Behavior of Lateral Earth Pressure around the Underpass Constructed by the STS Construction Method

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ABSTRACT
Recently developed trenchless construction methods ensure stability for the ground settlement by inserting steel pipes along the underpass section and integrating steel pipes before ground excavation to form pipe-roof. This study is to confirm the reinforcing effect of pipe-roof by measuring lateral earth pressure acting on the underpass constructed by the STS (Steel Tube Slab) construction method. For this purpose, lateral earth pressure was measured at the left and right side of the pipe-roof after installing earth pressure cells. As a result, lateral earth pressure was measured with considerable reduction because the integrated pipe-roof shared surcharge. Therefore, economic design for the underpass could be expected by sharing design load by pipe-roof. In addition, construction cost was analyzed according to the design-load sharing ratio by pipe-roof. As pipe-roof shares design load by 40%, the total construction cost can decrease by almost 10% in the case of four-lane underpass.

Key words: Trenchless Construction Method, Pipe-roof, STS Construction Method, Lateral Earth Pressure, Earth Pressure Cell, Design Load, Construction Cost

1. Introduction

Recently, for underpass construction, it has become unavoidable to increasingly use the trenchless construction method rather than the cut-and-cover lining in order to prevent disturbance of existing traffic flow. A special method of trenchless construction is mostly applied similar to the pipe-roof construction method. Here, construction of steel pipes surrounding the underpass are done prior to excavation. This method prevents subsidence during excavation and reduces surcharge and earth pressure.

Recently, cross-sectional flexural rigidity or stiffness in trenchless construction method is enhanced by inserting large diameter steel pipes (more than 600mm diameter) to the underpass prior to excavation and transversely connecting steel plates or rebars to strengthen fastened mortars, afterwards. Such a highly rigid pipe-roof shares surcharge load. Thus, it is expected that stresses acting on actual underpass will decrease and design plan for underpass needs to be improved.

The studies related to trenchless construction method has been performed numerously focusing on earth surface settlement measure or construction examples in terms of safety. Considering the safety of ground movement and subsidence, studies concerning construction examples (Lee et al., 2003; Kimura et al., 2005), indoor experiments (Histake and Ohno, 2008; Eum et al., 2010; Choi et al., 2012b) and numerical interpretation (Ahuja and Sterling, 2008, Choi et al., 2012a) etc., were performed. The research conducted by Kimura et al. (2005) introduced a new construction example of two-lane Baikoh tunnel passing through the downtown area. On the other hand, Histake and Ohno (2008) performed a centrifugal model experiment to verify the effect of displacement control on the upper tunnel area through the pipe-roof method. They investigated the displacement for strengthened cases using pipe-roofs and for cases without pipe-roofs using the two methods, the total cross section excavation and ring-cut excavation methods. Ahuja and

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Sterling (2008) carried out numerical analysis on the tunnel excavation method using the pipe-roof application. However, even if safety is increased using the pipe-roofs’ enhanced rigidity, there has not been many research conducted to estimate the design load sharing ratio of pipe-roofs. Sim et al. (2013) conducted the numerical analysis with the finite difference method about surrounding underground earth pressure characteristics. The result verified the large reduction of earth pressure applied to the body of underpass concrete structure compared to its original state. In this study, axial force of supporting beam was reduced by 80% compared to the original stress state of the ground.

Moreover, Sim et al. (2015) installed an earth pressure cell and tried to verify the reduction status of earth pressure due to pipe-roofs in the UPRS (Upgraded Pipe-Roof Structure) method. Similar to the STS method, steel pipes are reinforced by connecting each other and the reinforced effect of pipe-roofs are expected in this UPRS method. The result showed that the applicable load to the underground roadway, for the UPRS (with stiffened pipe roofs), was reduced.

In this study, the lateral earth was measured surrounding pipe-roof in an underpass being constructed using the STS method to verify the reduction on earth pressure due to the pipe-roof.

2. Installation of earth pressure cell

The earth pressure cell used in the measurements was composed of a round-shaped stainless steel-plated cell structure, 10cm in diameter and could measure the stresses up to 500kPa (Fig. 1).

Fig. 1. Earth pressure cell used for earth pressure measurement (unit: mm)

Fig. 2 shows two different methods for installing earth pressure cells required to measure earth pressure. The first method (Fig. 2a) was done by simply attaching the earth pressure cell to external steel pipe side. This method had the possibility of suffering losses in measurements due to the possible occurrence of ground disturbance during steel pipe insertion and resulting to shock on the earth pressure cell. Therefore, the attachment should be made after completion of steel pipe insertion. The second method (Fig. 2b), on the other hand, needed drilling a round shape in the steel pipe similar to the shape of the earth pressure cell. After attaching the fastening device inside the steel pipe, it fastened the earth pressure cell, aligned with the external side of the steel pipe. This method was used in cases where earth pressure cells should be installed prior to steel pipe insertion.

3. Lateral earth pressure measurement around the underpass constructed using the STS construction method

3.1 STS construction method and measurement summary

The STS construction method is a method that integrates the steel pipe-roof inside the ground by filling the mortar and
strengthening inside after inserting the steel pipes that are more than 800mm in diameter (Fig. 3a). Steel pipes were inserted following the structural steel guide. To strengthen them, 1.2 cm thick steel plates and rebars were joined together. In this way, transverse bending stiffness was maximized and safety was increased.

Fig. 3b shows an underpass construction site using the STS construction method. It shows the front view of completely constructed integrated pipe roofs prior to underpass construction.

Table 1 shows the diameter of steel pipes used in the STS construction method, the ground depth (distance from upper underpass to the ground surface), and underpass structure data. The ground depth was about 2.8m in depth and the ground for earth pressure measurement was composed of filled layers.

Table 1. Diameter of steel pipe, soil cover and cross section of underpass (STS)

| Diameter of steel pipe (mm) | 812.8 |
|-----------------------------|-------|
| Ground depth (m)            | 2.765 |
| Cross section of underpass  |       |
| L (m)                       | 32    |
| B (m)                       | 18.25 |
| H (m)                       | 5.3   |
| Upper slab thickness (m)    | 0.9   |
| Side wall thickness (m)     | 0.9   |

Fig. 4 shows the front view of the pipe-roof and underpass and the installed location of the earth pressure cell. In order to measure earth pressure's around the underpass constructed using the STS construction method, earth pressure cells were installed at 2m and 13m points, lengthwise. The transverse section of the expressway was at 2m, lengthwise, near the sloping surface; and the 13m-point was located at the central point of the expressway. At the 2m point, earth pressure cell ① and earth pressure cell ③ were installed and at the 13m-point, earth pressure cell ② and ④ were installed.
The earth pressure cells ① and ② on the left side of the pipe roof were installed. Lateral earth pressure were measured at the 2m and 13m points lengthwise where reinforcing effect of pipe-roof was not occurred. The earth pressure cells ③ and ④ were installed on the right side of the pipe-roof. The lateral earth pressure were measured lengthwise at 2m and 13m distant points. Earth pressure cells at these points measured stress actually applied to the underpass.

Earth pressure cells ① and ② on the left side of the pipe-roof should be installed before steel pipe insertion and as shown in Fig. 2b. Fig. 5 illustrates this process. On the other hand, earth pressure cells ③ and ④ on the right side of the pipe-roof
were not affected by the time of installation as described method outlined in Fig. 2a on the external surface of the steel pipe.

3.2 Results and Analysis

Fig. 6 and Table 2 show earth pressure measurement results around the underpass constructed by the STS construction method.
3.2.1 Earth pressure cell measurement (earth pressure cells ① and ②)

Earth pressure cells ① and ②, installed on the left side of the pipe roof, measured lateral earth pressures and show irregular fluctuation of earth pressures after mid-July. It might be caused by earth pressure cell loss by disconnection of its cable during removal of the rear side of the earth plank. After the loss, recovery of earth pressure cell was made in August and October. Earth pressure cells ① and ② showed irregular conditions. Loss of cell was expected to influence the measured values to some degree.

In order to obtain reliability, average lateral earth pressure of earth pressure cells ① and ② were considered the date before loss on July 18th. As a result, the average measurement of transverse earth pressure taken at each sensor was 24.38kPa and 79.11kPa, relatively.

Earth pressure cell ① was near the free sloping surface. Since earth pressure cell ② was located at the center of the expressway, its lateral earth pressure value was much larger than the values obtained by earth pressure cell ①. In the case of earth pressure values measured by earth pressure cell ②, its location was approximately H=8.9 m from the ground surface; unit weight and angle of friction of buried layers were each assumed to be \(\gamma=18 \text{ kN/m}^3\) and \(\phi=35^\circ\). Jaky’s empirical equation, \(K_0=1-\sin\phi\), was used to determine the static coefficient of the lateral earth pressure which showed to be 68.3kPa. This value was almost similar to the estimated value of 79.11kPa. This indirectly verified that the earth pressure cell took normal earth pressure measurements.

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\sigma_h = K_0\sigma_v = (1 - \sin\phi)\gamma H = 68.3kPa
\]

3.2.2 Effect of pipe–roof (earth pressure cells ③ and ④)

As a result of lateral earth pressure measurements, earth pressure cells ③ and ④, installed on the right side of the pipe roof, showed almost no stress operation to the underpass. Average data value of earth pressure cell ③ before the loss was 0.06kPa and 3.56kPa for earth pressure cell ④. Thus, the rigidity of the integrated pipe roof showed resistance to the lateral earth pressure.

4. Analysis on the construction cost concerning design load sharing by pipe–roof

4.1 Analysis summary

As previously described, if the pipe–roof shared the lateral earth pressure, it would also share the vertical earth pressure and an economical design of the underpass would then be possible. Thus, the entire design load (vertical earth pressure and lateral earth pressure due to dead and live load) was expected to decrease. Due to reduction in design load, cross sectional reduction of

| Earth pressure cell | Lateral earth pressure (kPa) |
|---------------------|-----------------------------|
| ①                   | 5/15 6/5 6/22 6/29 7/6 7/13 7/15 8/8 8/17 8/24 |
| ②                   | 72.92 73.48 85.96 89.00 81.94 90.22 86.63 96.29 308.83 154.19 |
| ③                   | 1.76 -0.81 0.54 1.56 -1.62 0.74(7/10) - 0.34 -1.74 -1.15 |
| ④                   | 3.52 2.82 3.46 3.46 2.15 4.57 5.82 4.85 6.31 |

| Earth pressure cell | Lateral earth Pressure (kPa) |
|---------------------|-----------------------------|
| ①                   | 8/31 9/7 9/15 9/18 10/2 10/5 10/16 10/30 11/20 11/21 |
| ②                   | -54.39 -113.61 -134.62 -120.25 -172.81 -172.81 65.77 119.0 79.96 75.76 |
| ③                   | 119.64 60.16 63.49 55.83 57.99 57.99 49.34 45.26 33.26 33.78 |
| ④                   | 3.45 -0.07 -2.70 -3.38 -5.0 -4.73 -2.56 -3.16 -0.07 0.0 |
| ⑤                   | 10.52 7.20 5.68 5.68 5.4 5.4 6.72 8.23 7.45 7.37 |

Note :
- Installation of earth pressure cells ① and ② (11/3/2011), Insertion of steel pipe (11/8/2011). Installation of earth pressure cells ③ and ④ (1/18/2012)
- Completion of excavation (1/11/2012), Placement of foundation structure (2/25/2012). Placement of upper slab concrete (5/15~5/20/2012)
- Cable disconnection during excavation wall removal and backfilling : earth pressure cell ③ (7/12/2012) cell ④ (7/13/2012), earth pressure cells ① and ② (7/18/2016)
- Starting measurement after recovering earth pressure cell (8/8/2016)
underpass was possible and the construction cost was also expected to decrease.

Therefore, in this research, reduced conditions of 20% and 40% each were assumed among cross sectional data of the underpass and the corresponding construction cost were compared to the existing construction designs.

### Table 3. Design conditions

| Classification   | General Road       |
|------------------|--------------------|
| Underpass        | Number of lanes: two lanes, four lanes |
| Extension        | 40m                |
| Upper Cohesive Soil Depth | 3.0m              |
| Underground Water Level | GL-1m             |
| Live Load        | DB 24              |

4.2 Applied design criterion and conditions

Manual for concrete structure design (KCI, 2007) and design criterion for the highway bridges (KRTA, 2010) were applied for the design criterion of underpass regular roads, and the applied safety factor of 1.2. Other than these, design conditions were those outlined in Table 4 ~ Table 7.

### Table 4. Strength and elastic modulus for concrete and rebar

| Classification | Design strength (MPa) | Elastic modulus (MPa) |
|----------------|-----------------------|-----------------------|
| Concrete       | $f_{ck} = 27$         | $E_C = 0.077m_{c}^{1.53} \sqrt{f_{cu}}$ |
| Rebar          | $f_y = 400$           | $E_S = 200,000$       |

### Table 5. Properties of pavement layer

| Classification | Unit Weight (kN/m³) | Thickness (m) |
|----------------|--------------------|---------------|
| Asphalt Surface layer | 23              | 0.15          |
| Base layer    | 23                | 0.30          |
| Midlayer      | 20                | 0.10          |
| Sublayer      | 20                | 0.30          |
| Thickness of total pavement layer | 0.85             |               |

### Table 6. Ground properties

| Classification | Unit Weight (kN/m³) | Cohesion (kPa) | Internal friction angle | N |
|----------------|--------------------|---------------|-------------------------|---|
| Filled layer   | 20                 | 0             | 30                      | N=30 (Calculation of the coefficient of bearing capacity) |

### Table 7. Seismic design criterion

| Classification | Design condition |
|----------------|------------------|
| Seismic grade  | Seismic grade 1 applied |
| Earthquake area coefficient | Earthquake zone 1 Area coefficient (0.11) |
| Coefficient of risk | Performance function: 0.570 Prevention of destruction: 1.400 |
| Ground earthquake coefficient | Earthquake coefficient according to ground classification: $Ca = 0.16$ (ground type: $Sd$) |
| Seismic design objective | Level of performance function and securing performance, fulfilling the level of destruction prevention |

### Table 8. Decrease in construction cost in the two-lane underpass

| Classification | Construction type | Net construction cost (thousand won) | Total construction cost (thousand won) | Decrease in total construction cost (thousand won) |
|----------------|-------------------|--------------------------------------|---------------------------------------|--------------------------------------------------|
| CASE①          | Concrete(m³) 1,150 | 155,806                              | 399,425                               | -                                               |
|                | Rebar(ton) 155.806 |                                      |                                       |                                                  |
| CASE②          | Concrete(m³) 1,073 | 148,029                              | 382,742                               | 24,192 (4%▼)                                    |
|                | Rebar(ton) 148,029 |                                      |                                       |                                                  |
| CASE③          | Concrete(m³) 997  | 141,371                              | 367,923                               | 45,679 (8%▼)                                    |
|                | Rebar(ton) 141,371 |                                      |                                       |                                                  |

### Table 9. Decrease in construction cost in the four-lane underpass

| Classification | Construction type | Net construction cost (thousand won) | Total construction cost (thousand won) | Decrease in total construction cost (thousand won) |
|----------------|-------------------|--------------------------------------|---------------------------------------|--------------------------------------------------|
| CASE①          | Concrete(m³) 1,822 | 246,874                              | 896,237                               | 0                                               |
|                | Rebar(ton) 246,874 |                                      |                                       |                                                  |
| CASE②          | Concrete(m³) 1,714 | 244,304                              | 878,785                               | 17,453 (2%▼)                                    |
|                | Rebar(ton) 244,304 |                                      |                                       |                                                  |
| CASE③          | Concrete(m³) 1,608 | 218,990                              | 818,192                               | 78,046 (9%▼)                                    |
|                | Rebar(ton) 218,990 |                                      |                                       |                                                  |
4.3 Cost of construction comparison

In the case of the two-lane underpass (Table 8), results revealed that CASE ② decreased by 4% and CASE ③ decreased by 8% in terms of total construction cost, including miscellaneous costs. In the case of four-lane underpasses (Table 9), CASE ② showed 2% decrease and CASE ③ showed 9% decrease. Specifically, the four-lane underpasses, CASE ② and CASE ③ demonstrated large increase compared to the two-lane underpasses.

Moreover, we could see that every time the design load-share ratio of pipe-roof increased, the cross-sectional thickness decreased as shown in Table 10. In the case of the two-lane underpass, CASE ② decreased by 10% and CASE ③ decreased by 15%. In the case of the four-lane underpass, CASE ② decreased by 7% and CASE ③ decreased by 14%. This means that as the structure’s cross-section decreased, the amount of steel pipe required for insertion also decreased resulting in further reduction of construction cost.

Table 10. Thickness of underpass section (unit: mm)

| Classification | two-lane underpass | four-lane underpass |
|----------------|-------------------|---------------------|
| CASE①         | 660               | 750                 |
| CASE②         | 600 (10%▼)       | 700 (7%▼)          |
| CASE③         | 550 (15%▼)       | 650 (14%▼)         |

5. Conclusions and recommendations for future study

This research had taken measurements of lateral earth pressure around the underpass constructed using the STS construction method, the pipe-roof trenchless construction method. Comparing the left and right lateral earth pressure measurements, the reduction in earth pressure due to the pipe-roof was verified. Moreover, on the assumption of reduced earth pressure, the economic analysis of the design load-sharing ratio was performed.

The following conclusions were made:

1) Using the STS method, the earth pressure acting on the underpass decreased to some degree. Since the underpass structures were constructed at the site by placing with concrete, strengthening of iron plates and rebars in transverse direction should be performed to increase safety. That is, it is shown that the enhanced strength of pipe-roof results in decrease in earth pressure.

2) In designing the cross-section of the underpass, economical designing seemed to be possible, if the effect of the pipe-roof’s rigidity according to the design-load sharing ratio was considered. In case of 20% and 40% design load-sharing ratio, the 2-lane underpasses were found to show 4~8% decrease in construction cost; and 2~9% decrease for the 4-lane underpasses compared to existing construction cost.

3) In addition, thickness of the underpass cross-section also decreased by 10~15% for 2-lane roads and 7~14% for 4-lane roads. Analysis predicted improved space utilization and design. Decrease in the thickness of cross-section results in decreased number of steel pipe insertions, therefore, additional decrease in construction cost was expected.

4) Aside from the STS method, the construction method using the iron plate and rebar integrated pipe-roof structures resulted in partial sharing of earth pressure by the pipe-roof on the concrete structures of the underpass. Upon decrease in design load, decrease in cross-section was possible during cross-section designing; this resulted to more economical and efficient designs.

5) As an additional remark, more quantitative verification regarding design load-sharing ratio through more abundant measurements since there were insufficient measurement data and there was loss of earth pressure cell during underpass construction.

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