Skin friction properties of absorbent polymer using sheet pile pull-out

K. Okamoto
Interdisciplinary Graduate School of Science and Technology (Doctoral Program), Shinshu University, Japan (Nippon Shokubai Co., Ltd., Japan)

T. Umezaki & T. Kawamura
Department of Civil Engineering, Shinshu University, Japan

K. Lin
Formerly Science and Technology (Master's Program), Shinshu University, Japan

A. Hattori
Nippon Shokubai Co., Ltd., Japan

ABSTRACT: A construction method was developed by which the surface of steel is coated with a chemical agent made from superabsorbent polymer, in order to reduce skin friction at pull-out removal of a steel sheet pile. After installing a pile coated with the agent in the ground, the agent contacts ground water and changes to absorbed gel. In this paper, a series of swelling tests and skin friction tests was carried out. Swelling properties of the chemical agent under confining pressure and skin friction properties between the soil and the steel with the agent were discussed. Results confirmed that the agent swells under the large depth of about 100m, and that the friction angle between the soil and the steel with the agent is extremely small, regardless of the type of soil. Furthermore, field pull-out tests of sheet piles were conducted at different sites, and the effectiveness and durability of the method were confirmed.

1 INTRODUCTION

A lot of steel sheet piles are installed in the ground as temporary structures (e.g., earth retaining wall). Pull-out removal of these steel piles is difficult, because large skin friction occurs between the soil and the steel surface. For compulsory pull-out, soils adhere to the steel surface because of the skin friction, a large amount of soil is discharged from the ground, and harmful deformation of the ground (e.g., crack and settlement) occurs. Therefore, in order to reduce the skin friction, a construction method in which the steel surface is coated with a chemical agent made from superabsorbent polymer was developed (Nippon Shokubai Co., Ltd. 2005). After installing the pile with the chemical agent in the ground, the agent contacts water in the ground and changes to absorbed gel after a certain time. Thus, a reducing skin friction layer is formed at the steel surface. However, skin friction properties between the soil and the steel with the chemical agent in the ground have not been sufficiently evaluated.

In this paper, first, a series of column swelling tests was conducted. The swelling properties of the chemical agent under confining pressure were discussed. Second, a series of skin friction tests was conducted, and the friction properties between the soil and the steel surface coated with the chemical agent were discussed. Furthermore, field pull-out tests of steel sheet piles with the chemical agent were conducted. The effectiveness and durability of the method were verified.

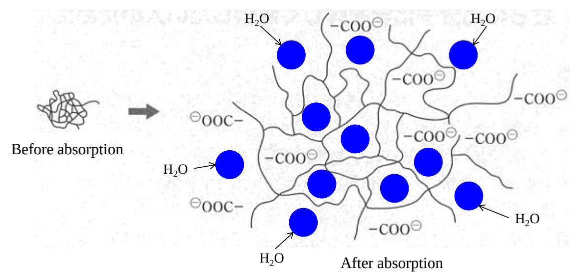


Fig. 1 Absorption mechanism of superabsorbent polymer (Kawakami 2001)

2 SUPERABSORBENT POLYMER

Superabsorbent polymer has a three-dimensional network made by cross-linked polymers with io-

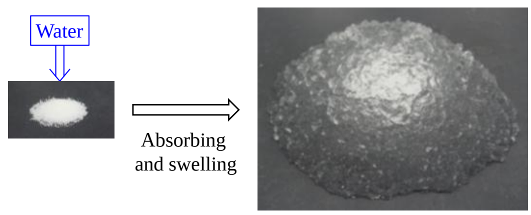


Fig. 2 Absorbing and swelling of superabsorbent polymer

nicity groups, and it is like a folded casting net before water absorption. When water is added, since the ion concentration inside the gel is high, osmotic pressure rises. Water infiltrates into the mesh by osmotic pressure and the affinity of a polymer electrolyte for water. It absorbs until the network structure has fully spread (Fig. 1). The polymer is used for water absorption agents (e.g., disposable diapers) and can absorb water tens to thousands times the self-weight of the agent (Fig. 2). The chemical agent used in the method was newly developed from an improved polymer, for application to construction works (Nippon Shokubai Co., Ltd. 2005).

3 LABORATORY TEST AND FIELD TEST

3.1 *Swelling test*

A column swelling test apparatus (Fig. 3) was newly assembled. The specimen is the chemical agent that coats filter paper. The coating thickness is H_i = 0.173 to 0.200mm. The thickness of the filter paper is 0.21mm, and the diameter of the particle reservation is 1μm. The specimen and filter paper with no coating were stuck on the loading plate and the lower plate with the silicon bond (Fig. 3).

Figure 4 shows test procedure of applying double suction method, which is generally used in order to saturate the specimen in soil test. Here, p is cell pressure, u is water pressure in the tube and p' (= p-u) is effective confining pressure. Firstly, the different negative pressures, p = -75 kN/m^2 and u = -95 kN/m^2, are applied for three hours in order to dry the tube. Secondly, under constant pressure, u = -95 kN/m^2, p is increased until p' (= p + 95 kN/m^2) becomes a specified value. Then in the condition of constant p', p and u are increased gradually until u becomes zero. During this process, water flows into the tube, and the specimen absorbs and swells. Vertical displacement and inflow into tube are measured.

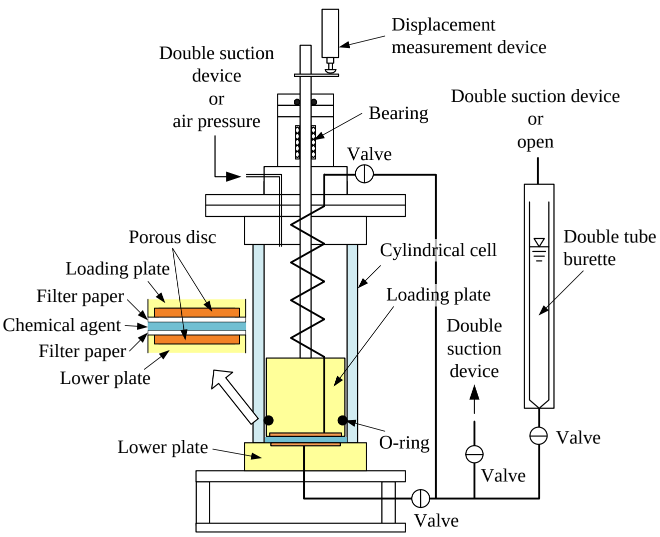


Fig. 3 Column swelling test apparatus

3.2 *Skin friction test*

A box shear test apparatus (Fig. 5), following the Standards of Japanese Geotechnical Society (JIS 0560-2000, 0561-2000), was used for the skin friction test. Soil samples are Kasaoka clay (ρ_s = 2.649g/cm^3, w_L = 58.4%, w_P = 23.3%, I_P = 35.1) and Toyoura sand (ρ_s = 2.702 g/cm^3, ρ_{max} = 1.634g/cm^3, ρ_{min} = 1.341g/cm^3), where ρ_s is soil particle density, w_L is liquid limit, w_P is plastic limit, I_P is plasticity index, ρ_{max} is maximum density, and ρ_{min} is minimum density. Kasaoka clay in a slurry condition was consolidated by vertical stress of 98 kN/m^2, and a specimen with 60mm diameter and 10mm height was prepared. For Toyoura sand, a specimen with 10mm height and relative density $D_r \approx$ 80% was prepared by air-pluviation. Standardized steel material, SS400, was used (Photo 1). The surface of the steel material is treated rustproof and very smooth. The coating thicknesses of the chemical agent were 0.1 and 0.2mm for Kasaoka clay and 0.2 mm for Toyoura sand.

As shown in Fig. 6, the steel material with 10 mm height was inserted into the lower shear box, and the soil specimen was installed on it. After consolidating by a certain vertical stress, the opening between the upper and lower shear boxes was set to 0.2mm by removing the spacer for the opening of the shear box. Pure water was fully poured into the water cell, and the chemical agent absorbed and swelled while the specimen was left in the water for one hour. However, a large amount of absorbed gel leaked from the opening of the shear box. Shear was carried out to 7 mm of horizontal displacement by shear speed of 0.2 mm/min. During the shear stage, the vertical stress was controlled manually to maintain a constant volume in the Kasaoka clay and a constant pressure in the Toyoura sand. For 0.1 mm of the chemical agent in Kasaoka clay and 0.2 mm in Toyoura sand, skin friction between the soil and the steel with the absorbed gel was measured. Because soil

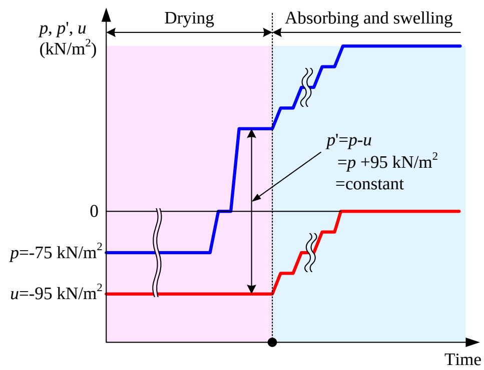


Fig. 4 Test procedure of swelling test

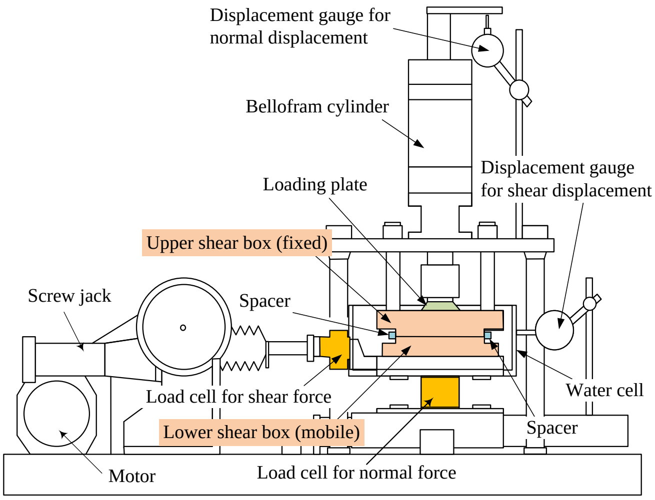


Fig. 5 Box shear test apparatus

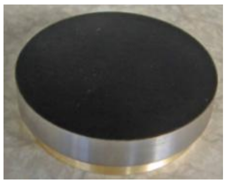


Photo 1. Steel material (SS400)

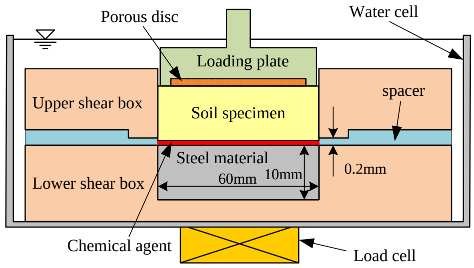
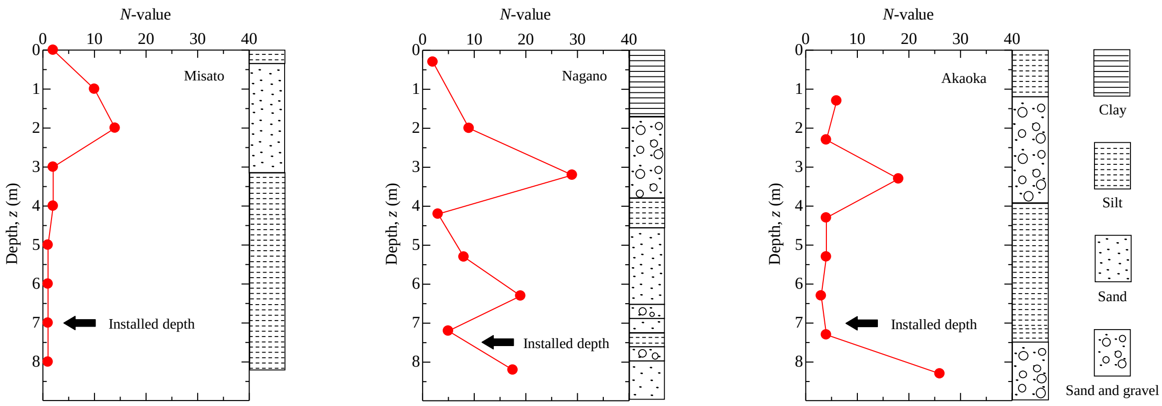


Fig. 6 Cross-section view of specimen and shear box



(a) Misato City (b) Nagano City (c) Akaoka Town

Fig. 7 Ground conditions at test sites in Japan

and absorbed gel exist half and half in the shear zone, which is the opening of the shear box. On the other hand, for 0.2 mm in Kasaoka clay, only the absorbed gel existed in the shear zone, and the internal friction of the gel was measured. In addition, skin friction tests between the soil and the steel material with no coating were carried out similarly, and soil shear tests of Kasaoka clay and Toyoura sand were also carried out.

3.3 *Field pull-out test of steel sheet pile*

At three sites in Japan (Misato City in Saitama Prefecture, Nagano City in Nagano Prefecture, and Akaoka Town in Kochi Prefecture), field pull-out tests of steel sheet piles were carried out. Ground conditions and *N*-values obtained from standard penetration tests are shown in Figs. 7 (a) – (c). Ground conditions are very different for each site. The same type of sheet piles were used, and the installed depths were almost equal for all sites. Steel sheet piles with and without coating were installed in the ground by a hydraulic piler, and they were pulled-out after different elapsed times. The chemical agent coated one side in Misato City, and both sides in Nagano City and Akaoka Town. The coating thickness was 0.4mm in Misato City and 0.2mm in Nagano City and Akaoka Town. In both Nagano City and Akaoka Town, the pull-out force was measured. Pull-out tests were also carried out after one year in Nagano City for study of the durability of the chemical agent.

4 TEST RESULTS AND DISCUSSIONS

4.1 *Swelling properties*

Figures 8 (a) and (b) show the results of a test under constant effective confining pressure, p' (= $p-u$) = 46.5 kN/m^2. Here, ε_v is vertical strain while the chemical agent absorbs and swells. ε_v tends to converge to a constant value with elapsed time. The curve in Fig. 8 (b) is approximated by a hyperbola. The coefficient of correlation is more than 0.99, and the applicability of hyperbola approximation is very high. The convergence value is determined as the swelling amount, ε_s.

Figure 9 shows the relation between effective confining pressure, p', and the swelling amount, ε_s. As the value of p' becomes larger, that of ε_s becomes smaller. This relation can be approximated by a straight line. Here, p' corresponding to $\varepsilon_s = 0$ is defined as swelling pressure, p_s', and the value is $p_s' \approx 400$ kN/m^2. The chemical agent swells under a confining pressure of less than 400 kN/m^2.

Based on the approximated straight line in Fig. 9, the relationships between the thickness of the reducing skin friction layer of the absorbed gel, H_s, and depth, z, are calculated as a trial in Fig. 10. The conditions of trial calculation were assumed as follows. The stress condition in the ground is earth pressure at rest, $K_0 = 0.5$. The ground water level is the same as the ground surface level, G.W.L. = 0 m. The ground is saturated, S_r = 100%. The wet densities of the soil are changed to ρ_t= 1.4 to 1.8g/cm^3, and the density of water is ρ_w = 1.0g/cm^3.The coating thickness of the chemical agent on the steel sheet pile is H_i = 0.2 mm. According to the result of the skin friction test, the thickness of the absorbed gel, H_s = 0.1 mm, is enough for the reducing skin friction layer. Even if installed in the deep ground of 100 m, a layer of reducing skin friction can be formed.

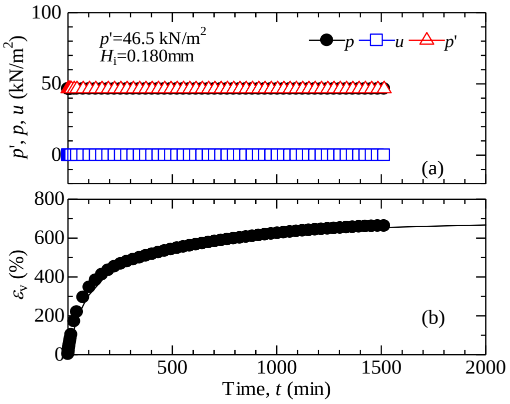


Fig. 8 An example of swelling test result

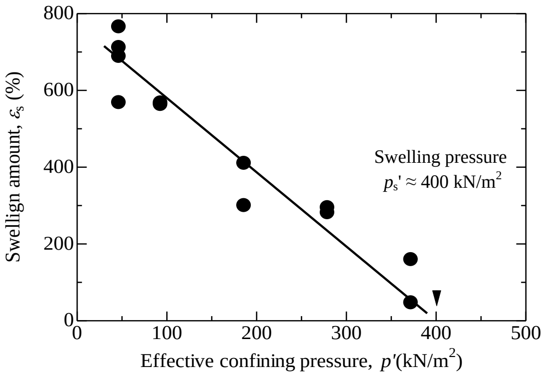


Fig. 9 Relationships between effective confining pressure and swelling amount

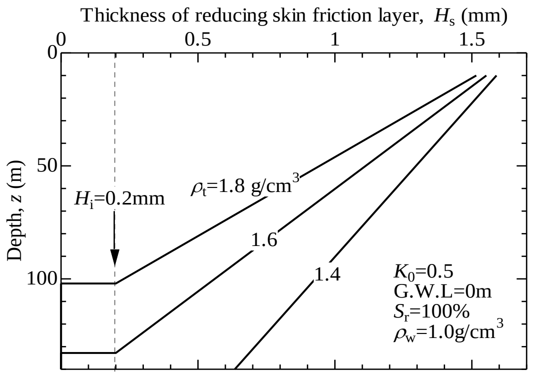


Fig. 10 Trial calculation of the thickness of the layer reducing skin friction

4.2 *Skin friction properties*

Photo 2 shows the absorbed gel on the surface of the steel material after the shear test. The chemical agent changes to the absorbed gel and leaks to the outside of the steel material.

Figures 11 (a) and (b) show the results under initial effective normal stress, σ_{n0}' = 245 kN/m^2. Here, τ is shear stress, σ_{n0}' is effective normal stress, and D is shear displacement. The relation between τ and D in the skin friction test of clay and steel material with no coating differs from that of the shear test of clay (Fig. 11 (a-1)). A peak of τ mobilizes at small displacement, and the value is slightly smaller than that of clay. And τ decreases rapidly and converges to a steady value. The shapes of the $\tau - D$ curves in two different tests using the absorbed gel are similar to that in the test between clay and steel material. However, each peak value is extremely small. Effective normal stress, σ_n', expresses the behavior of dilatancy, and dilatancy in tests other than the shear test of clay rarely occurs (Fig. 11 (a-2)). Figure 11 (b-1) shows the results of the test using sand. In $\tau - D$ curves in two skin friction tests other than the shear test of sand, the maximum value of τ appears at small displacement. Afterward, the values are held almost constant. The maximum value of τ in the skin friction test between sand and steel material is much smaller than that in the shear test of sand. Furthermore, the value of τ in the test between sand and the gel is still smaller. Dilatancy in two skin friction tests other than the shear test of sand also rarely occur.

Figures 12 (a) and (b) show failure lines obtained from the maximum value of τ. All lines can be approximated as straight lines passing through the origin, and the apparent cohesion in all cases is $c' = c_d = c = 0$. As shown in Fig. 12 (a), the internal friction angle of clay is ϕ' = 28.4°, the friction angle between the clay and steel material with the gel is δ= 3.5° and that without the gel is δ= 22.2°.

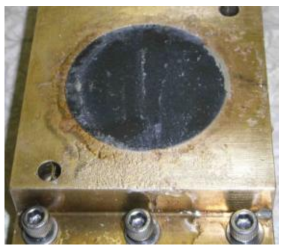
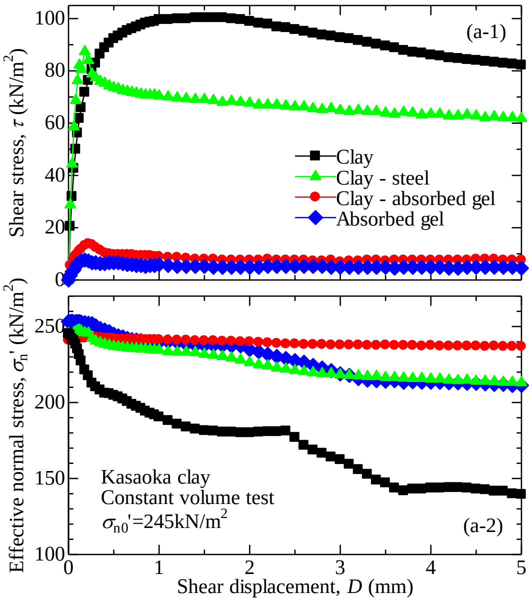
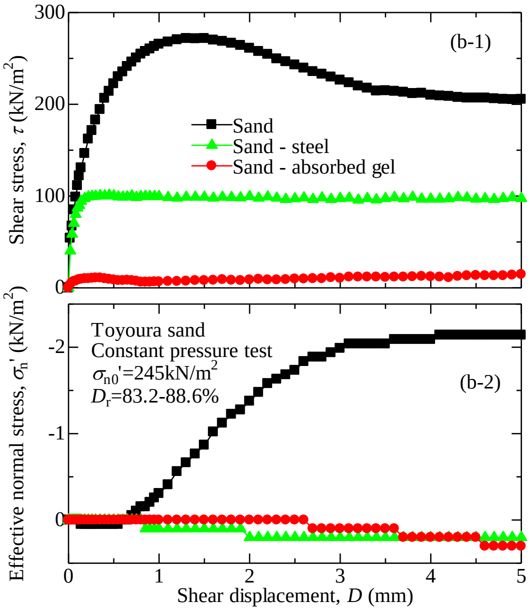


Photo 2. Absorbed gel on steel material after shear test



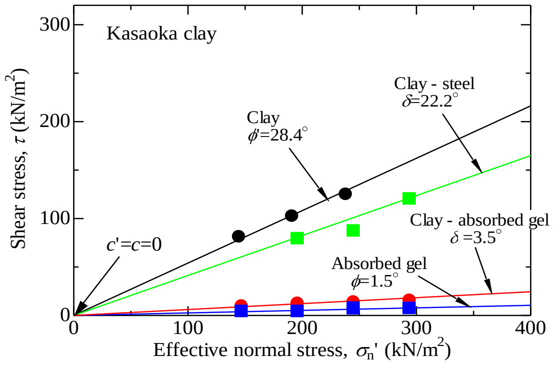
(a) Kasaoka clay



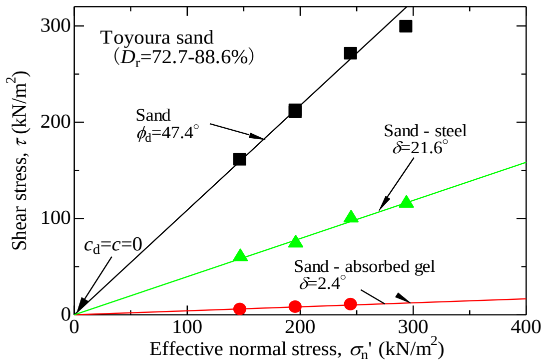
(b) Toyoura sand

Fig. 11 Examples of skin friction test results

Furthermore, the internal friction angle of the absorbed gel is $\phi = 1.5°$, which is extremely small. For Toyoura sand (Fig. 12 (b)), $\phi_d = 47.4°$. The value of δ of the sand and steel material with the gel is $\delta = 2.4°$, and that without the gel is $\delta = 21.6°$. The steel surface used in the tests is very smooth. If steel roughness measured by a roughness gauge with a stylus is more than $R_{max} = 10$ μm in clay or $R_{max} = 70$ μm in sand, the friction angle between the soil and the steel material becomes almost equal to the internal friction angle of the soil (Tsubakihara et al. 1993; Uesugi et al. 1988). Therefore, when the surface of steel rusts, the friction angle becomes the same as the internal friction angle of soil. However, it is supposed that the friction angle between the soil and the steel material



(a) Kasaoka clay



(b) Toyoura sand

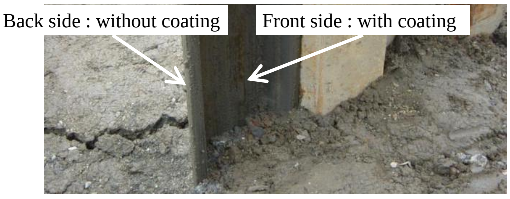
Fig. 12 Internal friction angles and friction angles

coated with the chemical agent is extremely small, regardless of the type of soil.

4.3 *Ground behavior in sheet pile pull-out*

Photos 3 (a) - (c) show the adhesion of soil on a surface of steel sheet pile and the ground behavior at three sites. No adhesion of soil is observed on the front side, which is coated with the chemical agent, and ground deformation hardly occurs (Photo 3 (a)). The chemical agent absorbs and swells by contacting ground water, and the absorbed gel adheres to the sheet pile surface. This use of a chemical agent is effective because when the steel surface rusts, skin friction of the sheet pile with the agent becomes very small. However, a crack on the ground surface grows on the back side of the sheet pile with no coating (Photo 3 (a)). In the steel sheet pile with no coating, a lot of soils adhere to the concave part of the sheet pile and are discharged from the ground (Photos 3 (b-1) and (c-1)). However, for the sheet pile with the chemical agent, no adhesion of soil is observed, even if sites and types of soil are different (Photos 3 (b-2) and (c-2)). Photo (c-3) shows the ground surface after the sheet pile with the chemical agent was pulled out. Only the opening where the steel sheet pile was installed remains on the ground surface.

Figure 13 shows the changes in the maximum pull-out force of the steel sheet pile, F, with elapsed time in Nagano City and Akaoka Town.



(a) With coating on one side (Misato)

(b-1) Without coating (Nagano)

(b-2) With coating (Nagano)

(c-1) Without coating (Akaoka)

(c-2) With coating (Akaoka)

(b-3) Ground surface after pulled-out of sheet pile with chemical agent (Akaoka)

Photo 3. Pull-out tests of steel sheet piles at three sites

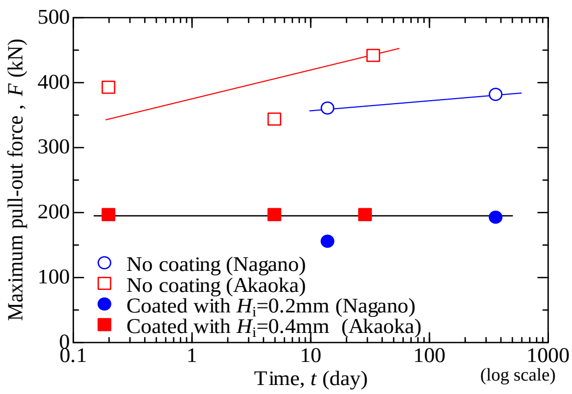


Fig. 13 Maximum pull-out forces in field tests

The installed lengths of the steel sheet piles, 7 and 7.5m, at the two sites are almost the same. The values of F for the pile with no coating are different for each site and each value slightly increases with elapsed time. However, the values of F with the chemical agent are almost the same at both sites, because the friction angle between the soil and the absorbed gel is almost the same, regardless of the type of soil (Figs. 12 (a) and (b)). The friction angles with coating are smaller than 10% of the internal friction angle of soil, but the values of F with coating are almost half of those with no coating, because of the effect of bending and joint of the sheet pile. The values of F with the agent hardly change with elapsed time. In Nagano City, the effect of reducing skin friction was sufficient after one year.

5 CONCLUSIONS

The main conclusions are as follows.

(1) As the effective confining pressure becomes larger, the swelling amount of the chemical agent becomes smaller. The chemical agent can absorb and swell under a confining pressure of less than 400 kN/m^2. Even if installed in the ground at a depth of 100 m, a reducing skin friction layer of absorbed gel can be formed.

(2) Compared with the internal friction angles of soil for Kasaoka clay (c' = 0, ϕ' = 28.4°) and Toyoura sand (c_d = 0, ϕ_d = 47.4°), the friction angle of the absorbed gel is extremely small: δ = 1.5° (c = 0).

(3) Regardless of the type of soil, the friction angle between the soil and steel coated with the chemical agent is also very small: δ = 2.4–3.5°. The value of δ is smaller than 10% of that of soil.

(4) The steel sheet pile with the chemical agent can be pulled-out without adhesion of soil to the surface, and crack and deformation of the ground hardly occur.

(5) By coating the chemical agent, the maximum pull-out force of the sheet pile can be reduced to a value smaller than half of that with no coating. When the length of sheet pile is the same, the maximum pull-out force is the same even if the site is different. The effectiveness and durability of the method were confirmed.

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