TEST AND TEST RESULTS ANALYSIS

3.1 Static Load Test

After Post-Grouting for grouted piles (TP2, TP3) and a 15 days curing period, static load tests were conducted in 3 cases of piles including the non-grouted pile (TP1). The maximum test loads were set to be 3139.20 kN for grouted piles and 2354.4 kN for non-grouted piles, considering the allowable load and design load of the test pile. Six adjacent piles were used as reaction piles.

Table 1. Design efficiency of PHC precast pile

Pile	Allowable Load(kN)	Design Load(kN)	Design Efficiency(%)
PHC 400	1030.05	784.80	76
PHC 500	1618.65	889.90	55
PHC 600	2501.55	1177.20	47

3.2 Test Results

To determine the yielding load, four analysis methods using load-settlement curves were selected including P-S (Load-settlement), LogP-LogS, S-LogT, and R-E (Residual-Elastic settlement) curves. Also, two criteria using settlement were used; the England Foundation Industry Standard, which determines the limit load as the load with a total settlement of 10% of the pile diameter, and DIN 4206, which determines the limit load as the load with a residual settlement of 2.5% of the pile diameter.

3.2.1 Non-grouted pile, TP1

In the case of TP1, a test load was applied to 2354.4 kN without unloading-reloading procedure. The total settlement was 34.31 mm at maximum test load, and the residual settlement was measured as 30.18 mm after the unloading procedure. The test results are shown in Figures 5-8.

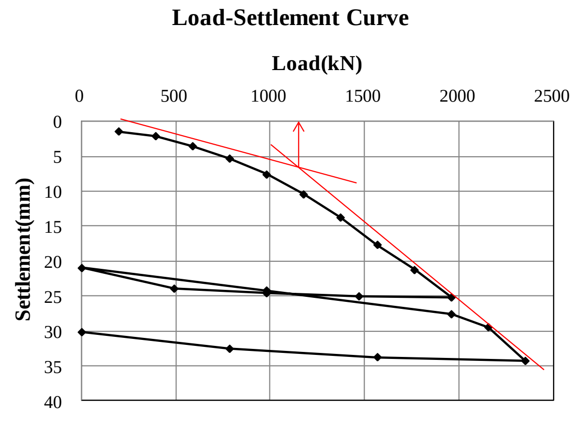

Figure 5. P-S curve of TP1

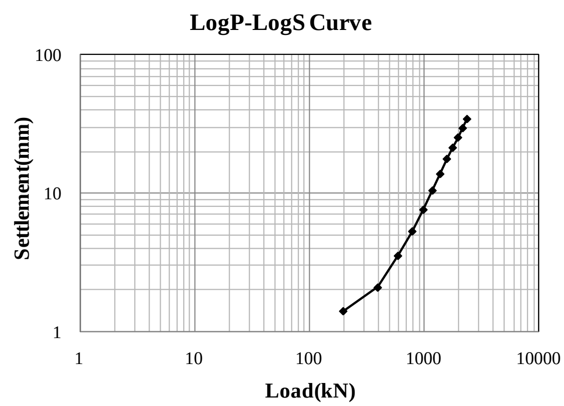

Figure 6. LogP-LogS curve of TP1

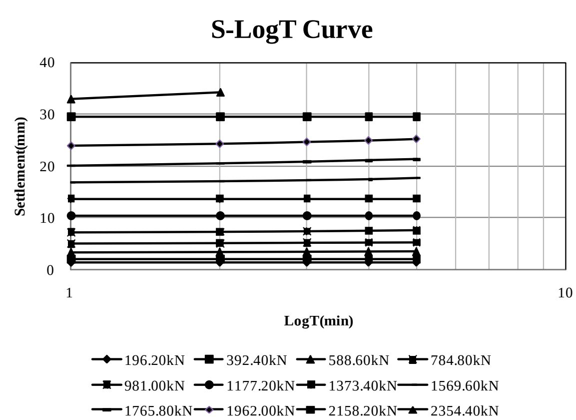

Figure 7. S-LogT curve of TP1 for each load step

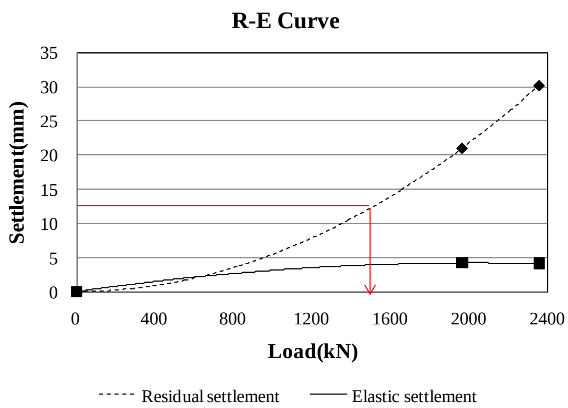

Figure 8. R-E curve of TP1

The yielding load is defined as the point at which the load-settlement curve becomes linear again after an initial region, followed by a curved transition region in the P-S curve (Figure 5), and is determined as the load corresponding to residual settlement which is equal to 2.5% of the pile diameter in the R-E curve (Figure 8). Because there was no yielding load in the LogP-LogS and S-LogT curves, the average load of the P-S and R-E curves was determined as the yielding load of TP1. A safety factor of 2.0 was then applied and the allowable load (677.28 kN) was calculated. The test results of TP1 are listed in Table 2.

Table 2. Test results of TP1

Pile No.	Analysis method		Yielding load (kN)	FOS	Allowable load(kN)
TP1	Load-Settlement analysis	P - S	1137.96	2.0	568.98
		log P - log S	≥ 2354.40	2.0	≥ 1177.20
		S-Log T	≥ 2354.40	2.0	≥ 1177.20
		R-E CURVE	1571.17	2.0	785.59
	Settlement criteria	0.1D (50.0mm)	Total settlement	34.31mm (insufficient settlement)	
		0.025D (12.50mm)	Residual settlement	30.18mm (This criterion used in R-E curve)	
	Allowable load (kN)	677.28 (average of P-S / R-E curve methods)			

3.2.2 Grouted pile, TP2 (P_{max}=1.9 MPa)

In the case of TP2, the test load was applied to 3139.20 kN without an unloading-reloading procedure. The total settlement was 16.24 mm at maximum test load, and the residual settlement was measured as 4.21 mm. The test results are shown in Figures 9-11.

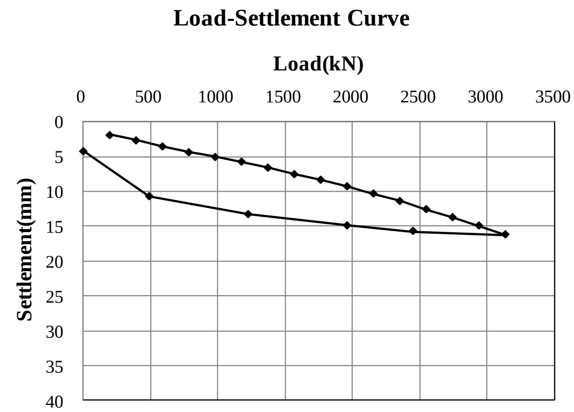

Figure 9. P-S curve of TP2

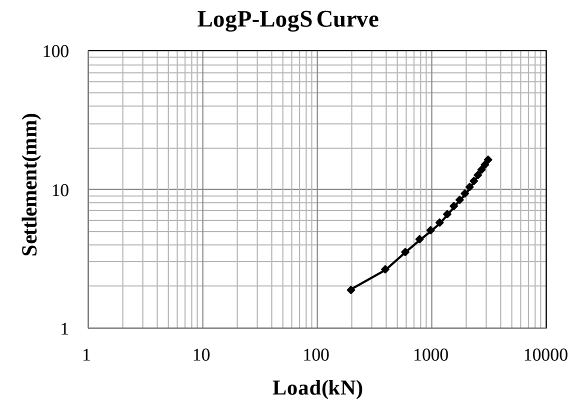

Figure 10. LogP-LogS curve of TP2

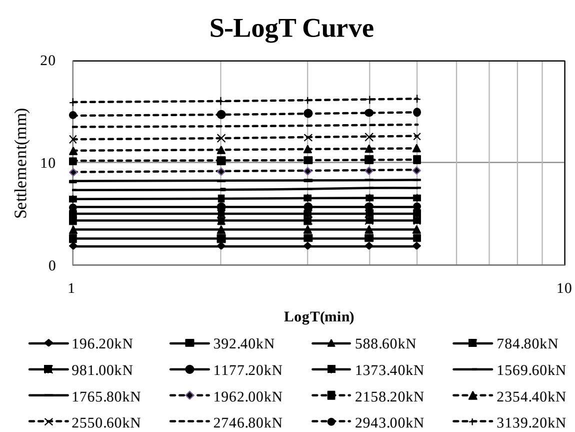

Figure 11. S-LogT curve of TP2 for each load step

Unlike TP1, there was no slope transition region and the loads increased linearly in the P-S and LogP-LogS curves of the grouted pile (TP2). Also, it was not possible to determine the yielding load in the S-LogT curve because of the absence of settlement increase with time. This means that the yielding load of TP2 exceeded the maximum test load. Therefore, the maximum test loads were assumed as the yielding load and the allowable load was calculated by applying the safety factor. The test results of TP2 are shown in Table 3.

Table 3. Test results of TP2

<table>
<tr><th>Pile No.</th><th colspan="2">Analysis method</th><th>Yielding load (kN)</th><th>FOS</th><th>Allowable load (kN)</th></tr>
<tr><td rowspan="7">TP2</td><td rowspan="4">Load-Settlement analysis</td><td>P - S</td><td>≥ 3139.20</td><td>2.0</td><td></td></tr>
<tr><td>log P - log S</td><td>≥ 3139.20</td><td>2.0</td><td></td></tr>
<tr><td>S-Log T</td><td>≥ 3139.20</td><td>2.0</td><td></td></tr>
<tr><td>R-E CURVE</td><td>-</td><td>2.0</td><td></td></tr>
<tr><td rowspan="2">Settlement criteria</td><td>0.1D (50.0mm)</td><td>Total settlement</td><td colspan="2">16.24mm (insufficient settlement)</td></tr>
<tr><td>0.025D (12.50mm)</td><td>Residual settlement</td><td colspan="2">4.21mm (insufficient settlement)</td></tr>
<tr><td>Allowable load (kN)</td><td colspan="4">≥ 1569.60</td></tr>
</table>

3.2.3 Grouted pile, TP3 (P_{max}=3.5 MPa)

As an excessive settlement occurred in the pile head reinforcing element in initial loading (1177.20 kN) of TP3, the pile was fully unloaded and reloaded after fixing the reinforcing element. The maximum test load was 2943 kN. The total settlement was 7.06 mm at maximum test load, and the residual settlement was measured as 0.77 mm. The test results are shown in Figures 12-14.

The test results of TP3 were similar to those of TP2. The yielding loads were not determined in the P-S, LogP-LogS, and S-LogT curves. The total settlement and residual settlement were also smaller than each criterion. Therefore, the maximum test loads were again assumed as the yielding load and the allowable load was calculated by applying a safety factor equal to 2.0. The test results of TP3 are shown in Table 4.

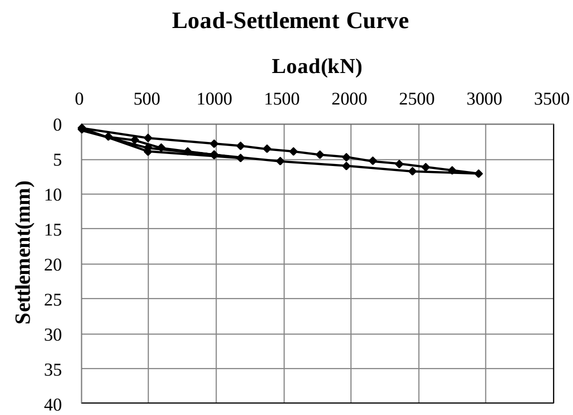

Figure 12. P-S curve of TP3

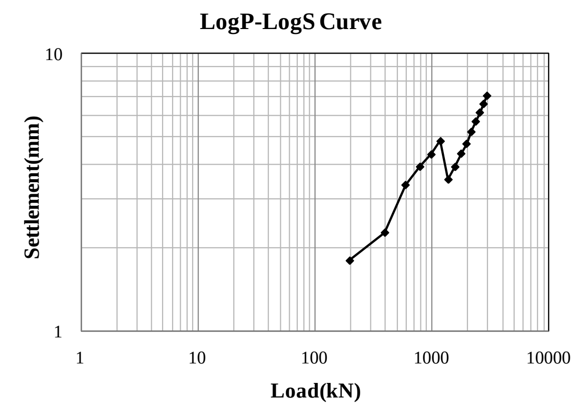

Figure 13. LogP-LogS curve of TP3

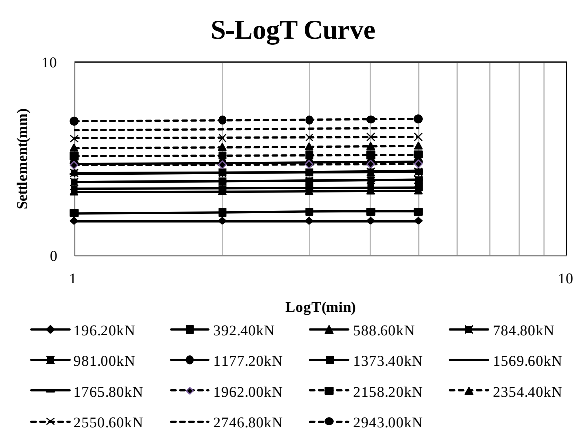

Figure 14. S-LogT curve of TP3 for each load step

Table 4. Test results of TP3

Pile No.	Analysis method		Yielding load (kN)	FOS	Allowable load (kN)
TP3	Load-Settlement analysis	P - S	≥ 2943	2.0	
		log P - log S	≥ 2943	2.0	
		S-Log T	≥ 2943	2.0	
		R-E CURVE	-	2.0	
	Settlement criteria	0.1D(50.0mm)	Total settlement	7.060mm (insufficient settlement)	
		0.025D(12.50mm)	Residual settlement	0.770mm (insufficient settlement)	
	Allowable load (kN)	≥ 1471.50			

3.3 Comparison of bearing capacity

The resulting allowable bearing capacities for TP1 to TP3 are summarized in Table 5. The bearing capacity of grouted piles was about two times greater than that of the non-grouted pile, and the design efficiencies compared to the capacity of pile concrete increased to more than 90%. Thus, when the grouting improvement method is applied, bearing capacities can be governed by the allowable load of the pile concrete. For the particular case of this study, the limit pressure was assumed to be around 2.0 MPa. Thus, the maximum effective grout pressure should be predetermined at each construction site.

Table 5. Comparison of bearing capacity with grout pressure

Pile No.	Grout pressure (MPa)	Grout volume (L)	bearing capacity of test pile (kN)	Design efficiency compared to the allowable load of pile concrete (1618.65 kN) (%)
TP 1	-	-	677.28	42%
TP 2	1.9	290	> 1569.6	> 97%
TP 3	3.5	398	> 1471.5	> 91%

3.4 Axial rigidity vs. grout pressure

The load-settlement curves of the test piles are shown in Figure 15 to compare the axial rigidity with grout pressure. Axial rigidities equal to the slope of the curves increase with increasing grout pressure. When the allowable settlement of the superstructure on the pile foundation governs the design of the foundation, the grout pressure can be controlled to fulfill the requirement of the superstructure. Further studies are required to evaluate the relationship between grout pressure and axial rigidity.

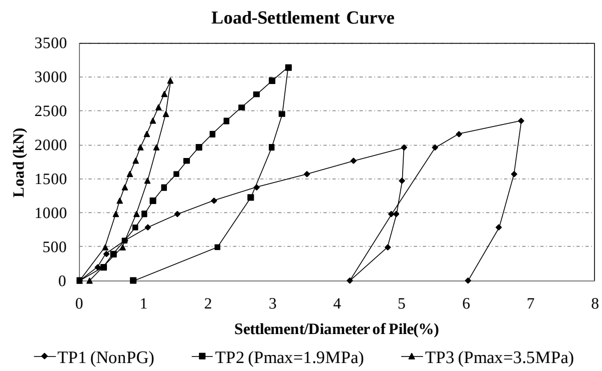

Figure 15. Load-settlement curves of test piles

4 CONCLUSIONS

In this paper, the effectiveness of Post-Grouting was studied by performing 3 cases of a pile load test on PHC piles. The test piles were constructed with and without Post-Grouting pressure and the grouting pressure was applied using two dissimilar pressures. From the tests, conclusions are drawn as follows;

1. The bearing capacity of grouted piles was about two times greater than that of the non-grouted pile, and the design efficiency (allowable ground bearing capacity/pile material capacity) increased to more than 90%. Thus, it was confirmed that the pressure grout can considerably increase the pile capacity.

2. It is shown that if the grout pressure increases beyond a certain value, the bearing capacity of a pile would be governed by the strength of the pile material. Thus, it is necessary to determine the limit grout pressure at each construction site to obtain an economical pressure grout.

3. It is observed that the vertical pile stiffness upon loading increases as the grout pressure increases. Therefore, if the allowable settlement of a foundation (rather than the pile capacity) governs the design of the foundation, the grout pressure may be increased beyond the limit value in order to control the pile settlement under the design load. For this purpose, an empirical relation between the grout pressure and the vertical pile stiffness may be established for such a construction site.

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