# Study on bulb form and capacity characteristic of multi-injection ground anchor

## Étude des ancrages à injections multiples (creation de bulbes): formes des bulbes, et caractéristiques de leurs états limités

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ABSTRACT: This paper presents the Multi-Injection Ground Anchor System, which is a special type of grouting method for reinforcing weak grounds for permanent anchorage. In this study, laboratory tests were performed using a large-scaled cylindrical tank filled with sandy soil. The density of sand was adjusted and actual ground anchors were used for multi-injection tests. Based on these test results, technical properties regarding injection counts, pressure, quantity and expansion bulb form were examined. It reveals that the pull-out capacity of ground anchor increases due to the effect of multi-injection. Cavity expansion pressure theory is applied to study this phenomenon as well as to explain the mechanism for the increase in the capacity. The relationships of anchor's equivalent diameter, surface frictional capacity and injection pressure were examined. In this paper, a method for estimating anchor ground capacity is proposed based on the relationship between the tests results and the theoretical values.

RÉSUMÉ: Les anchrages au sol places a l'interieur de trous fores peuvent etre classes en deux categories: les anchrages temporaires et les anchorages permanents. Les premiers sont utilises pour des ouvrages temporaries alors que les seconds sont utilises dans des structures permanentes. Des tests d' injection multiple et a l'arrachement ont ete effectues a l'aide d'ancrages reels. Dans cet article, le nombre d'essai d'injection, la pression d'injection, la quantitc de coulis de beton injecte, et les characteristiques techniques de la forme des bulbes d'expansion ont ete examines. Les resultats revellent que la resistance a l'arrachement augmente grace a l'effet d'injection multiple de coulis. Ce phenomene est etudie selon la theorie de la pression d'expansion de cavite de bulbe, ainsi que le mechanisme d'augmentation de la resistance.

## 1 INTRODUCTION

Ground anchor construction method can be distinguished into two parts, namely, the free length part (tension is acting) and the fixed part (anchor itself). The former applies pre-stress to the structure and the latter uses grout for fixation underground. Especially in the case where permanent anchor is used, the anchor should be installed under a strong and stable ground. Meanwhile, the anchor installation in fracture zones, common fills, loose sandy grounds and cohesive soils has been studied recently. These types of ground are generally regarded to be inappropriate for anchor fixation due to unfavorable geographical conditions and uneconomical reasons.

In this paper, "multi-injected anchorage method" refers to the improvement of soft and weak grounds using a special injection method; thus, making permanent anchorage possible in grounds traditionally considered inappropriate.

Multi-injection and pull-out tests using actual anchor were carried out in this study. The illustration of the test apparatus is shown in Fig. 1, where sands of controlled density were placed inside a large cylindrical container of 900mm in diameter and 1500mm in height. In this paper, the examination of number of injections, injection pressure, injected grout quantity and technical characteristics of bulb expansion form, which were obtained from the test results, are performed first.

Moreover, it is expected that the pull-out resistance of anchor increases due to the effect of multi-injection of grout. In this study, this phenomenon is investigated according to bulb cavity expansion pressure theory and the mechanism of the increase in the resistance was analyzed.

## 2 SUMMARY OF LABORATORY TEST

The material used for test ground was Okagaki sand where its physical properties are clarified. It was placed inside a container using a special device for scattering sand evenly so that it would have a uniform density and was saturated later. The test ground was formed to have an average dry density of $\rho_d$=14 (kN/m$^3$) and a relative density of approximately $D_r$=32%. Also, its internal friction angle is $\phi$ ≒37° according to the existing physical test results. Grout quantity, injection pressure, soil pressure and water pressure were measured during the anchor injection test using the measuring system illustrated in Fig. 1. Moreover, in the pull-out tests, the anchor is pulled out at a rate of 1mm per minute.

It is classified in this paper that the sleeve grout anchor (abbr. S.G.) is considered as the traditional type of anchor, while the

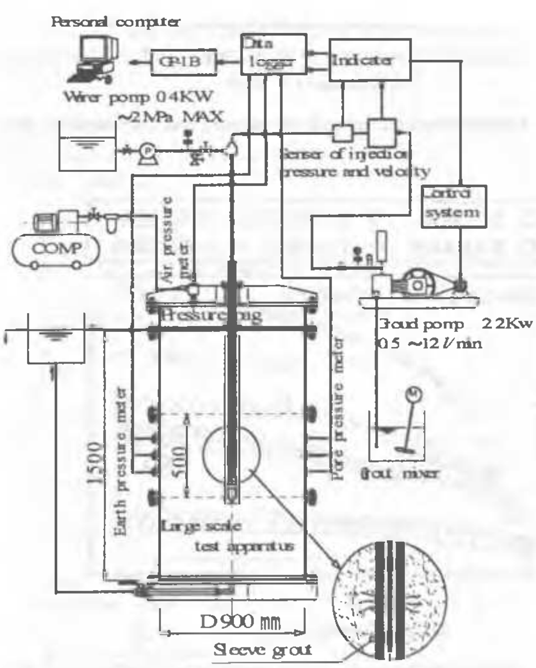



Figure 1. Test apparatus of multi-injection anchor.

anchor used herein is the multi-injected anchor (abbr. M.I.) where there are two-types according to the number of injections, that is 1M.I. and 2M.I.

## 3 PULL-OUT RESISTANCE OF ANCHOR

The characteristics of pull-out resistance of anchor were determined from the experiments. Here, the standard diameter (initial value) of anchor, $d_A$, that corresponds to sleeve grout, and the equivalent diameter, $D_A$, for considering the equivalent cylindrical form of anchor after pull-out tests are taken into account. Also, the equivalent skin friction resistance, $6_y$, $6_y'$, with respect to $d_A$ and $D_A$ are computed, where the effective length of the anchor is 500mm.

It was found that the equivalent diameter, skin friction resistance and injection pressure increase with the number of injection. Figures 2 and 3 show typical examples of load and displacement relationship. Here, the yield forces of S.G. and M.I. anchors are determined using an arithmetic graduation diagram where yield force, $T_y$, corresponds to the maximum curvature along the stress-strain curve.

The following observations regarding pull-out characteristics of multi-injection anchor are obtained based on the above test results.

1) In sand ground, single injection improves pull-out resistance by 2.5 to 3.5 times.

2) Pull-out resistance increased furthermore when injection is made twice. Compared to the usual sleeve grout, the increase is approximately 5 to 6 times. Thus, the effectiveness of multi-injection is clarified.

3) The effect of overburden pressure with respect to the increase of pull-out resistance is proportional to each other, both for common sleeve grout and multi-injection anchor. Moreover, it is found that the relationship is linearly proportional within low-pressure range (between 98kPa and 147kPa) and becomes unremarkable under high pressure (over 147kPa) in multi-injection anchor. However, the effect of number of injection is dominant for high-pressure range.

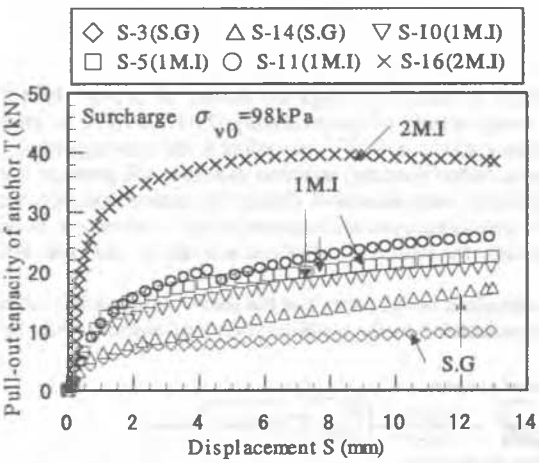



Figure 2. Relationship between pull-out capacity and displacement. (Example 1)

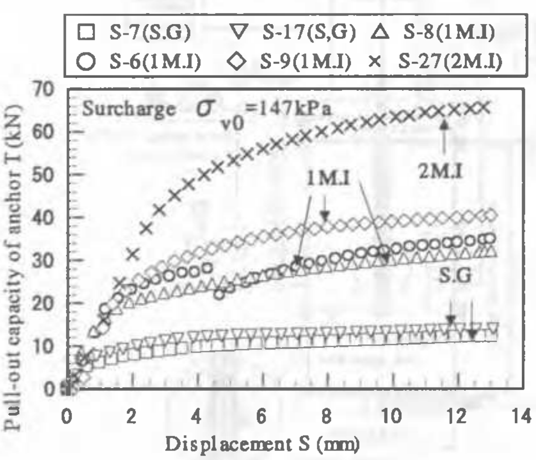



Figure 3. Relationship between pull-out capacity and displacement. (Example 2)

## 4 RELATIONSHIP OF INJECTION PRESSURE AND GROUT QUANTITY AND THEIR CHARACTERISTICS

Figure 4 shows the relationships of the injection quantity, $Q$, for one and two injections, injection pressure, $P$, rate of injection, $v$, and wall pressure increment, $\Delta\sigma_{rw}'$ when the overburden pressure, $\sigma_{v0}$, is 147kPa. In order to find the change of soil pressure, pressure gauges were placed at three points underground between the injection pipe and wall and a point on the wall. Figure 6 shows the relationships of pressure radius, $r$, injection pressure, $P$, and stress increment, $\Delta\sigma_r'$. It illustrates the distribution of stress increment during the first injection, the point when the injection pressure is maximum in the second injection and after injection where pressure becomes consistent. However, only the readings of pressure gauges are used in determining the residual pressure.

Although the rate of injection is constant, it increases while pulsating in order to correct the loss of injection pressure due to resistant force of pipe (see Fig. 4). This illustrates the process where the plastic region of ground widens while ground expands when cement milk is injected inside the cylinder of sleeve grout without permeation (see Fig. 5). Moreover, the soil pressure un-

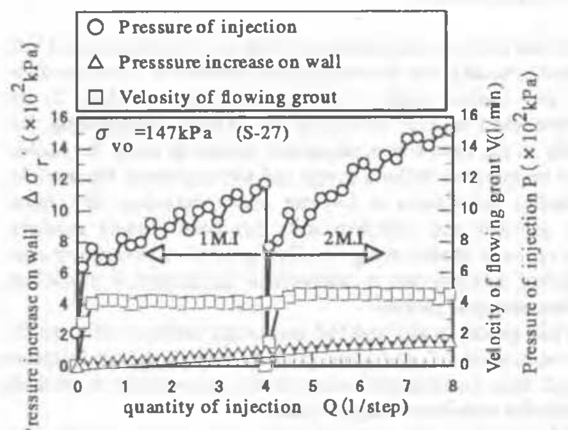
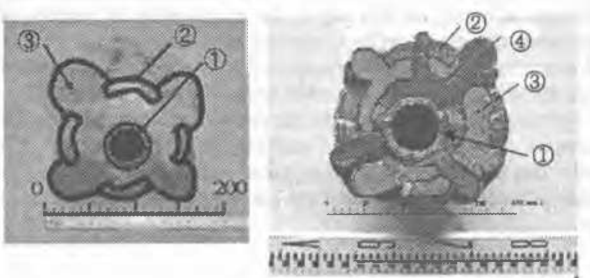



Figure 4. Relationship of quantity, pressure, rate of injection and pressure increment on wall.




(a) (b)

①Injection tube $\phi$ 48.6mm,
②Sleeve grout, ③First injection, ④Second injection
(a) Cross section of first injection
(b) Cross section of second injection

Figure 5. Cross section of ground anchor after injection

der the ground and on the wall changes due to the effect of expansion of the plastic region.

## 5 MECHANISM AND EVALUATION OF PULL-OUT RESISTANCE

### 5.1 *Evaluation of ground pressure distribution based on bulb expansion theory*

If the ground is assumed to be uniform and boundless with constant confined pressure, and the limit pressure, $P_u$, is considered as maximum stress, the plastic region will expand in a circular form (see Fig. 7). In this case, the limit pressure is constant for soil with a bilinear type of stress and strain relationship. However, since sand is used, the deformation due to compression progresses and the density increases, thus, the limit pressure also grows. The test results shown in Figs. 4 and 6 illustrate that density increases around the soil and the limit pressure gradually rises. In order to study these results theoretically, Vesic's columnar cylindrical expansion pressure theory illustrated in Fig. 7 is applied.

The validity of the theory is investigated by determining whether it would reveal the same maximum injection pressure for the first and second injections indicated in Fig. 6. Using equations 1 and 2 based on the theory and the internal angle of friction of Okagaki sand, ö'(=38°), the equation of the fitted curve reveal equations 3 and 4 corresponding to the peaks of first and second injections. Moreover, equations 5 and 6 indicate the residual pressure based on measurement results of each injection.

The unit of equations 3 and 4 is 102 kPa and $\sigma_{r0}'$ is the initial stress of cylindrical cavity which is computed using static pressure coefficient $K_0$=1-sinö' in Jaky's formula. Also, $\sigma_r'$, $\sigma_{r0}'$, $P_u$, $R_u$ and ö' represents the stress along the radial direction after expansion, the initial stress along radial direction, the limit expansion pressure, radius corresponding to the limit pressure and the internal friction angle of soil, respectively.

$$\sigma_r' = \sigma_{r0}' + \Delta\sigma_r' \tag{1}$$

$$\sigma_r' = P_u\left[\frac{R_u}{r}\right]^{\frac{2\sin\phi'}{1+\sin\phi'}} \tag{2}$$

Peak stress for first injection:

$$\Delta\sigma_{1p}' = 12.25\left[\frac{45}{r}\right]^{0.76} - 0.62 \tag{3}$$

Peak stress for second injection:

$$\Delta\sigma_{2p}' = 15.13\left[\frac{67}{r}\right]^{0.76} - 0.62 \tag{4}$$

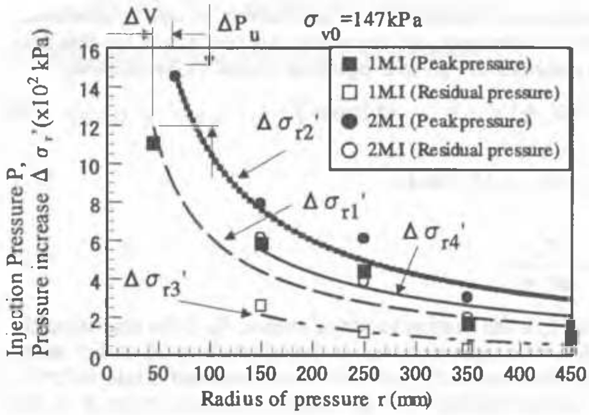
Residual stress for first injection:

$$\Delta\sigma_{1r}' = 6.85\left[\frac{45}{r}\right]^{0.76} - 0.62 \tag{5}$$

Residual stress for second injection:

$$\Delta\sigma_{2r}' = 11.22\left[\frac{67}{r}\right]^{0.76} - 0.62 \tag{6}$$

According to the above equations, the limit pressure further rises due to the expansion of cylindrical cavity. Also, it can explain the change in the stress of ground using cylindrical cavity expansion stress theory. Figure 6 indicates the peak stress during injection and the distribution of the residual pressure after injection. The theory shows good correlation for both cases. Thus, it can be said that due to the effect of multi-injection, the volume (or surface area) increment, $\Delta V$, and radius of plastic region, $R_p$, grow with the pressure increment, $\Delta P$, shown in Fig. 6.




Estimated equation

$\Delta\sigma_{r1}'=12.47\times(45/r)^{0.76}-0.62$ $\Delta\sigma_{r2}'=15.13\times(67/r)^{0.76}-0.62$

$\Delta\sigma_{r3}'=6.85\times(45/r)^{0.76}-0.62$ $\Delta\sigma_{r4}'=11.22\times(67/r)^{0.76}-0.62$

Figure 6. Relationship between injection pressure, pressure increment and radius of pressure.

### 5.2 *Proposed evaluation for pull-out resistance*

The factors which contribute to the increase in pull-out capacity are as follows.

1) The expansion of preceded sleeve grout and proceeding grout due to system's injection pressure, P, thus, also means the increase of anchor diameter, $d_A$ (see equations 7 and 8 indicating the increase of $d_A$ to $D_A$).

2) The increase of skin friction resistance due to the increase in the confined pressure as a result of expansion of anchor diameter (see increase of initial confined pressure, $\sigma_{n0}'$, according to equation 7 to the confined pressure after expansion, $\sigma_n'$, indicated in equation 8).

Assuming that the distribution of skin friction resistance, ($\sigma_y$,$\sigma_y'$), is uniform, the yield pull-out capacity of ordinary anchor, Ty, and that of multi-injection type, $T_y'$, can be expressed by equations 7 and 8, respectively. Provided that the stresses are effective stresses for both cases.

$$T_y = \pi d_A \tau_a (c'+\sigma_{no}'\tan\phi'), \tag{7}$$

$$T_y' = \pi D_A \tau_a (c'+\sigma_n'\tan\phi'). \tag{8}$$

The pull-out capacity of multi-injection anchorage, $T_y'$, in equation 8 can be transformed to equation 9 by considering cav-

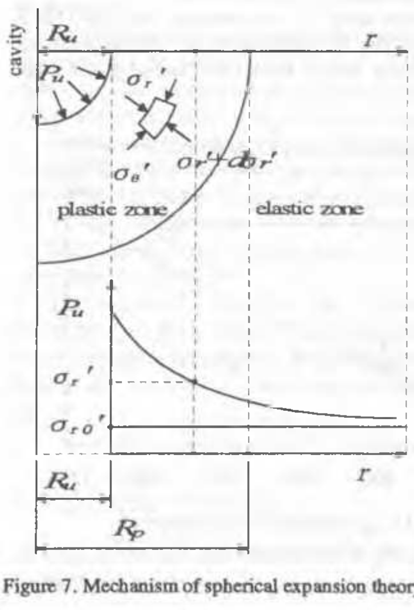



Figure 7. Mechanism of spherical expansion theory.

ity expansion pressure theory and factors 1) and 2) mentioned above. Furthermore, the theoretical and test values for skin friction resistance are given in equations 10 and 11, respectively.

$$T_y' = \pi D_A l_a \left\{ c' + (\sigma_{r0}' + \Delta P_e)\tan\phi' \right\}, \tag{9}$$

$$\tau_{yca}' = (\sigma_{r0}' + \Delta P_e)\tan\phi', \tag{10}$$

$$\tau_y' = \frac{T_y'}{\pi D_A l_a}, \tag{11}$$

where, $l_a$ is the fixation length of anchor, $D_A$ is the equivalent diameter after expansion, $6_{r0}'$ is the initial stress of anchor along radial direction, $ÅP_e$ is the effective increment stress ($ÅP_e = P_e - 6_{r0}'$) around anchor, $P_e$ is the effective residual stress, ö' is the internal friction angle of soil. Provided that the sand ground is considered to have a cohesion of $c'=0$ and internal friction angle of 38°.

There are two unknown factors in equation 10, which are the stress increment and the anchor diameter increment. This equation expresses a relationship considering only the skin friction resistance and without taking account of passive resistance. Moreover, equation 9 represents test values where passive resistance and skin friction resistance are considered. It was verified in the past study (Wada et al. 2000) that the passive resistance could be ignored for the test anchor similar to the behavior of friction piles where the maximum friction capacity occurs when the settlement is about 2% of pile diameter).

Therefore, skin friction resistance can be estimated using the maximum injection pressure, $P_{max}$, during grout injection or the limit pressure, $P_u$, if the effective residual stress, $P_e$, can be found by equations 10 and 11. Assuming that the maximum pressure of injection or the limit pressure gradually reduce after the consolidation of ground. Here, the effective residual stress after the pull-out of anchor is assumed using equation 12,

$$P_e = \beta P_{max}, \tag{12}$$

where $P_e$ is the effective residual pressure after the pull-out of anchor, $P_{max}$ is the maximum injection pressure (or using limit pressure, $P_u$), â is the reduction coefficient of pressure.

Figure 8 shows the relationship between $t_{yca}'$ and skin friction resistance test values, $t_y'$, for one (1M.I.) and two (2M.I.) injections. The values of $t_{yca}'$ are computed by changing the right term of equation 10, i.e. ($s_{r0}' + \Delta P_e = P_e$) to ($s_{r0}' + ÅP_e = P_{max}$). Here, $t_y'$ represents the skin friction resistance with respect to the equivalent diameter $D_A$ calculated using equivalent volume. Moreover, the reduction coefficients of pressure, â, determined from the slope of straight line, $t_y' = t_{yca}'$, are compared.

The values in vertical axis, $t_y'$, are constant for S.G., 1M.I. and 2M.I. types only within the surface area increment of anchor since it is corrected by unit area. It is found from Fig. 8 that there

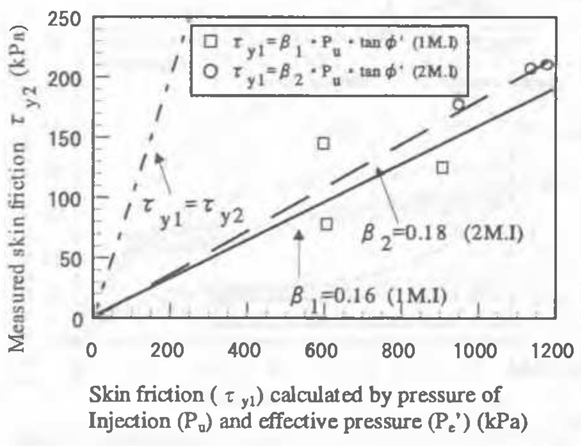



Figure 8. Evaluation of skin friction in multi-injection anchor.

is a pressure effect according to changes in $t_y'$. Here, $P_{max}$ is multiplied by a factor $\beta_1$=0.15 for one injection and $\beta_2$=0.18 for two injections in order to obtain a relationship, $t_y' \fallingdotseq t_{yca}'$. This is because approximately 1/5 to 1/7 of $P_{max}$ is considered as residual, $P_e$, in the sand ground test.

## 6 CONCLUSIONS

The following summarizes the primary results regarding injection characteristics and pull-out resistance of multi-injection anchor based on the test results of this study.

1) Pull-out resistance of multi-injection anchor in loose sand ground is effectively improved. Also, resistance rises further by increasing the number of injections.

2) In multi-injection, the preceded sleeve grout and proceeding multi-injected grout becomes circular passive pressure wall of injection pressure, pushing the soil out, and the anchor expands.

3) The cylindrical cavity expansion pressure theory is effective for estimating limit pressure and underground pressure when cement milk is multi-injected to sandy ground.

4) The factors that contribute to the increase of pull-out resistance in a ground like sand are pressure increment, $ÅP$, due to expansion of anchor and volume increment, $ÅV$.

5) The pull-out resistance of anchor computed as friction resistance on surface area is almost equal to test values with equivalent cylindrical surface area, provided that it is necessary to consider the decrease of effective pressure.

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