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Experimental Investigation on Flexural Behaviors in Framed Structure of PST Method

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***Abstract*—**Existing underground pipe jacking methods use a reinforcing rod in a steel tube to obtain structural stiffness. However, some problems such as inconvenience of works and expensive materials resulted from limited working space and reinforcing works are existed. To resolve these problems, a new pipe jacking method, namely PST (Prestressed Segment Tunnel) method, was developed which used joint to connect the steel segment and form erection structure. For evaluating the flexural capacity of the PST method structure, a experimental test was conducted. The parameters considered in the test were span-to-depth ratio of segment, diameter of steel tube at the corner, prestressing force, and welding of joint. The flexural behaviours with the effect of load capacity in serviceability state according to different parameters were examined.. The frame with long segments could increase flexural stiffness and the specimen with large diameter of concave corner showed excellent resistance ability to the negative moment. In addition, welding of joints increased the flexural capacity.

***Keywords*—**PST method, Pipe jacking method, Flexural behavior, Prestressed concrete.

I. INTRODUCTION

WHEN constructing a new highway in a zone barred by railway or superhighway, road should be constructed by culvert in underground using trenchless technology. Pipe jacking methods are commonly used for trenchless installation of pipelines under highways, watercourses, environmentally sensitive areas, and congested urban settings where open-cut trenching is not viable [1]. Pipe-jacking, defined as constructing tunnels by pushing factory-made pipes into the ground, by methods of hydraulic jacks, has long been noted as an economical urban tunneling method free from any environmental problems [2].

When it comes to the common procedure of the methods, firstly constructing erection structure in underground and the final structure will be constructed inside. The widely using erection structure is constructed by pressing steel tube in soil as a form of roof [3].

The Pipe jacking methods have various types in terms of the erection structure form and construction method. Nowadays, the pipe jacking methods commercialized in Korea are UPRS (Upgraded Pipe Roof Structure) method, TRCM (Tubular Roof Construction Method), NTR (New Tubular Roof) method and STS (Steel Tube Slab) method [4]. The characteristic of UPRS method is that tubes are engaged with another by anchor system. So the erection structure can be constructed precisely. The TRCM method uses erection structure as a final structure, so it is economical. The NTR method presses large-sized steel tube for constructing the erection structure which gives advantages that the excavation work is easy and there is no need of repairing for maintenance. And the STS method is superior in structural stability which applies a connecting method composed with anchor plate, reinforcement and mortar to strengthen weak part at joint. Although the existing methods have their own advantages and characteristics, some problems are also existed. When it comes to UPRS method, TRCM method and NTR method, they are reinforcing steel bar in steel tube which brings inconvenience of construction work. The STS method has problems that the reinforcing work is complicated and the quality control is difficult.

The existing pipe jacking methods reinforce steel bar in the erection structure to gain the stiffness of structure, but it brings inconvenience of construction work. To resolve these problems, a new method, namely PST (Prestressed Segment Tunnel) method, was developed. The PST method prestresses the installed strands for obtaining the stiffness instead of reinforcing the steel bar. Unlike the existing pipe jacking method structures, the structure of PST method is a prestressed segment frame. So the examination for the flexural behaviors of the structure was needed. For investigating the flexural behaviors of the PST method structure, flexural test was conducted with 7 frames.

II. PRESTRESSED SEGMENT TUNNEL METHOD

PST method uses quadrangular steel segments to construct structure in underground and strands installed in steel tube for prestressing. After completing the construction of erection structure, one can bond the precast panels at the inner wall and the bottom of slab. TABLE I shows the construction stages of PST method.

Unlike the existing pipe jacking method, PST method prestresses the strands installed in the slab which is comprised of steel segments for obtaining the structural stiffness without reinforcing the steel bars. Therefore, the construction period can be shortened due to the simple construction process and the mat erials can be reduced effectively as well. What’s more, the structure can be constructed precisely using joint at the connection region.

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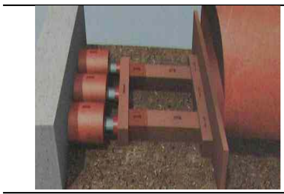
TABLE I
CONSTRUCTION STAGE OF PST METHOD

Stage 1: Prestressing the steel tube in the soil	Stage 2: Propelling and connecting the segments
	
Stage 3: Side wall boring and PC strands inserting	Stage 4: Concrete placing and PC strands tensioning
	
Stage 5: Tunnel excavation and bottom strut installing	Stage 6: Floor concrete pouring and finishing the work
	

III. EXPERIMENTAL PROGRAM

The specimens are comprised of slab, corner, and wall as showed in Fig.1. The experiments were carried out by using the span-to-depth ratio, diameter of steel tube at the corner, prestressing force and welding of joint as parameters.

A. Parameters and Dimensions of Specimens

Seven prestressed segment frames were fabricated and tested. The parameters of the flexural tests under static loading are summarized in TABLE II. The first specimen (ST-1) was used as a control frame. Specimens ST-2, ST-3's length of segments are 147% and 306% of the control frame respectively. JT-1 is the specimen whose diameter of concave corner is about 50% of control frame. And PS-1 is the specimen which has been prestressed 50% tensioning force on strands. WD-1 and WD-2 are the specimens that the joints of specimen were welded for comparing the load capacity against to the control specimen (ST-1). WD-1 has been welded joints in negative moment region of upper steel plate. Three joints were welded at the inner side of each concave corner. And WD-2 is the frame welded every joint in all region of lower steel plate. h, a and D shown in TABLE II and Fig.1 are depth of slab, longitudinal length of segment and diameter of steel tube respectively. Entire span of slab is 3600mm and length of wall without corner tube is 500mm. The loaded span for every specimen is 4000mm. Horizontal length of all frame is 600 mm.

TABLE II
SPECIMEN DETAILS AND TEST VARIABLES

Specimen name	Size of segment		Size of concave corner		Prestressing force (kN)	Joint welding
	h:a	a (mm)	D:h	D (mm)		
ST -1	1:1.06	233	2.1:1	457	680	-
ST -2	1:1.56	343	2.1:1	457	680	-
ST -3	1:3.34	713	2.1:1	457	680	-
JT -1	1:1.06	233	1.2:1	267	680	-
PS -1	1:1.06	233	2.1:1	457	340	-
WD -1	1:1.06	233	2.1:1	457	680	Negative moment region of upper steel
WD -2	1:1.06	233	2.1:1	457	680	All region of lower steel

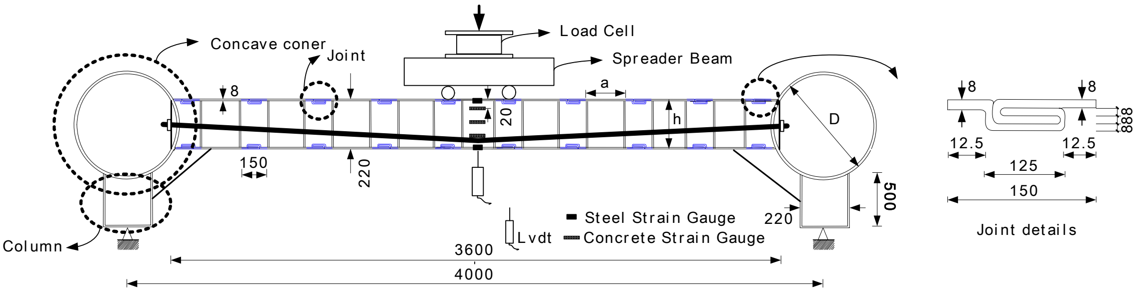


Fig. 1 Specimen shape and gauge installation (units: mm)

B. Material Properties

The concrete mix poured in segments and steel tubes was designed for a target 28-day compressive strength of 35 MPa for post-tensioning. 15.2mm diameter strands were installed in the slab which is composed with segments. Joints used for connecting segments were fabricated from SPY345 sheet pile in Korean Standard (KS). Tensional tests were undertaken to evaluate the tensile strength of joints. Compressive strength of concrete was investigated from a standard cylinder test. The material properties of the test frame are summarized in TABLE III.

TABLE III
MATERIAL PROPERTIES OF THE TEST FRAME

Material properties	Concrete		Joints	
	Slab and wall	Corner	Joints	Basic material of joints
Compressive strength(MPa)	37.34	30.65	-	-
Splitting tensile strength(MPa)	1.30	1.12	-	-
Yield strength(MPa)	-	-	66.13	445.84
Tensile strength(MPa)	-	-		536.47

C. Procedure of Specimen Frame

The general procedure of specimen frame (refer to TABLE I) is as follows. (1) Steel tubes and segments are fabricated previously. (2) Boring the side wall of every segment for inserting strands and welding the joints to the segment plates. (3) Positioning all the segments and steel tubes on t he right site. (4) Connecting all segments and steel tubes. (5) Installing strands through the holes bored in segments. (6) Pouring concrete in segments and walls and Post tensioning the strands after curing. (7) Pouring concrete in steel tubes.

D. Test Setup

Flexural tests were carried out in load frame where installed actuator with 2,000kN load capacity and static load was measured by load cell. Vertical displacement was measured by linear variable differential transformers (LVDTs) which were placed on a mid span. During fabrication of test specimens, a total of ten strain gauges were embedded in each frame. Four steel gauges were installed on the upper and lower steel plate at mid span and six concrete gauges were mounted onto the upper part, the central part and the lower part of concrete at mid span. All data were recorded through an UCAM 500 data logger. Additional detail is given in Fig 1.

IV. TEST RESULTS

To investigate the behaviors of PST method structures and analysis the results, deflections of all specimens against ultimate load are shown in TABLE IV. And the effectiveness of load capacity depends on span-to-depth ratio, diameter of steel tube, prestressing force, and welding of joints were examined also.

TABLE IV
MEASURED ULTIMATE LOAD AND DEFLECTION OF SPECIMENS

Specimen	Ultimate load (kN)	P_{TEST}/P_{ST-1}	Deflection (mm)	$\delta_{TEST}/\delta_{ST-1}$
ST-1	420	1	75	1
ST-2	465	1.11	90	1.20
ST-3	518	1.23	95	1.23
JT-1	313	0.75	53	0.71
PS-1	320	0.76	48	0.64
WD-1	544	1.30	49	0.65
WD-2	610	1.45	33	0.44

A. Load-Deflection Curve

The mid-span deflections of the slabs against total loads on the frames were plotted in Fig. 2-Fig. 5. As shown in Fig. 2, the deflections of ST-2 and ST-3 were smaller than the deflection of specimen ST- 1 at ST-1's ultimate load. Especially, specimen ST-3 showed considerable reduction effect of deflection because it still behaved elastically at 420 kN. And one can conclude that the specimen with longer segment has fewer quantities of joints, which can make the segments contribute more resistance to the flexural load and reduce the deflection.

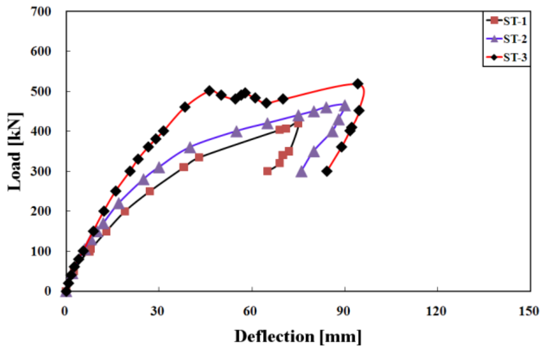


Fig. 2 Load-deflection relationship (ST-1, ST-2, ST-3)

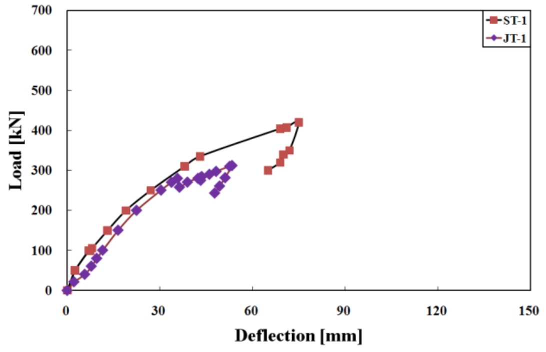


Fig. 3 Load-deflection relationship (ST-1, JT-1)

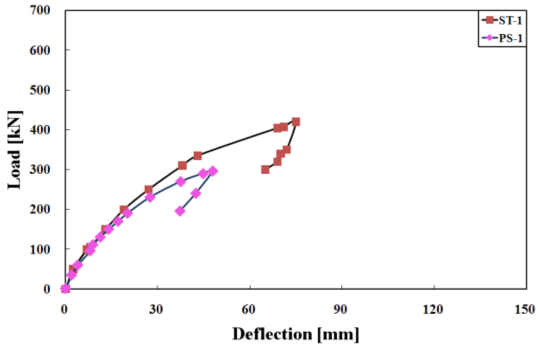


Fig. 4 Load-deflection relationship (ST-1, PS-1)

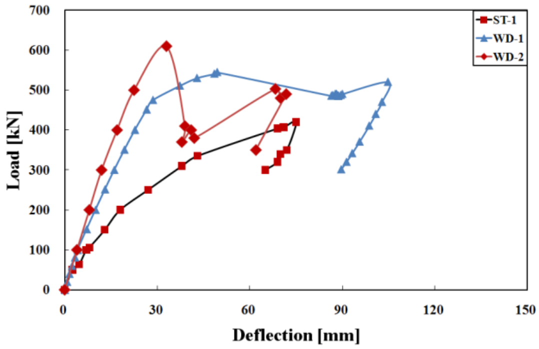


Fig. 5 Load-deflection relationship (ST-1, WD-1, WD-2)

The deflection of JT-1 was measured greater than the deflection of control frame against the ultimate load of JT-1 in Fig. 3. It is because that specimen with larger diameter of concave corner has greater resistance capacity against the negative moment and can reduce the deflection of the slab at mid-span. Fig. 5 demonstrates the load-deflection relation of the joint welding specimens compared against the control specimen. It is clear that the joints welding frames have much greater load carrying capacity than control frame.

B. Load-Strain Curve of Steel

Comparisons of load-strain relationship response in the lower steel plate (tensile zone) of segment at the mid-span were shown in Fig. 6-Fig. 9. As shown in Fig. 6, the strain gauges installed at each specimen did not yield up to the final load. And ST-3 showed greatest strain, ST-1 showed the smallest strain among three frames. Thus, one can conclude that if the longitudinal length of segment is longer, the quantity of segments of slab is smaller, which results the lower steel plate of segment at mid-span resists more tensional force. The strains of JT-1 and PS-1 at ultimate load are greater than control frame, which is appeared in Fig. 7-Fig. 8. From Fig. 7, one can estimate that the larger concave corner of frame can resist negative moment more effectively and increase the load carrying capacity to make less deflection occurred in the lower steel plate. In case of joint welded specimen, strain of ST-1(control specimen) is smaller than the strain of WD-2 and greater than the strain of WD-1. Welding the joints in all region of the lower steel plate made joints and segments resist the tensile force together. In case of WD-1, welding of negative moment region joints can increase the load carrying capacity of structure so that the strain of lower steel is smaller than that of control frame.

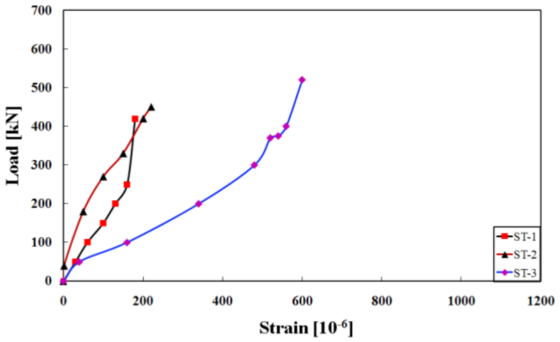


Fig. 6 Load-strain relationship of steel (ST-1, ST-2, ST-3)

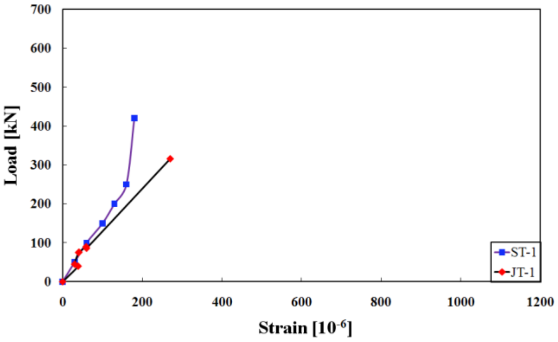


Fig. 7 Load-strain relationship of steel (ST-1, JT-1)

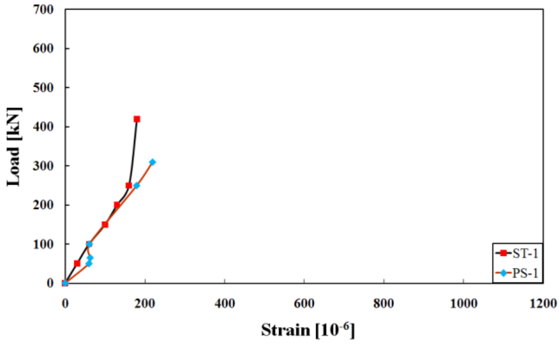


Fig. 8 Load-strain relationship of steel (ST-1, PS-1)

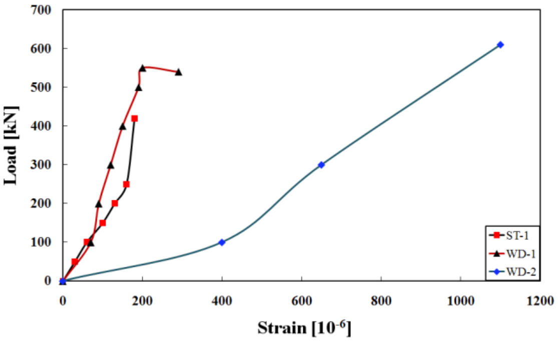


Fig. 9 Load-strain relationship of steel (ST-1, WD-1, WD-2)

C. Estimate for Serviceability Limit State

This paper used the deflection data obtained from flexural tests to estimate the serviceability limit state of specimens. The check of the deflection of the frame beam for the serviceability limit state is specified by Bridge Design Specification 2005 of Korea [5] as

$$\delta \le \frac{l}{500} \tag{1}$$

Where, δ is allowable deflection of the beam; and l is the span of the beam.

TABLE V
COMPARISON OF SERVICE LOAD

Specimen	Load (kN)	PTEST/PST-1
ST-1	106	1
ST-2	120	1.13
ST-3	129	1.22
JT-1	64	0.60
PS-1	96	0.90
WD-1	167	1.58
WD-2	200	1.89

For estimating the serviceability limit state of the specimens, load was set when the deflection increased up to for the serviceability limit state, and compared against the load of control frame in serviceability limit state. The results of specimens were listed in TABLE V.

From TABLE V, the load of ST-2, ST-3 in serviceability limit state are 13%, 22% higher than control frame respectively. And one can confirm the effect of span-to-depth ratio even against the load in serviceability limit state. From the data of JT-1, diameter of steel tube influences the load capacity remarkably even in allowable deflection scope. PS-1's load in serviceability limit state was 90% of control specimen. The joint welded specimens' loads are 158%, 189% of the ST-1, so welding the joints (especially welding of lower joints) can increases load capacity in serviceability limit state noticeably.

D. Ductility

Ductility is a qualitative concept representing inelastic deformational capacity of materials, sections, members or structures before they collapse. Ductility may be a very important safety factor delays local failure by redistributing redundant stresses in the critical section of a statically indeterminate structure. A ductility index or ductility factor is used to quantify ductility which is defined as ratios in terms of curvature, rotation and deflection. It is given by

$$\mu_\phi = \frac{\phi_u}{\phi_y}, \mu_\theta = \frac{\theta_u}{\theta_y}, \mu_\Delta = \frac{\Delta_u}{\Delta_y} \tag{2}$$

Where, μ is the ductility index; ϕ is rotation factor; θ and Δ are curvature and deflection of structure respectively.

TABLE VI
DUCTILITY INDEX OF SPECIMEN

Specimen	Yield state		Ultimate state		Ductility index
	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	
ST-1	338	45	420	75	1.67
ST-2	390	50	465	90	1.80
ST-3	450	38	518	95	2.48
JT-1	285	44	313	53	1.20
PS-1	211	22	320	48	2.18
WD-1	470	28	544	49	1.75
WD-2	540	25	610	33	1.32

In this paper, the ductility index is defined as the ratio of the deflection when the member is subjected to the ultimate loads when it yields. The ductility index of each specimen is given in TABLE VI.

As shown in TABLE VI, the ductility index of ST-1, ST-2 and ST-3 are 1.67, 1.80 and 2.48 respectively and it can be concluded that specimen, which has longer segments, shows more ductile behavior. It is because that the longer segments can resist to flexural force more effectively and delay the failure of joints. JT-1 has smaller ductility index than control specimen, which is because small size of concave corner cannot resist to negative moment sufficiently and also decrease the structure's flexural capacity. PS-1 appeared more ductile performance than control frame which is consistent with the theory that structure introduced less prestressing force behaves more ductilely. WD-2 showed little ductile than control specimen, which is caused by the failure of welded joints which reduced the load capacity of the structure and showed brittle performance.

V. CONCLUSION

Through the test to the specimens designed for estimating the characteristics of the flexural behavior of PST method structure, following conclusions can be reached.

1) The frame with long segments can increase flexural stiffness and reduce deflection of slab and shows greater serviceability. It is because the long segments which take the place of joints to resist to the tension force.

2) The specimen with large diameter of concave corner showed excellent resistance ability to the negative moment and has superior load capacity.
3) Prestressing more tension force can increase the flexural capacity and reduce the deflection and deformation of structure.
4) Welding of joints has remarkable effectiveness for increasement of flexural capacity, especially the welding of lower steel joints can raise resistance to the flexural force.
5) Increasing the length of segments, the diameter of steel tube and decreasing the prestressing force have advantage for obtaining structural ductility.

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