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Grouting and pull-out tests of hollow-type prestressing-strands for an internal strengthening system

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ABSTRACT

The present study focused on creation of an internal strengthening system, which involved embedding a post-tensioned PC tendon in a wedge-shaped anchorage of an existing concrete member. Under conditions with narrow work spaces, it was difficult to employ the previous system using a post-tensioned prestressing bar, as adequate backspace was required to install the bar. A flexible hollow corrugated pipe covered with steel wire cables seemed applicable even in such narrow spaces. Interestingly, the hollow stranded tendon could also be used as a grouting-pipe to fill the internal anchorage. The foci of this study were to develop a grouting material suitable for passage through a hollow corrugated pipe, and to determine the applicability of the hollow-type prestressing tendon for the internal strengthening system. In the study, a horizontal grouting test was first conducted using 5 m-long corrugated pipes of 10 mm internal diameter. It was confirmed from the grout and strength tests that some grouting materials were applicable for filling the hollow-type PC strands. In addition, pull-out tests of the prestressing tendon embedded in the anchorage of mock-up RC blocks were conducted to examine their load-bearing capacity. Furthermore, visible tests of the horizontal and upward grouting were conducted to confirm the filling condition in the wedge-shaped anchorage. The test results confirmed adequate load-bearing capacity of the hollow prestressing tendon embedded in the anchorage when the filler applicable to horizontal grouting was used.

1. Introduction

1.1. Objectives

General concrete is vulnerable to tensile forces, and cracks often occur due to internal and external forces. Post-tensioning prestressing is a reliable method for reinforcing concrete structures. Post-tensioned prestressed concrete (PC) members are generally employed in civil infrastructure such as bridges. Post-tensioning prestressing is also an effective method for strengthening existing concrete structures. The strengthening system with external prestressing cables is widely used to increase the load-bearing capacity of concrete bridge girders. However, it may be hard to arrange such prestressing cables for some concrete members, because the workspace available may be inadequate for the strengthening work. To avoid workspace issues, the authors [22,23] developed an internal prestress strengthening system for existing concrete members, by which a post-tension prestressing tendon is embedded in a wedge-shaped internal anchorage (Fig. 1). Previous studies confirmed that post-tensioned prestressing bars can be firmly anchored in the internal wedge hole filled with high-strength filling material and that the system can contribute to the durability of jointed concrete members. Rigid prestressing bars were used in previous investigations [22,23]. It should be noted that adequate backspace is often required for installing the rigid bars in the existing concrete members. Fig. 2 presents a typical application for strengthening the footing of bridge piers. It may be hard to install conventional rigid bars into such underground concrete members (Fig. 2a). On the other hand, a flexible prestressing tendon is more applicable, even in a narrow workspace (Fig. 2b).

The present study focuses on use of the internal prestressing system with flexible prestressing tendons. In particular, the applicability of a hollow-type prestressing tendon (a flexible hollow corrugated pipe covered with prestressing wire cables; Fig. 3) for this purpose was studied. Of interest is that the corrugated pipe can be used as a grouting

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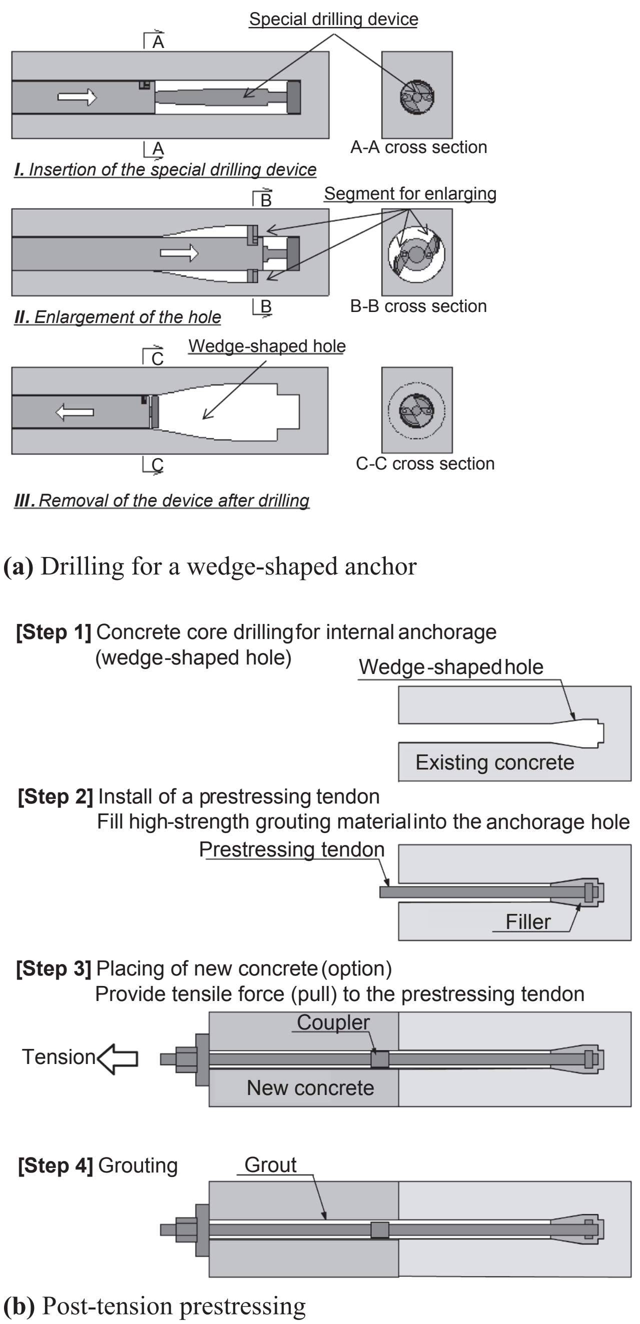


Fig. 1. Schematics of the developed strengthening system.

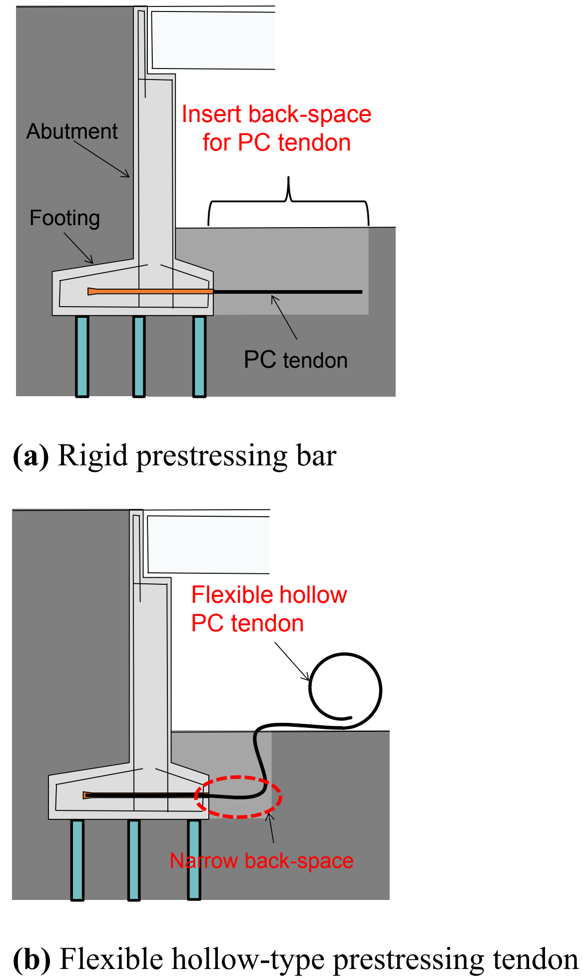


Fig. 2. Schematics of bridge footing applications.

pipe to add filling materials to the anchorage. The objectives of this study were to develop a grouting material suitable for passage through a hollow corrugated pipe, and to examine the pull-out loading capacity of the flexible prestressing tendon anchored in the wedge-shaped hole with the grouting material.

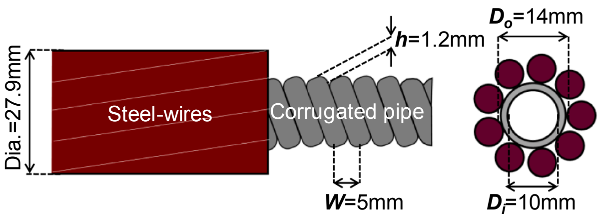
1.2. Review of research

Prestressing with an external and/or un-bonded tendon is a well-known method for strengthening concrete effectively. Ng and Tan [24] developed a simple "pseudo-section analysis" method for externally prestressed concrete beams subjected to flexure. In addition, Ng and Tan [25] examined the flexural behavior of prestressed beams and confirmed the applicability of the proposed analytical model. Vu et al. [32] proposed a structural model of post-tensioned prestressed beams with unbonded tendons. Their model accurately predicted the deformations observed in experimental flexural tests. Saleem and Tsubaki [28] focused on a post-installed two-layered anchor system for strengthening RC members and developed an analytical model for pull-out responses. Park et al. [26] conducted flexural tests of post-tensioned girders using high-strength strands. They reported that predictions of current design codes agreed well with the experiments while concrete crack widths and stresses of reinforcement slightly exceeded the specified limits. Yurdakul and Avşar [35] investigated the retrofitting technique by post-tensioning for an RC beam-column joint. Abela [2] reviewed investigations of a post-tension grouted anchor used for existing Tainter-gate anchorage systems. Faria et al. [8,7] investigated post-tension prestressing techniques for strengthening flat-slabs. The structural responses of post-tensioned concrete slab/wall structures have also been extensively reported [9,1,33,4,10].

Akiyama et al. [3] examined the flexural behaviors of cylindrical concrete piles prestressed with unbonded bars. This paper showed that the load capacity of a prestressed concrete pile was greatly increased by confining the pile between carbon fiber (CF) sheets. Kara et al. [13] conducted numerical analysis for estimating the curvature, deflection, and moment capacity of RC beams strengthened with prestressed NSM FRP bars/strips. The numerical parametric study indicated that higher prestressing levels improved structural performance; however, the levels decreased the beam ductility in comparison with beams strengthened with non-prestressed NSM FRP bars/strips. In addition, advanced materials such as fiber reinforced polymers (FRPs) have been used as alternatives to conventional steel tendons [5,16,29,34,6,20,21,17,18,36,19,27].

Grouting materials are also key factors for post-tensioning

(a) Hollow corrugated pipe covered with steel-wire cables



(b) Dimensions of hollow corrugated pipe

Fig. 3. Flexible prestressing tendon.

Table 1
Fundamental properties of prestressing tendons.

Materials	Rigid bar	Hollow-type tendon
Nominal diameter	23 mm	27.9 mm
Young's modulus	202 GPa	162 GPa
Yield strength	448.7 kN (1080 MPa)	N/A
Tensile strength	511.0 kN (1230 MPa)	588 kN (1732 MPa)
Standard	JIS G 3109	N/A

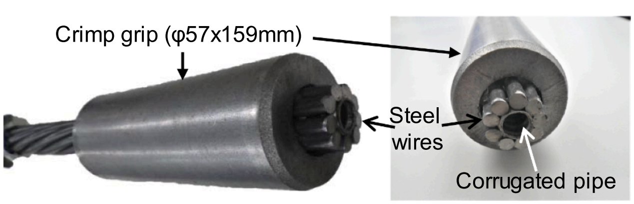


Fig. 4. Crim grip for flexible tendon.

prestressed concrete structures. Khayat et al. [14] conducted a laboratory test to develop a high-performance cementitious grout applicable in horizontal and vertical post-tensioning ducts. Schokker et al. [30] carried out a simulated field test on grouting materials for vertical and horizontal applications and recommended a suitable grout mixture. Schokker et al. [31] also conducted a pressure-filter test and reported a rational post-tensioning grout material for bleed-resistance. Kim et al. [15] examined fresh and hardened properties of steel-fiber reinforced grout applicable to PC substructures. The study revealed positive effects by ground, granulated blast-furnace slag (GGBS) on the chloride-penetration resistance and flowability of the grout. Kamalakannan et al. [12] conducted tests on fresh and hardened properties of premixed grouting materials for post-tensioned concrete. They evaluated the effect of binder fineness on the performance of the grouting materials.

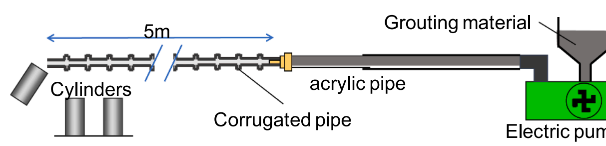
Mimoto et al. [22] developed a new internal strengthening technique using post-tensioned tendons and a wedge-shaped anchorage. In this study, a pull-out test was conducted to examine the load capacity of a prestressing tendon fixed in the internal anchorage. In addition, Mimoto et al. [23] conducted a flexural test using full-scale beams jointed by the post-tensioning technique. Rigid prestressing steel-bars (SBPR930/1080: yield strength of 1080 MPa) and a special pre-mixed mortar of high strength were used in these studies. The previous investigations confirmed the adequate load-bearing capacity of a rigid

Table 2
Materials and mixture proportions of grouting material.

Materials	Type	Density
Water (**W**)	Tap-water	1.00 g/cm^3
Cement (**C**)	Ordinary Portland cement	3.16 g/cm^3
Micro filler (**F**)	Silica fume	2.21 g/cm^3
Fine aggregate (**S**)	Crushed sand	2.60 g/cm^3
High-range water reducing agent (**HRWRA**)	Poly-carboxylic acid	1.04 g/cm^3
Shrinkage reducing agent (**SRA**)	Glycol ether	0.98 g/cm^3
Pre-mixed mortar (I)	Manufacturer S[a]	N/A
Pre-mixed material (II)	Manufacturer S[a]	N/A
Pre-mixed material (III)	Manufacturer T[a]	N/A

No.	*w/cm*	W	C	F	S	HRWRA	SRA
0	0.12	1.2 kg/mix	10 kg/mix[I]			0	0
1	0.20	2.0 kg/mix	10 kg/mix	N/A	0	***cm****1.4%	0
2	0.20	2.0 kg/mix	9.5 kg/mix	0.5 kg/mix	0	***cm****1.5%	**W***1.5%
3	0.20	2.0 kg/mix	9.0 kg/mix	1.0 kg/mix	0	***cm****1.5%	**W***1.5%
4	0.20	2.0 kg/mix	10 kg/mix[II]		0	0	0
5	0.26	2.6 kg/mix	10 kg/mix[III]		0	0	0

a: the components and mixture proportions cannot be released.
I: Pre-mixed mortar (I); II: Pre-mixed material (II); III: Pre-mixed material (III).



(a) Schematics

(b) Observed material segregation (No.3)

Fig. 5. Grouting test.

Table 3
Grouting test results.

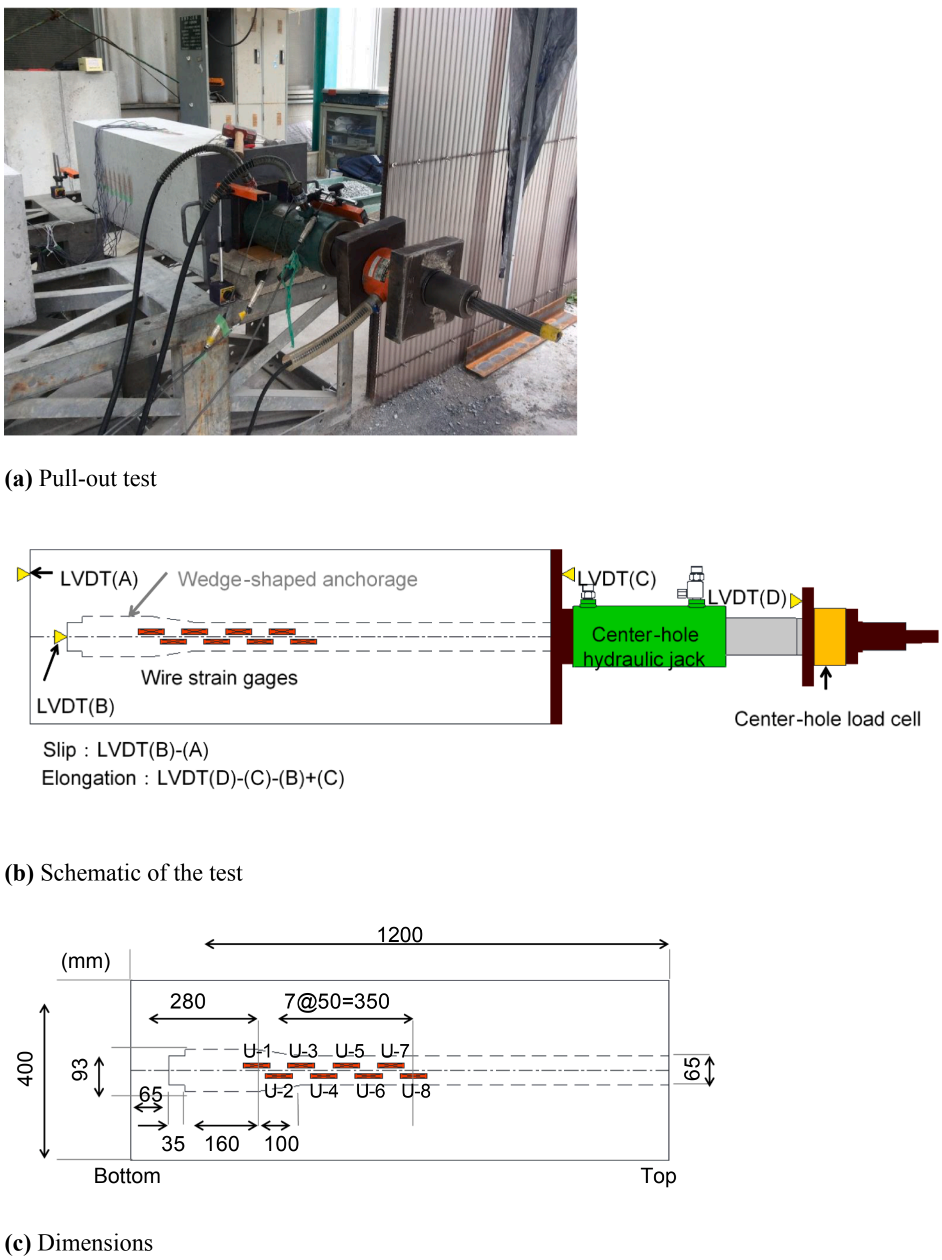
No.	Flow[a] (mm)	5 m long grouting	Segregation	f'_{7d} (MPa)	Filling condition
0	189	Incomplete	N/A	109.6[b]/–	N/A
1	> 300	Incomplete	Yes	104.5[b]/–	N/A
2	244	Complete	No	118.7[b]/ 132.7[c]	Full
3	193	Complete	Yes	90.1[b]/45.2[c]	N/A
4	265	Complete	No	113.0[b]/ 103.0[c]	Full
5	163	Complete	No	103.6[b]/ 98.4[c]	Full

[a] Table flow-test.
[b] The materials obtained from the mixer.
[c] The grouted materials for 5 m long.

prestressing bar embedded in the grout-filled anchorage, even under pull-out and flexural loadings.

2. Hollow-type prestressing tendon

As aforementioned, the footing of a bridge pier is one kind of application for the newly developed strengthening system. To install post-tensioning tendons on the existing concrete members, adequate backspace is often required for the placement of rigid prestressing bars, which was tested in previous studies [21,23]. The conventional prestressing rigid bars may not be applicable in narrow workspaces such as footings under the ground, as shown in Fig. 2(a). On the other hand, flexible prestressing wire-cables can be installed in the existing concrete even in such narrow work conditions, as illustrated in Fig. 2(b). The flexible hollow-type prestressing tendon must be a useful material to extend the applicability of the new strengthening method. A hollow-type corrugated pipe covered with twisted steel-wire cable (Fig. 3a) is

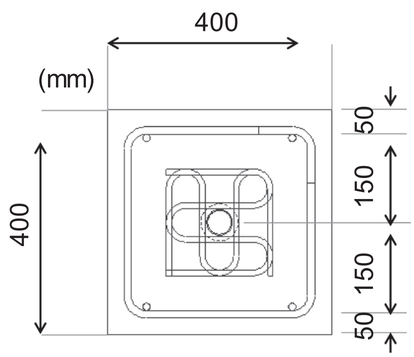


(a) Pull-out test

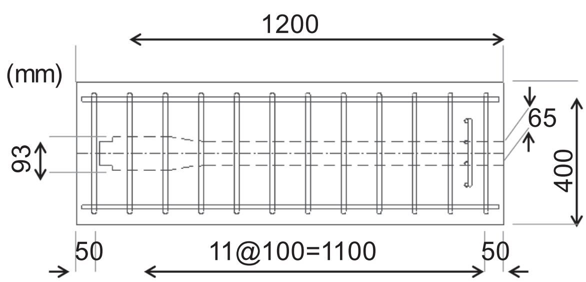
(b) Schematic of the test

(c) Dimensions

Fig. 6. Detail of RC block for pull-out test.



(d) Rebars arrangement -top view-



(e) Rebars arrangement -side view-

Fig. 6. (*continued*)

Table 4
Materials and concrete-mixture proportion for pull-out test.

Materials	Properties						
Reinforcing bar	JIS G-3112; Nominal diameter: 13 mm (D13) Yield strength: 345 MPa; Young's modulus: 206 GPa						
Hollow-type PC tendon	See Table 1						
Steel-sleeve	Crimp grip: 57 mm dia × 159 mm long						
Bearing plate with a hole	JIS G-3101; Dimensions: 120 × 120 × 25 mm Yield strength: 235 MPa; Young's modulus: 206 GPa						
Concrete materials	Type			Density			
Water (W)	Tap water			1.00 g/cm^3			
Cement (C)	Ordinary Portland cement			3.16 g/cm^3			
Fine aggregate (S)	Crushed sand			2.64 g/cm^3			
Coarse aggregate (G)	Crushed stone			2.68 g/cm^3			
Admixture (AD)	WRA			1.04 g/cm^3			
Type	*w/cm*	W kg/m^3	C kg/m^3	S kg/m^3	G kg/m^3	AD kg/m^3	Air %
Conc.	0.90	190	211	993	930	0.63	4.5

Table 5
Fundamental properties of filling materials and concrete.

Filling material	Flow	Comp. strength	Young's mod.	Poisson's ratio
No.2	244 mm	118.3 MPa	26.7 GPa	0.25
No.4	225 mm	89.2 MPa	20.2 GPa	0.24
No.5	160 mm	95.7 MPa	21.8 GPa	0.26
Concrete	Slump	Comp. strength	Young's mod.	Poisson's ratio
Conc.	80 mm	25.1 MPa	25.3 GPa	0.20

often used in mining and related activities. This material has the unique features of higher flexible and ductility. In the study reported herein, the focus was on the use of this material as a prestressing tendon for the strengthening system.

The hollow-type prestressing tendon had an outer diameter of 27.9 mm. The PC tendon consisted of corrugated steel-pipe of 10 mm inner diameter and 9 wires of 6.9 mm diameter. Fig. 3(b) describes the details of the corrugated pipe, which served as the inner material of the prestressing tendon. The inner pipe was used as a grouting pipe for adding filling material to the wedge-shaped anchorage.

The load capacity and the designed Young's modulus of the flexible tendon were 588 kN and 162 GPa, respectively. The fundamental properties of rigid and flexible tendons are summarized in Table 1. A crimp grip, a sort of steel-sleeve, was attached to the cable-end to resist the pulling force by the prestressing tendon (Fig. 4).

3. Grouting test with the hollow corrugated pipe

3.1. Materials and mixture proportions

Adequate flowability and pumpability are required for the grouting materials. In addition, high strength (90 MPa or higher) is required for the hardened grout in the internal anchorage. To achieve the required properties, the conventional materials given in Table 2 were prepared. Pre-mixed materials (I, II, III) were also tested. Furthermore, Table 2 shows the mixture proportions of the grouting materials. Mixture No. 0 is the grouting material used for the rigid bar in the previous investigations [21,23]. Mixtures No.4 and No.5 are pre-mixed grouting materials provided by different manufacturer. The primary components in these grouting materials are cementitious binder, expansive and viscous additives, water-reducing chemical agent while the mixture proportion cannot be revealed in public. Further information about these pre-mixed materials such as physical and chemical components cannot be released herein because of the commercial contract with the manufactures.

3.2. Grouting test method

Fig. 5(a) presents the grouting test conditions. To consider the general application, a grouting test for a corrugated pipe 5 m long was conducted using an electric pump (maximum rate: 2000 cm^3/min). The corrugated pipe was arranged horizontally to simulate transverse strengthening of concrete members. In such cases, air-removal and full-grouting at the anchorage should be examined carefully. To achieve adequate strength, segregation of the filling material after grouting cannot be allowed. Compressive strength was examined using grouting materials that traveled 5 m without material segregation, even at the end of the corrugated pipe. The dimensions of the cylindrical test specimens were 50 mm diameter and 100 mm length.

3.3. Test results and discussion

Table 3 summarizes the test results. All the test materials obtained from the mixing-bowl achieved compressive strength of 90 MPa or higher, which is what was required for the wedge-shaped anchorage. The conventional high-strength mortar (No. 0) and the plain cement paste (No. 1) hardly passed through the corrugated pipe 5 m long because of material-segregation in the pipe. The cement pastes incorporating silica-fume (No. 2, 3) completely passed to the end of the pipe 5 m long; however, material segregation at the pipe-end (Fig. 5b) was observed in grouting test No. 3. The compressive strength of filling material No. 3 obtained from the pipe-end, was only about half of the required minimum strength (90 MPa). It is remarkable that the other

(a) Drilling

(b) Drilling device

(c) Hollow-type PC strand

(d) Grouting

Fig. 7. Preparation of RC block for pull-out test.

grouting materials (No. 2, 4, and 5) passed through the 5 m corrugated pipe without segregation and achieved the required strength.

The filling test using the hollow-type prestressing tendon confirmed that the required conditions were met, even in the horizontal wedge-shaped anchorage. Based on the grouting tests, three filling materials (No. 2, 4, and 5) were employed in the pull-out tests shown in the next section.

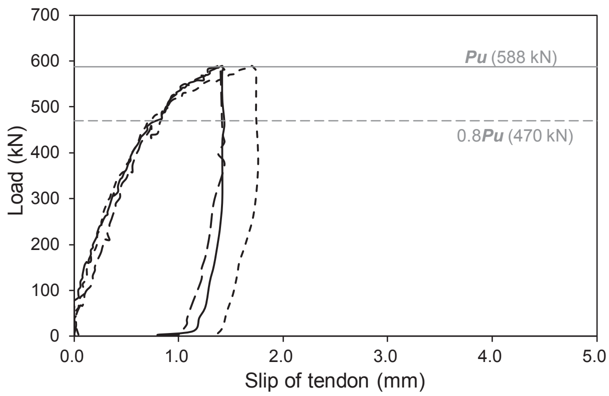
4. Pull-out test of the hollow-type prestressing tendon

4.1. Test specimens

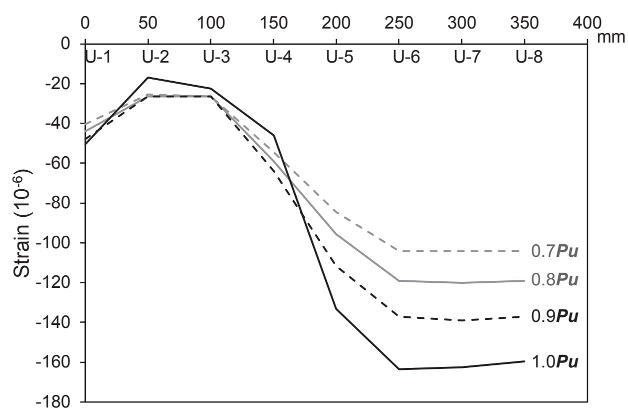
The study prepared 8 RC blocks for the pull-out test. Three specimens made by vertical grouting were used for each test (No.2 and No.4), and a specimen made by vertical grouting (No.5) was also tested. The last RC block was used for horizontal grouting and pull-out tests (described later). The dimensions of the mock-up RC blocks were 400 × 400 × 1200 mm. To avoid splitting failure, the cross section (400 × 400 mm) of the RC blocks was designed by referring to a previous study [22]. Fig. 6(a)–(e) describes the pull-out test and dimensions of the concrete blocks. The materials used in the RC blocks and the mixture proportions of the concrete are summarized in Table 4. The specified compressive strength of the concrete was 24 MPa at 28 days. To simulate a deteriorated concrete member, concrete was made with a relatively high water-cementitious material ratio ($\boldsymbol{w/cm}$ = 0.90). It should be noted that concrete with such high $\boldsymbol{w/cm}$-ratio was employed only for this experimental study and is hardly used in any practical application in Japan. Fundamental properties of the grouting materials (No.2, No.4, No.5) and the concrete for RC block were summarized in Table 5.

The wedge-shaped hole for the PC anchorage was made by drilling and enlarging. The diameter and length of the wedge-shaped hole was 93–65 mm and 100 mm, respectively. Fig. 7(a)–(d) describe the preparation of the tested RC blocks. The water and concrete shavings left after the drilling were removed with a vacuum (340 W), and the hole size was confirmed by a microscopy (8 mm diameter, 300,000 pixels).

A hollow-type corrugated tendon, with a steel sleeve attached to the tendon end, was installed in the wedge-shaped hole. The filling material

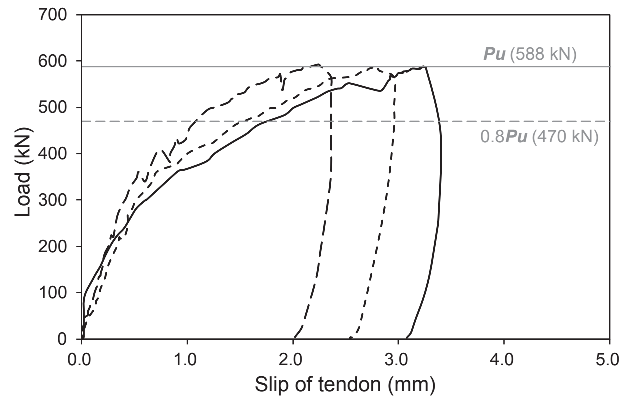


(a) Pull-out load – slip responses

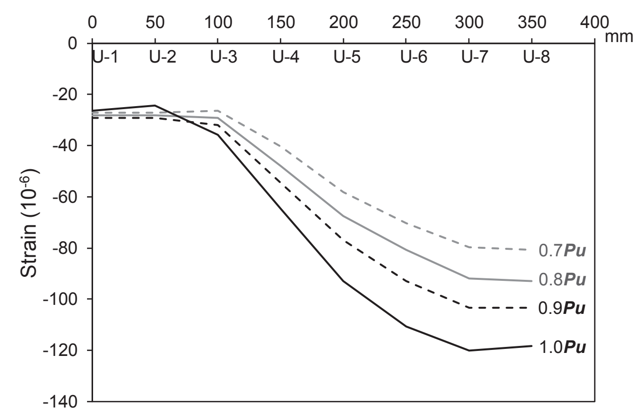


(b) Axial strain of concrete

Fig. 8. Pull-out test results (No.2).



(a) Pull-out load – slip responses



(b) Axial strain of concrete

Fig. 9. Pull-out test results (No.4).

(No. 2, 4, or 5) was grouted into the anchorage through the internal corrugated pipe. To ensure complete filling in the experimental study, vertical grouting was performed as shown in Fig. 7(d).

4.2. Test method

The pull-out load of the embedded PC tendon was provided to the test specimens by a center-hole hydraulic jack system. The load was statically increased to 588 kN, which is the capacity of the hollow-type prestressing tendon. A schematic of the pull-out test is illustrated in Fig. 6(b). A center-hole load cell (Max. 1000 kN) and 4 Linear Variable Differential Transformers (LVDT (A)-(D)) having the capacity of 100 mm were set as shown in the schematic figure. In addition, wire strain gauges (120 ohm, 60 mm long) were arranged on the concrete surface as shown in Fig. 6(c). The pull-out test was conducted at the grouting-material age of 12 days.

4.3. Pull-out load capacity and slip

The maximum loads of all test specimens exceeded the nominal load-capacity ($\boldsymbol{P_u}$ = 588 kN) of the flexible tendon. For safety in the experiment, the pull-out loads were maintained for a while (about 1 min. for observing cracks); then removed immediately when the measurement using the load-cell was 588 kN or higher. It is certain that the actual maximum loads were higher than the designed load-capacity ($\boldsymbol{P_u}$ = 588 kN). It is noteworthy that the observed loads were almost 100 kN higher than the maximum loads of the rigid tendon used in a previous study [22]. The observed elongations of the tendon were proportional to the load up to a load of approximately 490 kN. The prestressing tendons did not yield and were firmly fixed in the wedge-shaped anchorage by the filling material. The results confirm that the load-bearing capacity of the anchoring system was adequate for the prestressing tendon used in this study. The loading test for each of the three filling materials used is described below. Note is that the load-capacity ($\boldsymbol{P_u}$ = 588 kN) is the maximum tensile force guaranteed by the manufacturer and the criterion force (0.8 $\boldsymbol{Pu}$) shown below is defined in the Japanese specification [11].

4.3.1. Filling material No. 2

Fig. 8(a) and (b) show pull-out load-slip responses and concrete strains, respectively. Obvious increases of the tendon slip were observed at the pull-out load of 490 kN. The total slips of the tendon were in the range 0.7–0.8 mm at the load of 470 kN (=0.8 $\boldsymbol{P_u}$). The maximum strain at the concrete surface was −147 micro-strain at U-7 (300 mm from the anchorage edge) and was almost equal to the designed value (−145 micro-strain). Note is that the designed strain was calculated using the load and apparent Young's modulus of the RC block. The observed strain distribution confirms a constant compressive strain at U-6 (250 mm from the anchorage edge) or higher positions.

4.3.2. Filling material No. 4

Fig. 9(a) and (b) show pull-out load-slip responses and concrete

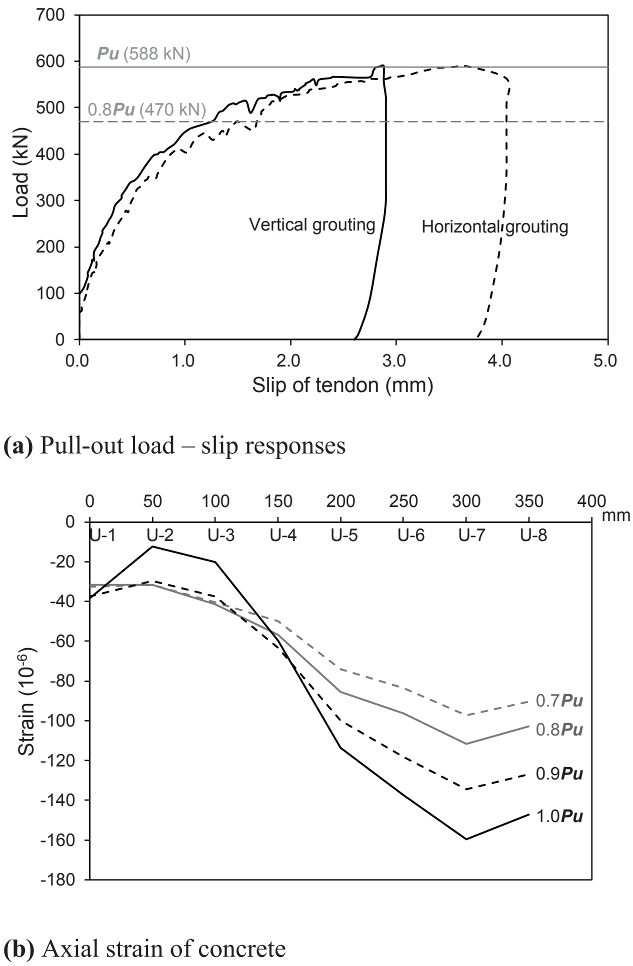


Fig. 10. Pull-out test results (No.5).

strains, respectively. As well as the test mentioned above, this test confirms that the tendon-slip significantly increased at the load of 490 kN. The total slips of the tendon were greater than the test results of No. 2, and were in the range 1.1–1.7 mm at the load of 470 kN (=0.8 P_u). The maximum strain at U-7 was −141 micro-strain, and the strain was almost equal to the maximum strain of No. 2 and the designed value. Hence, constant strain distributions were also observed in this test.

4.3.3. Filling material No. 5

Fig. 10(a) and (b) show pull-out load-slip responses and concrete strains, respectively. For comparison, the result obtained from the horizonal grouting test (discussed later) is shown in Fig. 10(a). The nonlinear response to the pull-out load was almost same as the test results (No. 2 and 4), the obvious increase of slip was observed at approximately 490 kN. The total slip of the tendon was 1.24 mm at the load of 470 kN (=0.8 P_u). The maximum strain was −161 micro-strain at U-7, and it was slightly greater than the designed value.

The test results (No. 2, 4, 5) showed that the load capacities were adequate for fixing the tendon and that the slips were little different. It is noted that these test results were obtained from the specimens having the tendon anchorage filled with high-strength materials. Therefore, horizontal and upward grouting into the anchorage was examined to investigate their practical application for the horizontal strengthening of concrete structures.

5. Experimental verifications

5.1. Visible test for horizontal and upward grouting

The greatest concern with horizontal grouting is having a void in the upper part of the anchorage. Grouting material may flow out of the anchorage because high fluidity is required to pass through the corrugated pipe. Hence, it may be hard to achieve adequate anchoring for the prestressing tendon. To examine complete filling even in horizontal grouting, a visible test was conducted using a transparent acrylic pipe that simulated the wedge-shaped anchorage (Fig. 11(a)). The fillers tested were the cementitious grouting materials (No. 2, 4, and 5) that achieved the fluidity appropriate for passing through the 5 m corrugated pipe and the capacity adequate for the (vertical) pull-out loading.

Transparent pipes 1 m long were used in the visible test (Fig. 11(b)). To prevent outflow of the filling material, steel-wool (sw) was set at the edge of the anchorage in some test cases (Fig. 11(c)). In addition to the horizontal grouting, upward grouting of 0.35 rad was also carried out in the visible test. A schematic of the visible filling test is illustrated in Fig. 11(d).

Fig. 12(a)–(c) illustrates grout-filling conditions of 0 rad, 0 rad + sw, and 0.35 rad + sw, respectively. In addition, the visible test results are summarized in Table 6. The test result confirms that grouting material No. 5 entirely filled the wedge-shaped acrylic pipe without the use of steel-wool. On the other hand, grouting materials No. 2 and 4 flowed out from the edge of the wedge-shaped pipe, and upper voids were observed in the pipe. The different results were due to the paste-flow, that is, 163 mm for filler No. 5 and over 200 mm for the other fillers (No. 2 and 4).

In the test using steel-wool, the grouting materials (No. 4 and 5) entirely filled the simulated anchorage. For filling material No. 2, an upper void was observed while the outflow was slightly reduced by the steel-wool. One remarkable observation was that the pseudo wedge-shaped anchorage of 0.35 rad (upward grouting) was entirely filled using material No. 5 and steel-wool. Filler No. 5 is a commercial premixed material that contains Portland cement, an expansive material, a thickener, and a high-range water reducing agent (HRWRA).

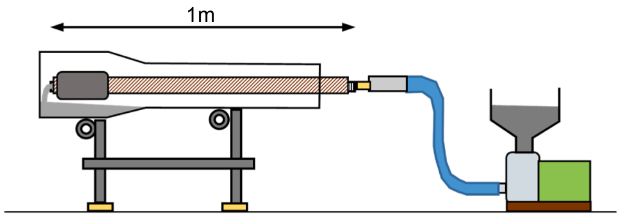
5.2. Horizontal pull-out loading test

In the visible test, material No. 5 was selected as the material suitable for horizontal grouting. To confirm the capacity of the material, a horizontal pull-out loading test was conducted as well as a vertical pull-out loading test. The loading and measurement systems were the same as for the pull-out test mentioned earlier. The horizontal grouting and the loading test are described in Fig. 13(a) and (b), respectively.

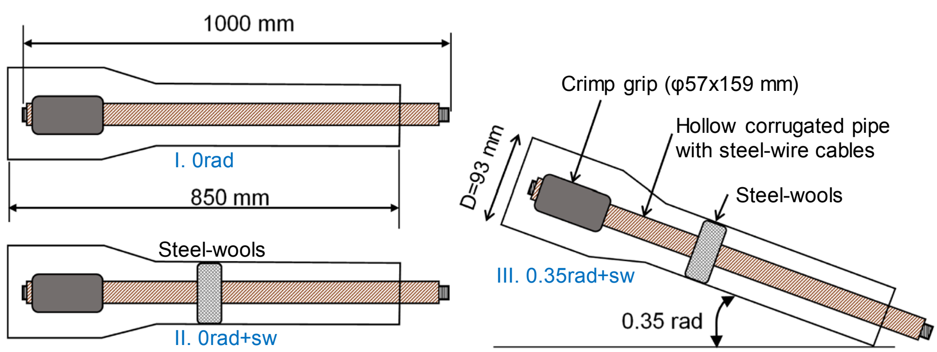
The load-slip responses shown in Fig. 10(a) represent the comparative test results of vertical (full) and horizontal grouting. The slip (approximately 4.0 mm) at the ultimate load of the horizontal grouting test was 1.1 mm greater than the slip with full grouting, while the slip (approximately 1.5 mm) at the load of 470 kN (=0.8 P_u) was almost equal to the slip at the same load in the full-grouting test.

Fig. 14(a) and (b) show pull-out load-deformation responses and concrete strains, respectively. As in the previous tests, the pull-out test confirmed that the maximum load exceeded the load-capacity (P_u = 588 kN) of the flexible tendon. The comparative test result confirmed that the maximum load and elongation of the flexible tendon were greater than the rigid prestressing tendon (steel-bar). It is noteworthy that the gradient of the load-elongation response was significantly lower than the test result with a rigid steel-bar. The observation implies that the flexible tendon can provide higher prestressing force and possibly decrease loss of the force caused from volume change of concrete. Furthermore, the elongation characteristic contributes to decrease the loss of prestressing force when the

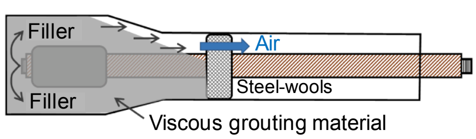
(a) Transparent acrylic pipe



(b) Schematic of grouting test



(c) Schematic of test parameters



(d) Air-removal from the wedge-shaped hole

Fig. 11. Visible grouting test.

prestressing strand is set at the end of concrete member. Note is that a longer hydraulic jack system is needed for prestressing with the flexible strand compared to the rigid bar.

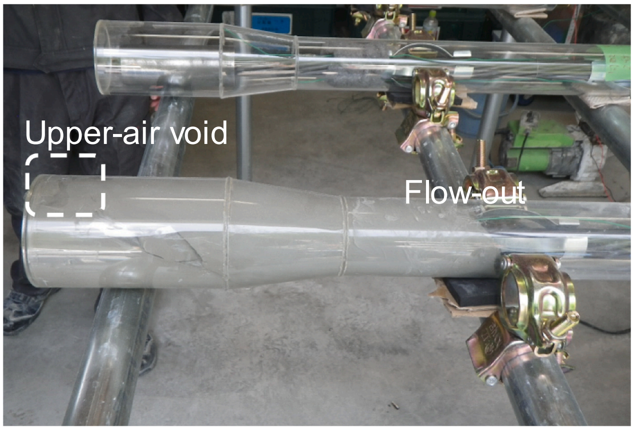
The maximum elongation of the tendon was about 55 mm under the load capacity ($\boldsymbol{P_u}$ = 588 kN), the maximum axial strain was −160 micro-strain at U-8 (350 mm from the anchorage edge). In addition, Fig. 14(b) confirms that the strains in the range of U-6 to U-8 (250–350 mm from the anchorage edge) were hardly different. These observed results were not different from the test using the specimens with an entirely filled anchorage. Based on the visible and pull-out tests, the study results indicated that filler No.5 was the most suitable grouting material for the post-tension strengthening system with a flexible hollow-type prestressing tendon.

Fig. 15 presents a cross-section of the anchorage exposed by saw-cutting a post-test specimen. It was confirmed that the grouting material in the anchorage was hardly damaged by the pull-out load. The photograph shows the tilted head of the prestressing tendon. The tilted head was due to the deadweight of the flexible tendon, the slant was observed to be 0.052 rad. Further research on the impact of such eccentricity should be done though a pull-out test to confirm adequate anchoring capacity for the tendon.

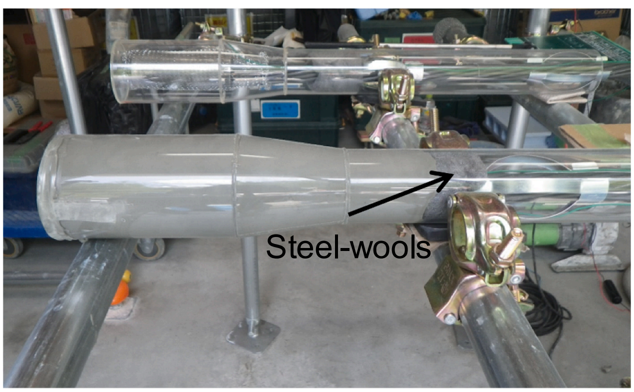
6. Conclusions

To develop an internal strengthening system using the hollow-type prestressing-strand, this study examined the grouting materials applicable for a horizontal hollow duct. A pull-out test of the PC tendon was conducted using 8 mock-up RC specimens. The remarkable findings in the experimental study are listed below.

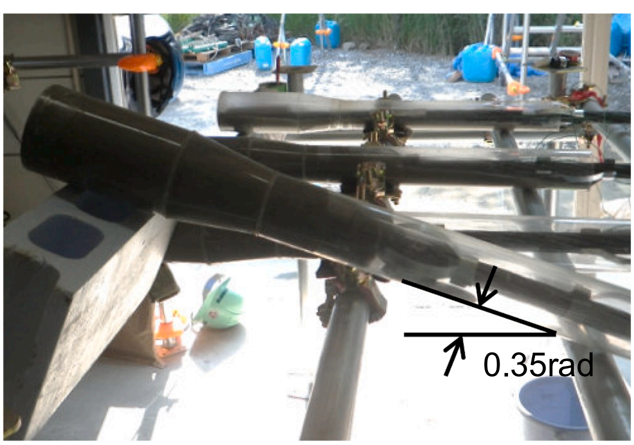
- The high-strength mortar used for the rigid prestressing tendon barely passed through the corrugated pipe 5 m long because



(a) I. 0rad



(b) II. 0rad+sw



(c) III. 0.35rad+sw

Fig. 12. Visible test results.

Table 6
Visible test results.

Case	Test parameters	Void		Flow-out	
		yes	no	yes	no
I	0 rad	No.2, 4	No.5	No.2, 4	No.5
II	0 rad + sw	No.2	No.4, 5	No.2	No.4, 5
III	0.35 rad + sw	No.2	No.4, 5	No.2	No.4, 5

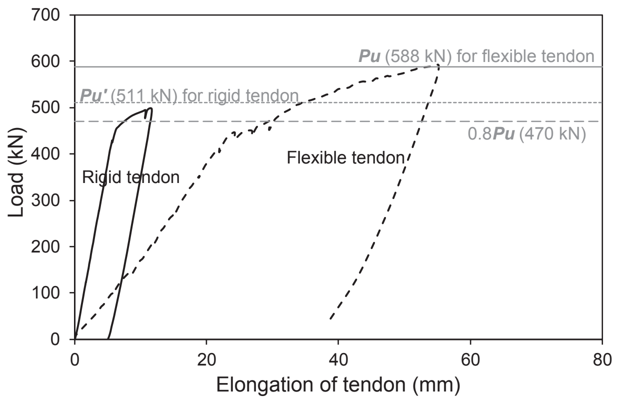
(a) Horizontal grouting

(b) Pull-out test

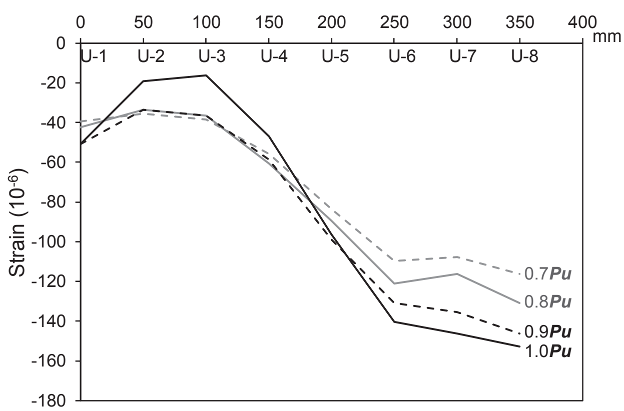
Fig. 13. Verification test.

segregation of the mortar occurred at the pipe-end.

- The grouting test confirmed that cement pastes without fine aggregate are an appropriate filling material for passage through the corrugated pipe.
- The pull-out test revealed that adequate load capacity and negligible slip of the flexible prestressing tendon embedded in the internal wedge-shaped anchorage can be provided by using filling materials that can pass through the corrugated pipe.
- One filling material (No. 5) was applicable even in the upward grouting (0.35 rad), so it was selected as the material most suitable for the post-tension strengthening system using the flexible hollow-type tendon.



(a) Pull-out load – deformation responses



(b) Axial strain of concrete

Fig. 14. Verification test results (No.5).

Fig. 15. Saw-cut anchorage embedding the flexible tendon.

The study concluded that the corrugated pipe covered with steel-wire can be used as a grouting pipe to fill the anchorage in addition to having the role of prestressing tendon for internal strengthening. Furthermore, the study presented a novel and meaningful observation that the post-tensioning system using the filler applicable for horizontal/upward grouting has the adequate load-capacity.

CRediT authorship contribution statement

Takafumi Mihara: Conceptualization, Methodology, Validation, Investigation, Writing - original draft, Visualization, Project administration. **Isamu Yoshitake:** Validation, Writing - original draft, Writing - review & editing, Supervision, Visualization, Project administration. **Ryosuke Anami:** Methodology, Validation, Investigation. **Naoyuki Tsumura:** Methodology, Investigation. **Tatsuhiko Mimoto:** Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.engstruct.2020.110176.

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