Pull-out Characteristics of Expanded Anchor Using Pulse Discharge Technology

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ABSTRACT
For the anchors that the load transfer is by shear resistance mobilized along the ground-grout interface, the ground disturbance during boring is inevitable which causes a reduction of resistance. Because of that, the length of an anchor should be extended to at least weathered rock layer, which is not appropriate where the length of anchor is limited.
This paper introduces PDT (Pulse Discharge Technology) anchoring method. Since this technique can make not only a bore hole expanded but also the ground improved by compaction, the anchor installed by PDT is expected to develop shaft and end bearing capacity efficiently. In order to investigate expansion characteristics, a series of experiments are conducted using a model container, whose dimensions are 1.0m in height, and 1.5m in diameter, in the laboratory. In addition, a couple of *full* scaled tests in order to figure out the increase of pullout capacity are performed at two different sites with loose sandy soil. As a result, the degree of expansion appears to increase up to 4 times with a decrease of relative density and an increase of the number of impulse, and the ultimate pullout capacity appears to highly increase comparing *with* straight shaft anchors with an increase of impulse.

RÉSUMÉ
Para los anclas que la carga se transfiere por la resistencia al esfuerzo cortante movilizado a lo largo del contacto terreno-lechada, la perturbación del terreno que reduce la resistencia durante sondeo es inevitable . Por tanto, la longitud de un ancla debe extenderse por lo menos a la capa de roca meteorizada, á donde no es apropiado limitar la longitud de un ancla.
Este artículo presenta el método de PDT(Tecnología de la Descarga de Pulso) anclaje. Puesto que este método no sólo puede hacer sondeos para ser ampliados, sino también puede mejorar el terreno por la compactación, las anclas instaladas por PDT se esperan para desarrollar eficientemente la capacidad de carga admisible de cañas y puntas. Con el fin de investigar las características de la expansión, una serie de experimentos se llevan a cabo utilizando un modelo de recipiente, cuya dimensión es de 1,0 m de altura y 1,5 m de diámetro, en el laboratorio.
Además, un par de pruebas en modelo de tamaño natural con el fin de determinar el aumento de la capacidad de arranque se realizó en dos sitios diferentes de suelo arenoso suelto. Como resultado, el grado de expansión aumenta hasta 4 veces a lo largo de una disminución de la densidad relativa y un incremento del impulso, y la capacidad final de extracción aumenta en alto grado en comparación con los anclas de caña recto a lo largo de un aumento del impulso.

1 INTRODUCTION

Ground anchor which was introduced in 1970s for the first time is one of the most popular ground improvement methods. It has been frequently adopted in many construction fields such as, subway, skyscraper, underground parking space as well as large scale of excavation in urban area because of its stability and efficient site usage. However, such a ground anchorage has several shortcomings. Firstly, it requires its free zone lengthened to bed rock and the space between anchors to be narrow for soft soil condition. It gives rise to an increase of total construction cost inevitably. Secondly, since the ground anchor goes deeper in order to secure proper resistance it is apt to intrude the field boundary especially in urban area. On the effort of overcoming, a few alternative methods such as, load distribution compression type of anchor, and JSP and pressure grouting using packer have been developed and used. However, the former may induce a local failure since the length of each tendon is different one another in order to mobilize load distribution effect, which requires alternative tensioning method or equipment to prevent load concentration. Meanwhile, it may be hard for the latter to expect the ground strength improvement because of uncertainty of infiltration into the ground. For these reasons, an alternative method is required to be developed. Pulse discharge technology (PDT) is an electric technique which induces an arc or a corona electric discharge in a few micro seconds. By means of electrical impact, the ground is compacted, and therefore the strength can be improved. Russian geotechnical engineers used the PDT-induced shockwave as an alternative method for pressurized-underreaming of pre-drilled ground borehole for cast-in place piles or anchors with small diameter which usually ranges from 120 to 250mm.

In this study, the relationship between pulsed power and the ground is investigated. To do so, a series of laboratory tests and full scaled field tests were carried out. In addition, the applicability of such an anchor system was examined by applying to a real cut slope.

2 PULSE DISCHARGE TECHNOLOGY (PDT)

2.1 Pulse Power

Pulsed power is the physical value that indicates the energy change per unit time (dE/dt). The power depends on how fast the energy is released. In other words, if a unit of energy is discharged in 1 sec, a watt of power will be generated. On the other hand, if the energy is discharged in 1 µs (10^{-6}sec) the power will be 1MW (10^{6}Watt) as shown in Figure 1.

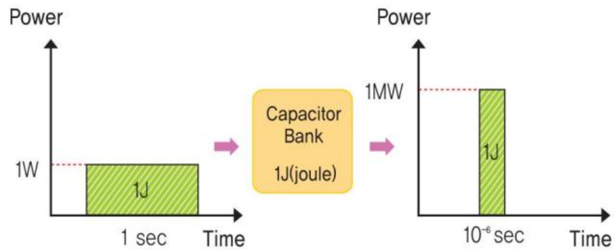


Figure 1. Pulsed power

2.2 Shock Wave

Shock wave can be generated by the pulse power in a fluidal medium. When a high voltage generates between two electrodes inserted in the medium, the fluidal material between electrodes may heat up. Then the material will expand outward. Meanwhile the material outside the electrodes remains cold and will restrain the heat-up material from expanding. Because of this opposite characteristics between expansion and restraint, a high pressure will be generated at the boundary. Finally this pressure is changed into a different type of energy so called shock wave and propagates through the medium until meets a different type of medium. Once the shock wave reaches the different type of medium, which herein represents a soil layer, it is trying to push the soil media. Finally the soil layer gets expanded. Figure 2 shows how the electrical energy changes to the shock wave and potential energy by the stage.

Figure 2. Energy transformation

The shock wave generated through the several energy transformations as shown earlier propagates to the ground and make it expanded and recompacted. Figure 3 shows the concept of expansion by the shock wave induced by the pulse power.

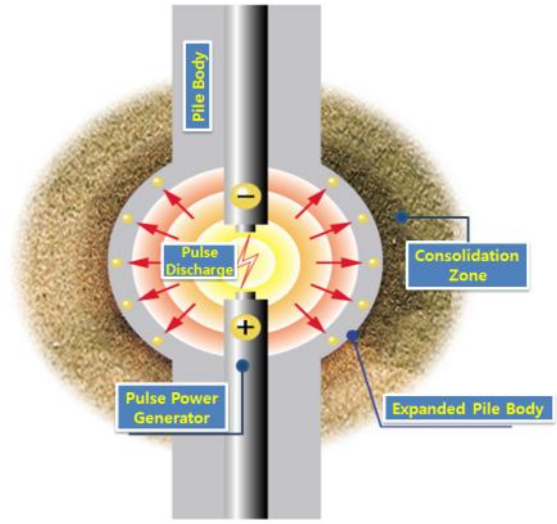


Figure 3. Conceptual view of ground expansion and an example

2.3 Coefficient of Expansion (E_c)

In order to calculate the bearing capacity of an anchor, the areas of shaft and tip of it are to be determined. In general, most anchors have constant shape and diameter along the longitudinal direction, which means the areas are constant. However, for the anchors installed using the pulsed power, the shape varies and therefore the areas are different one another depending on the pulsed power intensity. Therefore the most important thing for the calculation of bearing capacity is how to take into account the varied area. In this section, the coefficient of expansion is introduced. The details of derivation of the coefficient of expansion *(E_c)* are as follows. First, the shape of expansion in a hole is assumed to be sphere as shown in Figure 4, for the shock wave is expected to propagate in radial direction.

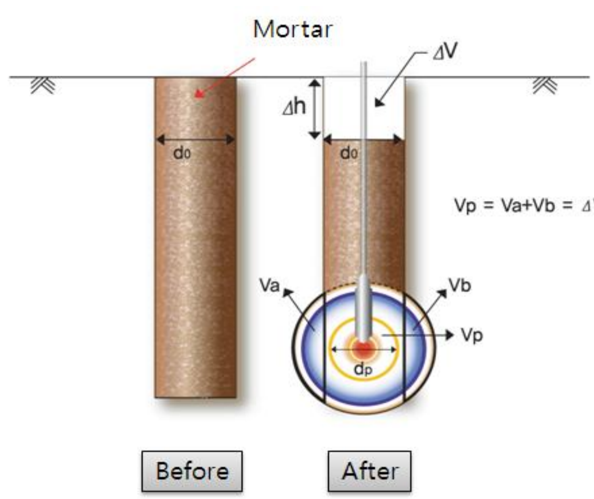


Figure 4. The assumed shape of a hole expansion by pulse discharge

In the Figure 4, d_0 represents the initial diameter of the hole, and Vp represents the volume of a space occurring instantly at impulse which is assumed to be sphere. If it is assumed that there is no loss of mortar during impulse, then it could be said that there occurs volume change, Δv, as much as the mortar is falling down because of the hole expansion.

The volumetric change by pulse discharge, V_p, can be calculated with easy on the basis of material mechanics. In the meantime, the coefficient of expansion (E_C) can be defined as the ratio of the final to the initial diameter as following

$$E_c = \frac{d_f}{d_0} \quad [1]$$

3 LABORATORY EXPERIMENT

3.1 PDT Equipment

The pulse discharge equipment consists of a main switch, capacitor banks, a coaxial power cable and load impact cell as shown in Figure 5. The process of pulsed power generation is as follows. At first, the commercial electricity is stored and compacted in a capacitor bank. Then the stored electricity is discharged in a moment using a special switching system for high electricity. The momentary discharged electricity generates a high electrical power, so called pulsed power. Finally this pulsed power of high electricity is translated to the ground through the load impact cell.

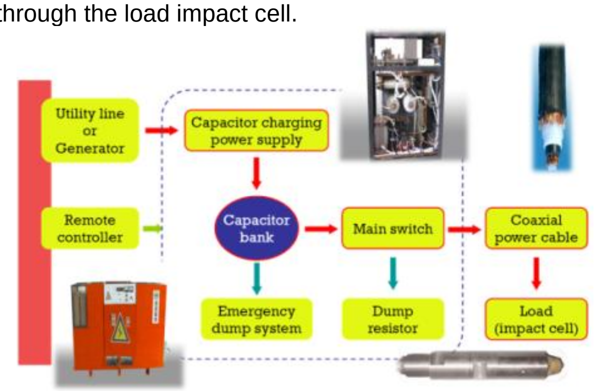


Figure 5. Component of pulse discharge equipment

In order to investigate the expansion characteristics a series of experiments were conducted in a model container in the laboratory. In general, the space between anchors is dependent on designed force, diameter of an anchor, length of fixed zone and so on. According to previous studies, when the ratio of space to diameter of anchors is the same or greater than 6, a similar pullout capacity would be expected for single or group anchors. A similar result was introduced from the experiments on Kanto loam layer in Japan. The result showed that the deformation characteristics of anchor group almost equals to those of single anchor if the ratio of embedded length to diameter of an anchor is larger than 20, or the space is larger than 1.0m. Besides Japanese geotechnical society recommend the space between anchors 10D and the minimum to be 1.5m. In addition, the effecting range of the pulsed power according to previous research is about 1.2m. On the basis of the above references the model container used in this study has dimensions 1.5m diameter and 1.0m height so as to take into account anchorage space in practice. A schematic view of the container is shown in Figure 6.

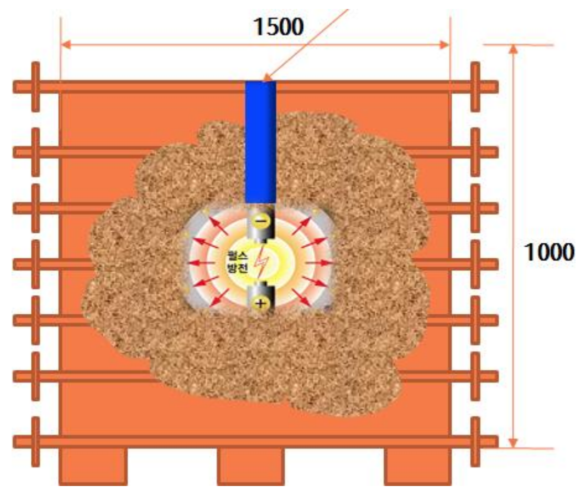


Figure 6. A schematic view of the model container

3.2 Model Ground Preparation

In the tests the model ground was prepared using Jumunjin sands. The ground is prepared by compaction dividing into several layers. Compaction is carried by means of a vibrator and a static compacter. During compaction, a hollow pipe which is for grout injection is installed in the middle of the ground. Having completed the ground preparation, a dynamic cone penetration test is carried out in order to verify the ground being made uniformity. Figure 7 shows the procedure of ground preparation.

[1]Sand raining [2]1st Compaction [3]Pipe installation

[4]2nd Compaction [5]Completion

Figure 7. Procedure of Ground Preparation

3.3 Laboratory Tests

The target ground condition is medium dense sandy soils. Therefore two different soil conditions with relative density of 40%, and 60% were selected as shown in Table 1. Since the goal of this study is to figure out the expansion characteristics of the ground a matrix of experiments with different number of impulse were also conducted on each soil condition as shown in Table 1.

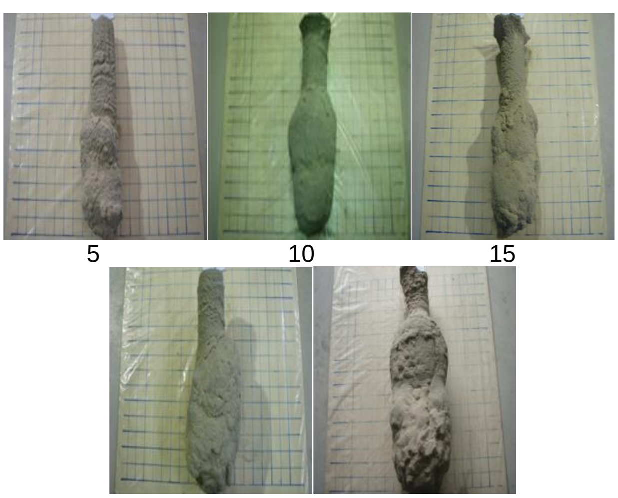
Table 1. Expansion Test Conditions

Material	Relative Density	No. of Impulse	Sets
Sand (Jumunjin sand)	40%	3	1
		5	2
		10	1
		15	1
		20	1
		40	1
	60%	5	1
		20	1
		40	1

Once the ground is prepared, cement paste that W/C is 50%, is poured into the hollow pipe to the top. Then the pipe is pulled up about 15cm in order for later impulse. After injection, the pipe is sealed perfectly with rubber valve so that no energy loss occurs during impulse. Then energy is discharged as designed. After impulse the falling depth of the grout was measured.

3.4 Results

Figure 8 shows the shape of anchor bodies at different numbers of impulse for the relative density of 40%. The shape seems to be rather cylinder than sphere, and the size becomes bigger with an increase of the number of impulse. From the result, it may be said that the effect of the number of pulse discharge on the ground expansion is dependent of ground condition, and remains constant at the end.



5 10 15

20 40

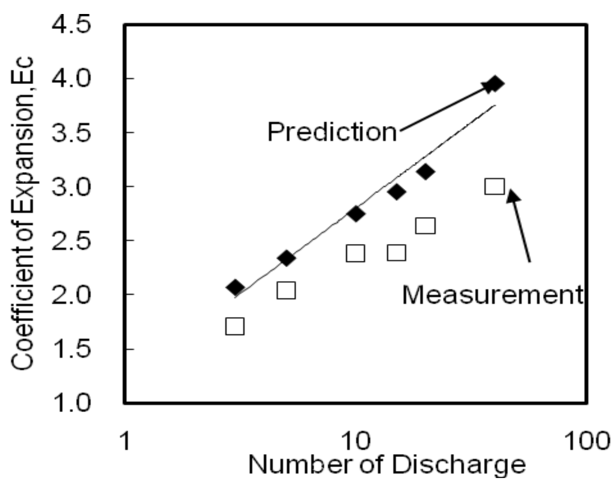
(a) Dr=40%

5 40

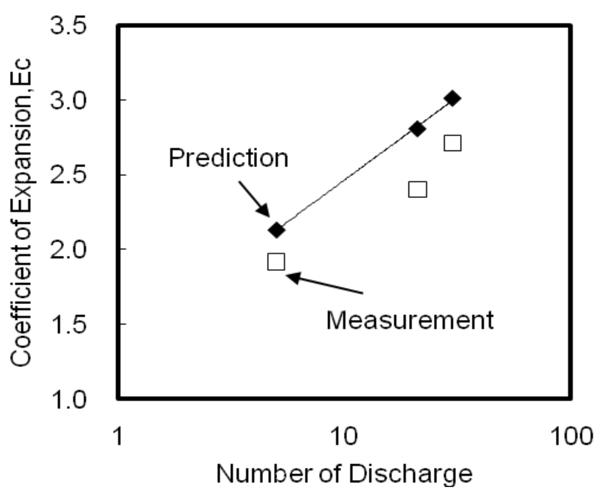
(b) Dr=60%

Figure 8. Shape of underreamed anchor body by pulse discharge

Figure 9 represents the coefficient of expansion with respect to the number of impulse on semi-log scale. In case of relative density of 40%, the coefficients appear to be 2.37 at 5 impulses and 3.95 at 40 impulses. On the other hand, it represents for 60% of relative density from 2.13 to 3.01. From these observation, it is clear that the more the number of impulse the larger the expansion coefficient. Meanwhile, it seems that the prediction estimated from the theory is much larger by 15 to 32% that those obtained from measurement.



(a) Dr=40%



(b) Dr=60%

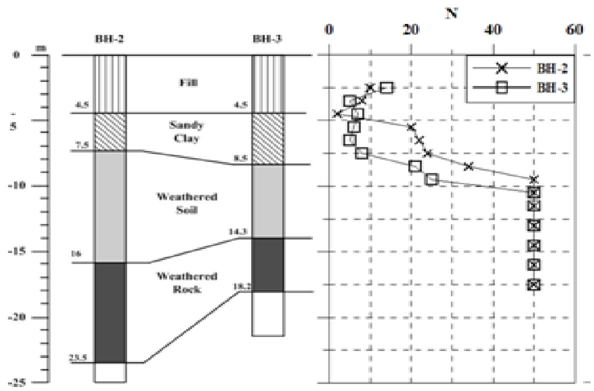
Figure 9. Coefficient of Expansion vs. No. impulse

4 FULL SCALED FIELD TEST

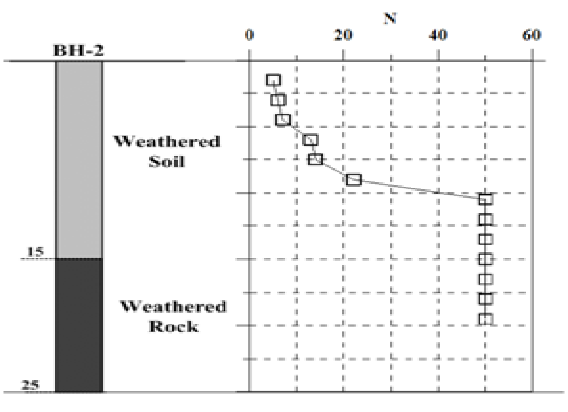
In order to measure the increase of the uplift capacity by the pulsed power, the full scaled field tests were performed.

4.1 Ground Condition

The sites for the tests were located in Suwon and Bupyung, Korea. The average value of standard penetration test, N, around fixed zone of anchors was about 20 as shown in Figure. 10. A hydraulic drilling machine was used to bore a hole. The ratio of water to cement was set to be 50% as usual.



(a) Suwon



(b) Bupyung

Figure 10. Ground profile and N_{SPT}

The matrix of the test condition with respect to discharge pressure, numbers of bulb and impulse are presented in Table 2.

Table 2. Field test Conditions

Area	No. of Bulbs	Initial Voltage	No. of Discharge	N_{SPT}
Suwon	1	5KV		25
	1	5KV	0,5,10, 20,40	20
Bupyung	2	5KV		20
	2	7KV		20

4.2 Results

Figure 11 shows the variation of pullout capacity according to the number of impulse at the pressures of pulse discharge of 5kV and 7kV. In case of 5kV discharge pressure, the pullout capacity appears to increase by about 85.4%, which is from 119.4kN with no impulse up to 221.81kN with 40 impulses. Meanwhile, the pullout capacity appears to increase up to 306.81kN at 7kV discharge pressure which is about 157%. The ground condition seems to have an effect on the pullout capacity as well. When the standard penetration test value, N is 25 the pullout capacity appears to increase from 250kN to 430kN, which is about 72% up. This is a little lower than when the SPT (N) is 20 that the rate of increase is 85.4%. However, such effects becomes gentle when the number of impulse is larger than 20.

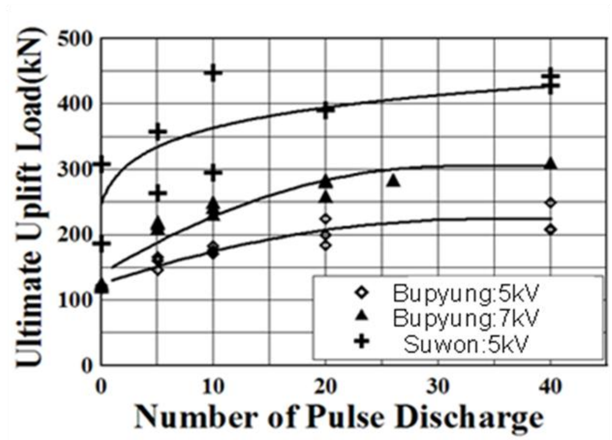


Figure 11. Number of pulse discharge - Uplift load curve by initial charging voltage

The variation of pullout capacity with respect to the number of bulb is shown in Figure 12. The pullout capacities with one and two bulbs appear to be 221.43kN and 325kN compared to the result with no impulse, which is about 85.4% and 172% increase respectively.

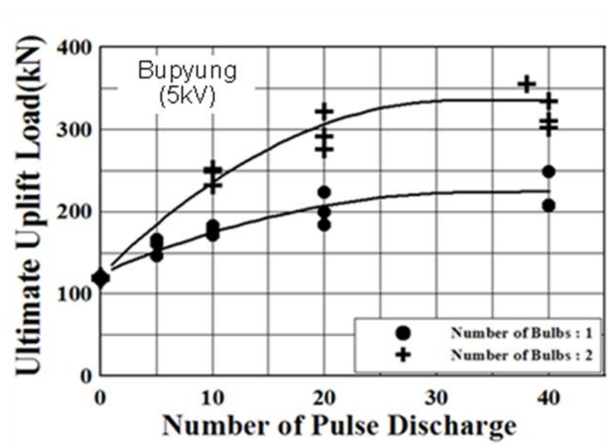


Figure 12. Number of bulbs – uplift load curve

5 FIELD APPLICATION

The pulsed anchor system was applied to the cut slope located in Gyungju, Korea. The site was originally reinforced by counterweight fill method to prevent the initial crack propagation. Unfortunately, additional cracks and further propagation were developed. To secure the slope stability, the pulsed anchor system was selected.

5.1 Site Condition

The ground condition is shown in Figure 13.

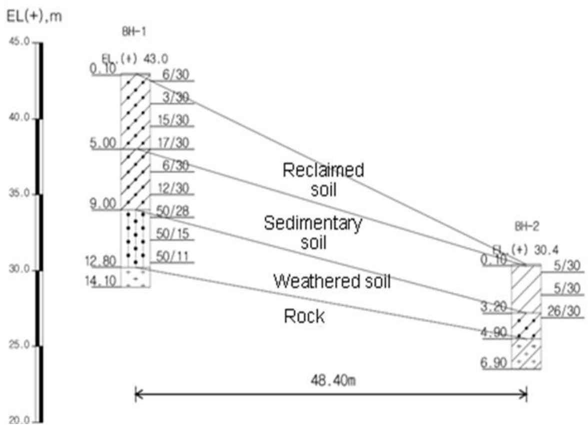


Figure 13. Ground profile

5.2 Reinforcement Design

A commercial program was adopted to analyze the slope with anchors. Since no program to take into account such an expanded anchor system was available, the analysis was performed by applying a general frictional anchor system as shown in Figure 14.

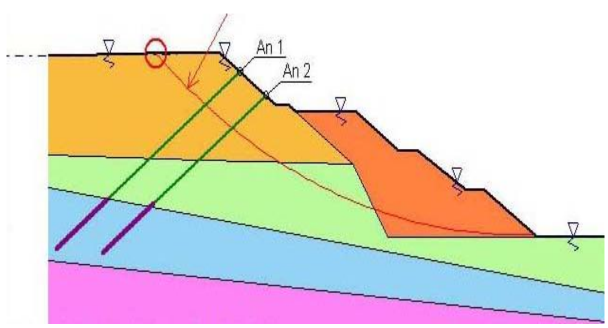


Figure 14. Slope stability results with anchor reinforcement

As a result, the calculated design anchor force was 264.6KN. The required fixed length of the pulsed anchor was estimated using Eq [2]. The length of fixed zone of the pulsed anchor with 10 impulses was estimated at 5.5m, while the existing anchor system estimates the fixed length at 9m.

$$Q_a = A\overline{\sigma'_{av_1}}\pi D L_a + B\sigma'_{av_2}\frac{\pi((CD)^2 - D^2)}{4} + A\overline{\sigma'_{av_3}}\pi C D L_b \quad [2]$$

$$Q_a = Q_{a1} + Q_{a2}$$

Figure 15 shows the cross section of a pulsed anchor.

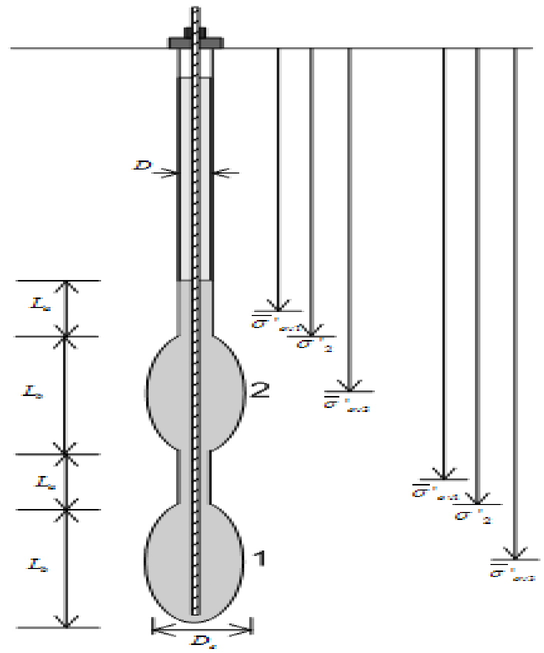


Figure 15. Overview of applied underreamed anchor

Where, *A*= Coefficient of friction

B= Coefficient of bearing capacity

C= Coefficient of Expansion (D_e/D)

D= Initial Diameter of borehole

D_e= Diameter of Expanded hole

L_a= Bonded Length above bulb

L_b= Length of bulb

σ_{av_1}'= Average Effective Stress of La above upper bulb

σ_{av_2}'= Effective Stress above bulb

σ_{av_3}'= Effective Stress in the center of bulb

The result of calculating the effective stress on the bulbs and the design parameters are shown in Table 2 and Table 3.

Table 3. The effective stresses on each bulb

Effective Stress	No.1 (KPa)	No.2 (KPa)
σ'_{av1}	191.10	165.62
σ'_{av2}	210.70	176.40
σ'_{av3}	212.66	178.36

Table 4. Parameters for ultimate uplift force

Design	No. 1	No. 2
L_a	2.3m	2.2m
L_b	0.5m	0.5m
C	1.32	
A	1.46	
B	60.7	

Table 5. Design of ground anchor

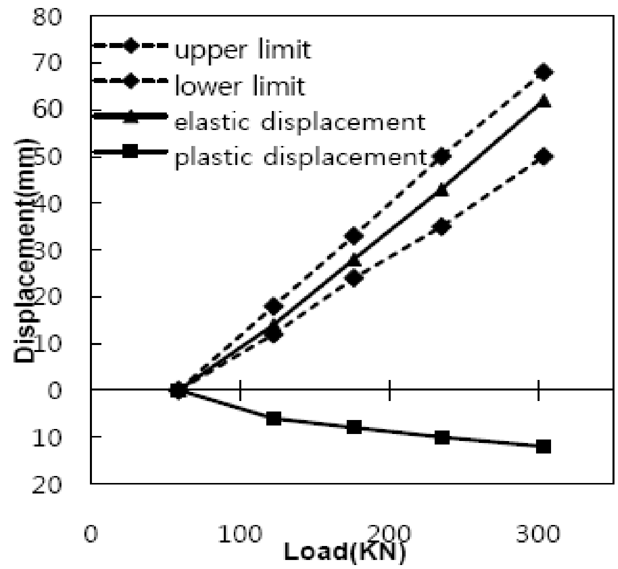
Step	Charging Voltage	Number of Discharges	Bonded Length	No. of Construction
1	-	0	9.0M	3
1	5kv	20	5.5M	22
2	5kv	20	5.5M	20

The pulsed anchor construction is almost the same as any other anchor systems except the stage of impulse as shown in Figure 16.

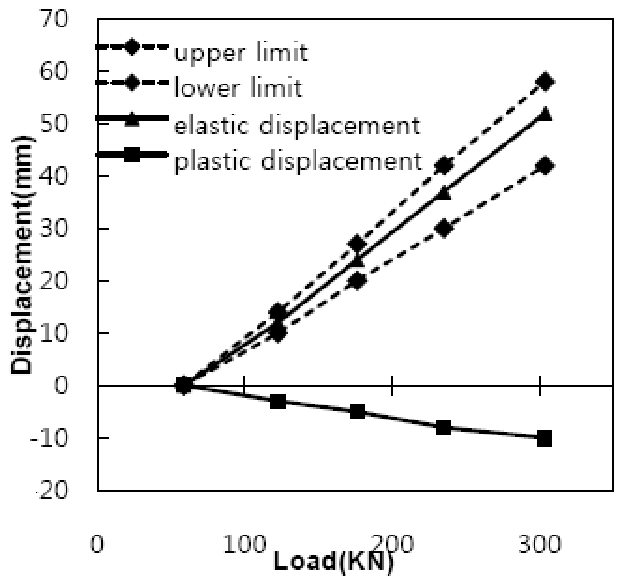
[1]Drilling [2] 1ST Grouting
[3]Cassing pullout [4] Pulse discharge
[5]Anchor installation [6] 2ND Grouting
[7]Measurement [8]Completion

Figure 16. PDT anchor installation

Two sets of two pullout tests were carried out. One set was performed on the anchors with no impulse and the other was on the anchors with impulse. In order to figure out if it is within the allowable boundary, displacement at each loading stage was examined. As a result, it was verified that all the displacements are within the allowable range.



(a) No Pulsed Anchor



(b) PDT-underreamed Anchor

Figure 17. Load-Displacement Curve

CONCLUSIONS

In this study, a new anchoring technique so called PDT anchoring technique was presented. In order to investigate the effect of pulsed power on the ground improvement, laboratory test and full scaled field test were performed. As a result, the following conclusions could be derived.

The shape seems to be rather cylinder than sphere, and the size becomes bigger with an increase of the number of impulse. The effect of the number of pulse discharge on the ground expansion is dependent of the ground condition.

The ultimate pullout capacity increases with an increase of the number of impulse. In case of 5kV discharge pressure, the pullout capacity increases by about 85.4%, while it increases by 157% at 7kV discharge pressure. In addition, the lower the SPT value the greater the effect of impulse.

Comparison of the ultimate pullout capacities with respect to the number of bulb shows that a higher pullout capacity is expected relatively at the anchor with 2 bulbs.

In case of the pulsed anchor system, the fixed length can be saved by about 40% corresponding to the required anchor force, which means its applicability is verified.

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