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Real-scale field testing for the applicability examination of an improved modular underground arch culvert with vertical walls

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Abstract. In this study, an improved modular arch system with the lower arch space composed of a precast arch block and an outrigger was proposed as an underground culvert, and its applicability and structural behaviors were confirmed. This modular arch culvert structure with vertical walls was designed using precast blocks and by adjusting the placement spacing of concrete blocks to the upper part form an arch shape and the lower part form a vertical wall shape, based on previously researched modular arch systems. Owing to the vertical wall of the proposed modular arch system, it is possible to secure a load-carrying capacity and an arch space that can sufficiently resist the earth pressure generated from the backfill soil and loading on the arch system. To verify the structural characteristics, and applicability of the proposed modular precast arch culvert structure, a full-scale modular culvert specimen was fabricated, and a loading test was conducted. By examining its construction process and loading test results, the applicability and constructability of the proposed structure were analyzed along with its structural characteristics. In addition, its the structural predictability and safety for the applicability were evaluated by comparing the construction process and loading test results with the FE analysis results.

Keywords: applicability; construction stage; load-resistance performance; modular underground arch culvert; real-scale field test

1. Introduction

Various arch structures have been applied to bridges and culverts according to the structural and aesthetic characteristics of arch systems (Bernini et al. 2000, Bernini 2001, Collings 2005, Hernandez-Montes et al. 2005, Bialy and Skrzypiec 2015, Altunisik et al. 2015, 2019, Yoo and Choi 2018, Alpaslan and Karaca 2021, Karalar and Yesil 2021). For the concrete arch structures currently used, various precast arch structures and systems have been proposed and constructed to improve the constructability, construction period, and economic feasibility of the existing cast-in-place concrete arch systems. Precast concrete arch structures have been proposed since the 1950s to replace existing single-span bridges and underground culverts, and the proposed precast concrete arch structures are designed to form a single arch system by connecting precast arch members on site. And their structural performance and structural durability were also confirmed (Segrestin and Brockbank 1995, Radic et al. 2005, Hutchinson 2004, Tan et al. 2013, 2014, Ong et al. 2015a, b). As the span of the arch increases, improvement of the fabrication, transportation, and construction of precast concrete arch members is required. Thus, modular precast arch structures with a simple construction process have been proposed by continuously connecting many precast blocks (Gupta et al. 2006, Taylor et al. 2006, Long et al. 2014, Hertz 2009, Halding et al. 2015, Chung et al. 2014a, b, Boothby and Fanning 2001, Boothby 2001, Boothby and Fanning 2004, Lacidogna and Accornero 2018, Nguyen et al. 2021, 2022). Among these modular precast arch structures, the modular arch system composed of steel outriggers and precast concrete blocks was developed by dividing the precast block to improve the transportability and construction process of the member, and the precast block ends were designed into circular protrusions and recesses to form an arch, such that the various arch curvatures could be conveniently applied (Jeon et al. 2021a, b). This proposed modular arch system was composed of steel outriggers and precast concrete blocks, and the arch members were connected by a V-shaped shear connection at the installation site; the assembled modular arch system was lifted and installed simultaneously to complete the arch structure. This modular arch system can structurally use backfill soil, which induces a ductile behavior similar to that of a corrugated steel underground arch structure having a flexible structural form.

Based on the comparison of the existing stone arch structure and precast concrete arch structure, a precast concrete arch structure can improve constructability and

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reduce construction costs by reducing the weight of the precast arch member and its simple installation process. However, when the proposed modular precast arch structure is applied as a culvert using the lower part of the arch structure depending on its rise ratio and its installation conditions, securing sufficient arch height may be difficult. Furthermore, since the applicable arch span length can be limited to the length of the arch culvert system, an improved modular underground arch culvert structure was proposed. In the improved modular underground arch culvert structure, the spacing of the precast concrete blocks was adjusted so that the lower part of the arch structure was installed vertically. Moreover, concrete was additionally poured on the rear surface of the vertically installed concrete block so that the installed concrete block and the steel outrigger were integrated into the concrete wall. Therefore, the vertical wall has sufficient rigidity against earth pressure and external load, and the upper concrete block can behave flexibly in the same way as before. Also, it can be applied to places where spans are relatively narrow compared to the height of the culvert structure, and workability can also be secured. To confirm the applicability of this modular arch culvert structure to vertical walls, it is necessary to analyze its structural behaviors and load-resistant characteristics. Thus, in this study, to confirm the structural behavior characteristics and the applicability of the proposed modular precast arch culvert structure, the modular underground arch culvert specimen was fabricated at a real scale that can be applied in practice. And the structural state and response during the construction process and loading test were evaluated and compared through structural analysis.

2. Improved modular underground arch culvert with vertical walls

To use the modular underground arch structure as a typical culvert structure to utilize the inner space in the modular underground arch system, securing sufficient height considering the height and size of a passing vehicle, such as a tunnel, is necessary. For this purpose, a precast modular underground arch culvert structure is proposed here, as shown in Fig. 1. In this modular underground arch culvert, the vertical part installed vertically was improved by using concrete blocks and adjusting the placement spacing based on the previously researched precast modular underground arch system. Since the vertical part of this proposed system is not arch-shaped, the structural characteristics of the arch do not appear, and reinforcement is required, considering the thrust and soil pressure of the upper arch. Thus, this vertical part of the proposed system is designed, and it can be constructed along with the wing wall simultaneously to reduce the construction period. Owing to this vertical part of the proposed modular arch system, it is possible to secure the load-carrying capacity and lower arch space that can sufficiently resist the thrust in the arch system and the soil pressure generated from the backfill soil. It is also possible to secure constructability and economy, the advantages of modular underground arches based on the structural behaviors and response of the previously researched precast modular underground arch system.

Since it is an arch system in which a wing wall with sufficient rigidity is installed in the end part of the previously studied modular arch system, this modular culvert structure exhibits structural characteristics of flexible arches that are the same as those of the thrust line of the previously studied modular arch system, as shown in Fig. 2 (Jeon et al. 2021a, b). Therefore, the possibility of it

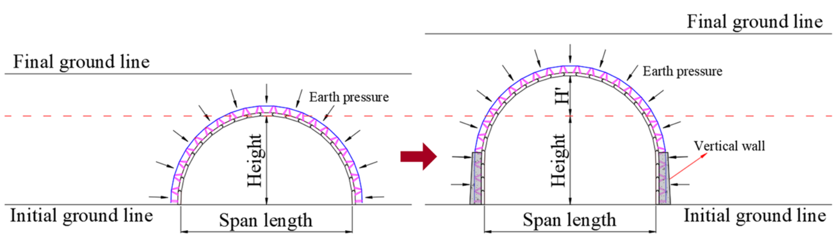


Fig. 1 Concept of improved modular underground arch culvert structure with vertical wall

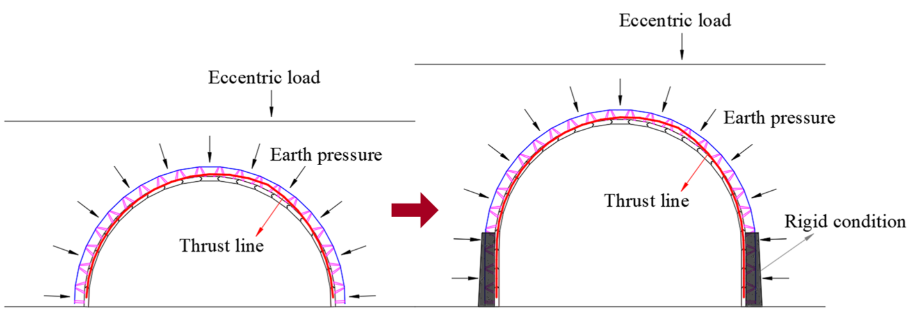
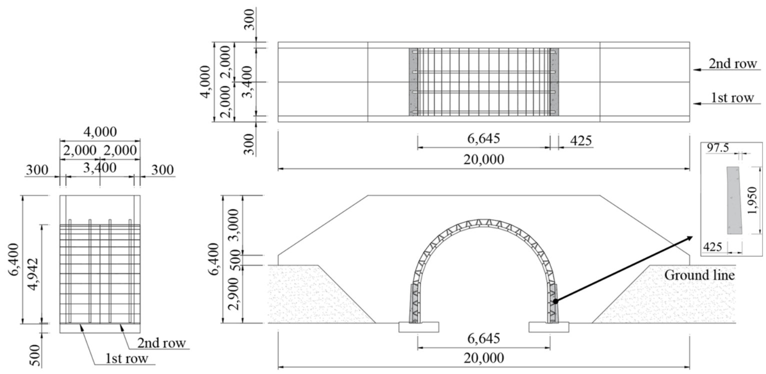
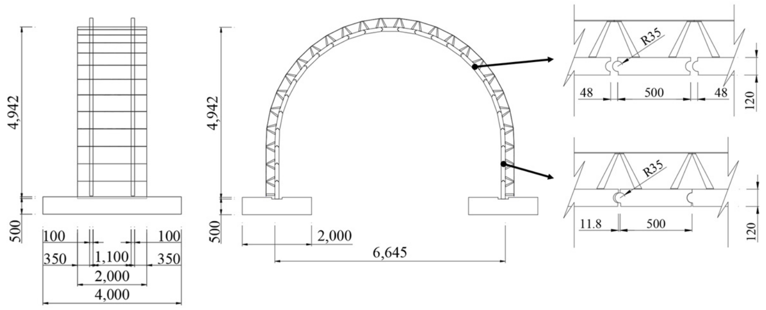


Fig. 2 Thrust line of improved modular underground arch culvert structure with vertical wall



(a) Dimension of modular underground arch specimen with vertical walls



(b) Dimension of the modular underground arch

Fig. 3 Detail of modular underground arch culvert specimen (unit: mm)

exhibiting the same behavior as the previously studied modular arch system is investigated in this study along with its constructability and applicability on site.

3. Applicability and loading test of improved modular underground arch culvert with vertical walls

3.1 Improved modular underground arch specimen with vertical walls and its loading test

3.1.1 Improved modular underground arch specimen

In this study, to examine the applicability and structural behaviors of improved modular underground arch culverts with vertical walls, a modular underground arch culvert specimen comprising two precast arches of 6.645 m span length and 4.942 m height was designed and constructed. It exhibited a total of 20 m length and 6.4 m height, with a wing wall installed at the end of the precast arch as shown in Fig. 3. For fabricating a modular underground arch culvert specimen in this study, a precast concrete block with a thickness of 120 mm and a width of 2,000 mm having a circular protrusion and a recess with a diameter of 70 mm was fabricated. Furthermore, a steel outrigger having a thickness of 4.5 mm and a width of 100 mm and a V-shaped shear connection member for connecting a precast concrete block with outriggers were also fabricated, as shown in Fig. 3.

To consider the structural characteristics and usability of the culvert, in the case of the modular arch specimen, the end precast concrete block was planned to be installed vertically at a height of approximately 2 m in the mounting stage, and it was integrated using cast-in-place concrete after its installation. Furthermore, the size, length, and height of the wing wall were determined by considering the installation of the modular underground arch culvert specimen and the loading condition of the underground modular arch structure (e.g., earth pressure) and loading tests. In the case of the V-shaped shear connection member for the connection of the concrete block and outrigger, the length of the upper part connecting to the outrigger was changed, considering the arch shape of the modular underground arch culvert structure. As the material properties of the structural members in the modular underground arch culvert specimen, the design compressive strengths of the precast concrete block and wing wall constituting the arch system were 35 MPa and 30 MPa, respectively, and SS275 grade steel was considered for the outrigger and V-type shear connection.

The fabrication and construction steps of the modular underground arch culvert specimen with vertical walls are presented in Fig. 4. The fabrication and construction steps were planned as follows: First, for the planned underground culvert site, the pre-made precast concrete blocks, V-shaped shear connection members, and steel outrigger were integrated and pre-assembled, and subsequently, it was lifted using a crane system. The length of the wire during the lifting process should be appropriately considered based on arch formation, and if it is exceedingly short or long, forming a planned span length or curvature may be difficult; thus, the lifting position of the assembled arch specimen was checked for pre-planned arch formation.

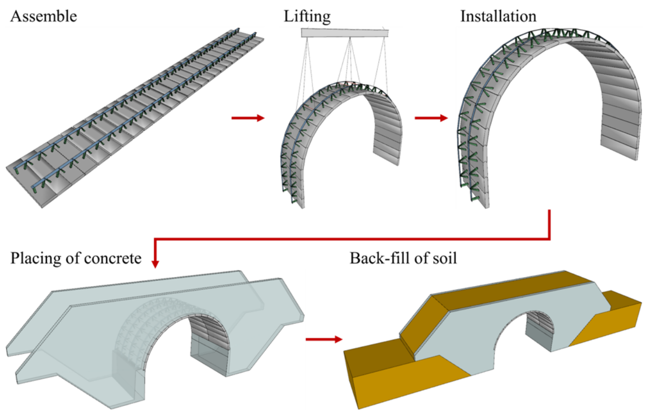


Fig. 4 Fabrication and construction steps of the modular underground arch culvert specimen

(a) Assembled arch members in site

(b) Lifting of assembled modular arch specimen

(c) Installation completion

(d) Wing wall and reinforcement wall

(e) First back fill

(f) Final back fill

Fig. 5 Construction process of the modular underground arch culvert specimen

After the installation of the assembled arch, the vertical wall of the arch was completed, and the wing wall and reinforcement wall were installed; after sufficient curing was completed, backfill and compaction were performed step by step. The construction process of the modular underground arch culvert specimen is summarized in Fig. 5.

Soil property, field density, specific gravity, and compaction tests were performed for analyzing the backfill soil material properties and the compaction level of the modular underground arch specimen. As a result of the soil property test on the backfill soil material, it was classified as SM via the unified classification method, and its average specific gravity value as a result of the specific gravity test was 2.66; its maximum dry unit weight was evaluated as 1.972 t/m^3, and the optimal water content was evaluated to be 9.72%. On-site compaction tests were conducted at the center and both sides of the modular underground arch culvert specimen, and the on-site compaction test results for the three sites were evaluated to be 96.42%, 98.41%, and 96.72% (97.18% in average). Fig. 6 shows the dry unit weight test result of the backfill soil.

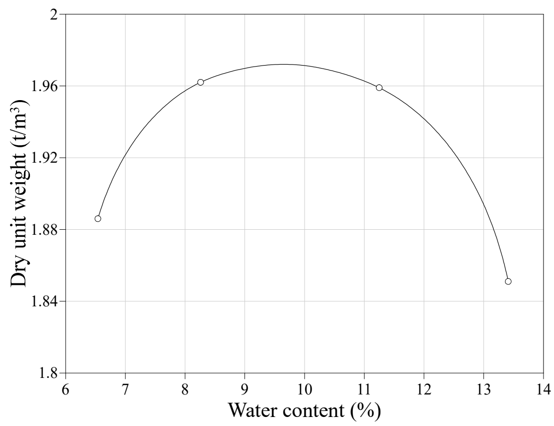


Fig. 6 Dry unit weight test result of the back fill soil

3.1.2 Loading test on modular underground arch specimen

A loading test was also conducted on the fabricated modular arch specimen to evaluate the load-resistant behavior and structural behavior characteristics of the improved modular arch culvert with vertical walls. To confirm the typical behavioral characteristics of the

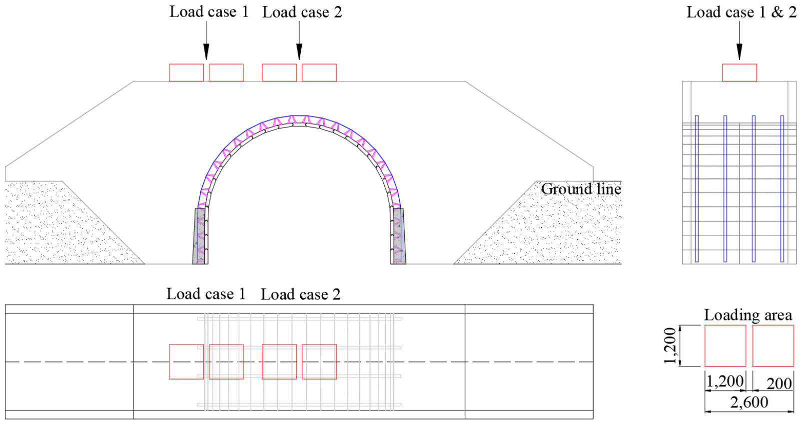


Fig. 7 Loading test cases

(a) Load case 1 (b) Load case 2

Fig. 8 Loading test on the modular arch specimen

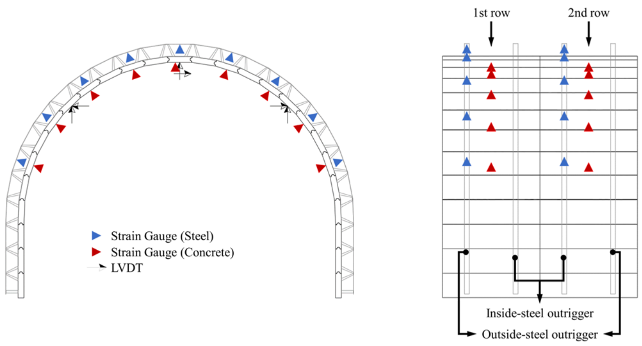


Fig. 9 Strain and displacement measurement location

modular arch structure, loading tests were conducted on the arch side span and the center of the arch specimen, as shown in Fig. 7. Pre-weighed concrete blocks were used in the loading test; A base block of 1200 mm × 1200 mm was first built at the planned location, and concrete blocks were stacked vertically on top of it so that the total load was 154.9 kN. Fig. 8 shows each loading test case.

3.1.3 Measurement set-up

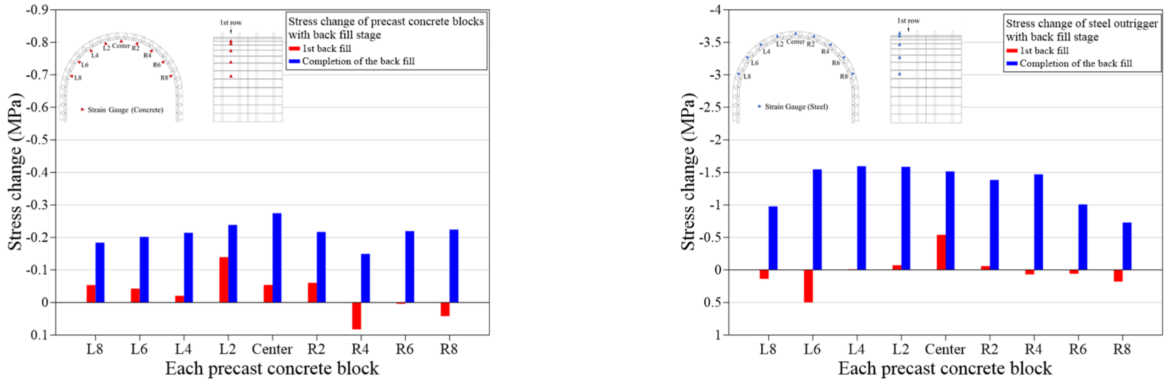
Strain and displacement on the arch specimen were measured to examine its structural state according to the construction process through loading tests using strain gauges and LVDTs. The stress change in the precast concrete block and the outside steel outrigger of the selected modular underground arch row were measured to examine the stress changes according to its construction stage. For displacement change, measurements were obtained relative to the inner side of the selected modular underground arch row (under the precast concrete block). In addition, since the vertical wall has relatively high rigidity by additionally pouring the concrete on the rear surface of the installed concrete block, it was judged that the displacement generated would be very small. Thus, the displacements of the vertical wall were not considered. For its strain and displacement measurement, strain gauges and LVDTs were installed and measured using a data logger (TDS-530), as shown in Fig. 9.

To measure the stress change and displacement of the modular arch specimen for loading tests, the strain, and displacement were also measured at the same member selected for the construction process. Since a relative difference between the first and second rows of the arch system may occur during the loading test process, the stress change in the precast concrete block of the second row was also measured. In addition, the outside steel outriggers were measured in the first row and the inside steel outriggers in the second row, to examine the differences between the inside and the outside outrigger, as shown in Fig. 9.

3.2 Construction stage and loading test results

3.2.1 Measurement result for construction stage

The measurement results of the modular underground arch culvert specimen were analyzed based on the construction stage. After lifting the specimen, only the behavior exhibited during its installation and backfill process were measured, such that the behavior that may occur during the construction stage can be analyzed. The stress change of the precast concrete block and steel outrigger measured during the construction process is shown in Fig. 10. As shown in Fig. 10, the changes in the compressive stress in the 1st backfill state were confirmed, and their compressive stress was shown to increase after the completion of backfilling. In addition, considering that the left and right side backfill are not filled to the same extent and that the same height and degree of compaction are difficult to be applied numerically, the compressive stress is judged to have decreased locally due to the action of one-sided soil pressure during the backfill process. After the completion of the backfill, the compressive stress is judged to have increased to a similar level, although there are differences between the left and right of the arch system, as



(a) Stress change in the concrete block

(b) Stress change in the steel outriggers

Fig. 10 Stress change according to construction stage

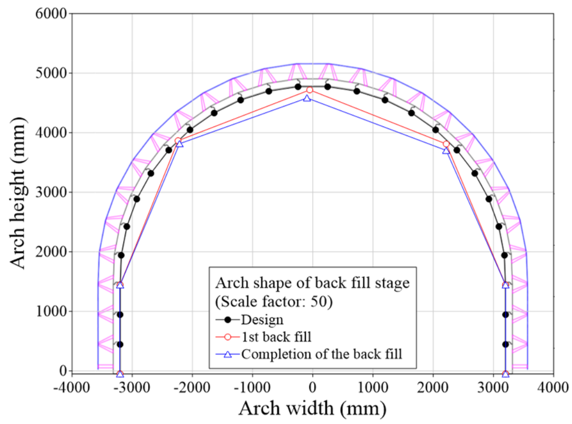


Fig. 11 Displacement measurement results according to construction stage

shown in Fig. 10.

Fig. 11 represents the displacement of the modular underground arch culvert specimen measured according to the construction step. The level of deformation generated in the construction step is relatively small; thus, the measured displacement based on the design value is summarized and compared in Table 1. The three-displacement measurement position was selected on the left and right based on the central block in the arch specimen. The vertical displacement is indicated using "–" sign for downward displacement, and "+" sign for upward displacement; the horizontal displacement is shown by "–" sign to the left and "+" sign to the right in Table 1. As shown in Fig. 11 and Table 1, since the backfill was alternately conducted between the left and right sides, the left and right sides of the measured displacement in the 1st backfill were not the same. However, after the completion of the backfill, the occurrence of horizontal displacement was confirmed toward the center based on the center of the arch, as the left and right sides acted at the same level of earth pressure. Overall, compared to the design arch shape, the level of horizontal and vertical displacement was confirmed to be extremely small, and arch-shaped behavior was exhibited. From these results, the vertical and horizontal displacement generated during backfill was reduced during the backfill of the upper part of the arch specimen, and the planned underground arch shape was formed accordingly. This can also be explained as the load transfer between the concrete blocks and the flexible behavior of the modular arch system, in line with previous test results (Jeon et al. 2021a).

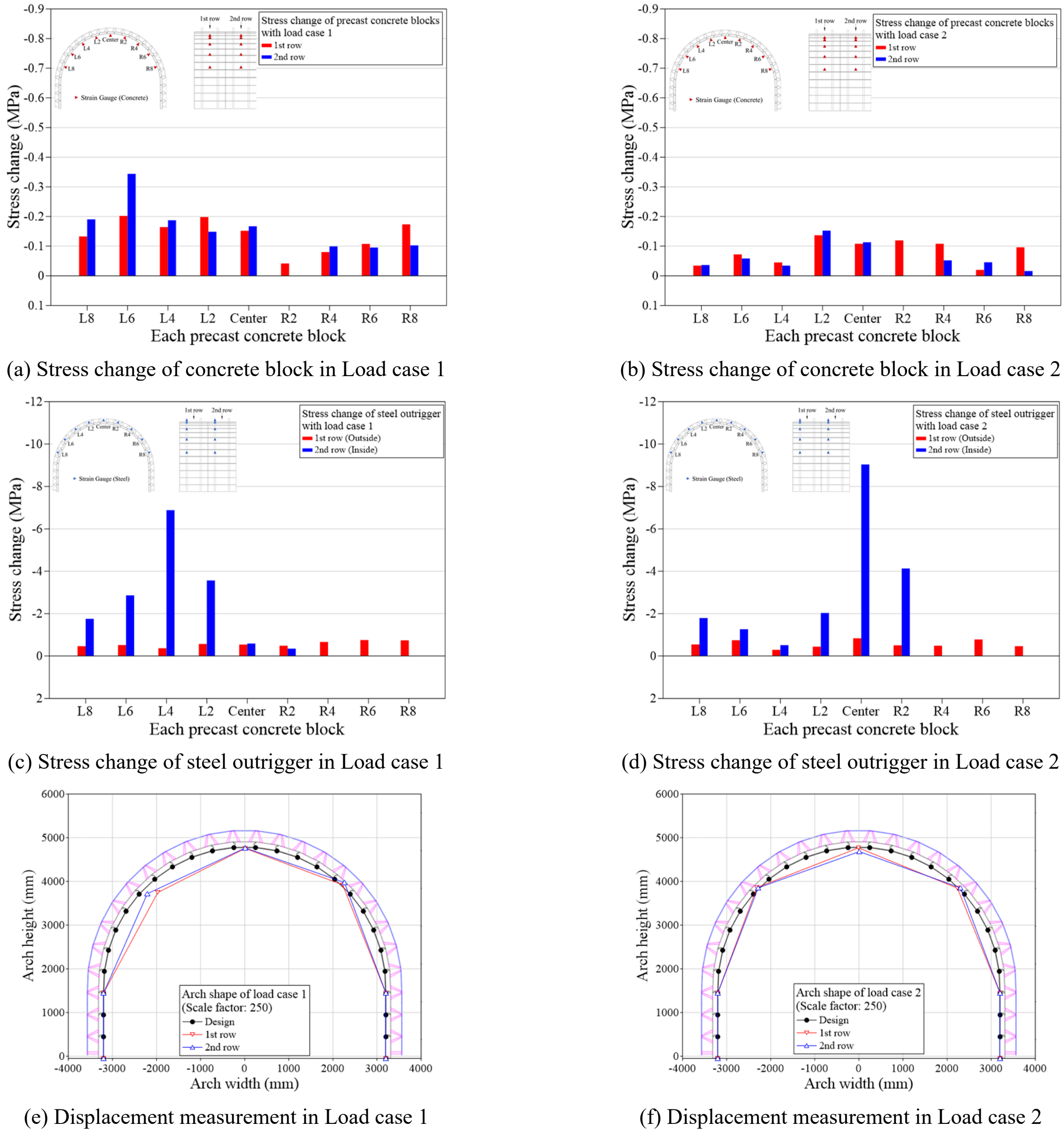
3.2.2 Loading test results

The stress change and displacement measurement results according to loading test cases of the modular underground arch culvert specimen are shown in Fig. 12 and Table 2. The damaged strain gauge results are not included in Fig. 12.

The stress change of the precast concrete block in the final loading state at each load position was measured at a maximum level of -0.34 MPa in Load Case 1 and -0.15 MPa in Load Case 2. The stress change of the steel outrigger was measured at a maximum of -0.75 MPa outside and -6.88 MPa inside for Load Case 1 and up to -0.83 MPa outside and up to -9.04 MPa inside for Load Case 2. In addition, it was confirmed that the maximum vertical displacement that occurred was -0.63 mm in Load Case 1 and -0.35 mm in Load Case 2, and the maximum horizontal displacement was 0.98 mm in Load Case 1 and 0.39 mm in Load Case 2. The measured stress and displacement difference between the first-row concrete block and second-

Table 1 Displacement measurement results according to construction stage (mm)

	1st Backfill of soil		Final Backfill of soil	
	Lateral dis.	Vertical dis.	Lateral dis.	Vertical dis.
L5 (Left side block)	-0.447	-0.231	0.074	-1.242
Center of arch	-1.028	-1.048	-1.930	-3.762
R5 (Right side Block)	-0.010	-1.332	-0.024	-3.500



(a) Stress change of concrete block in Load case 1

(b) Stress change of concrete block in Load case 2

(c) Stress change of steel outrigger in Load case 1

(d) Stress change of steel outrigger in Load case 2

(e) Displacement measurement in Load case 1

(f) Displacement measurement in Load case 2

Fig. 12 Measured stress and displacement distribution results for loading tests

row concrete block is attributed to the difficulty in applying the planned loading position and verticality of loading according to the loading method in this study. In Load Case 1, the concrete block was found to exhibit a larger increase in compressive stress in the loading position compared with that of the block on the opposite side. The inside steel outrigger was found to exhibit greater compressive stress change than that in the other position in the loading position, and the outside steel outrigger was found to exhibit greater compressive stress change than that in the other position in the opposite side of the loading position. Furthermore, the inside steel outrigger exhibited a greater increase in compressive stress than the outside steel outrigger. In Load Case 2, there is a difference between the first and second rows; however, considering the loading process and soil pressure, the stress change level on the left and right sides is judged to be similar relative to the arch center. In concrete blocks, the increase in compressive stress in the center was measured to be the largest. In addition, the outside steel outrigger was measured to exhibit a greater compressive stress increase than the other positions at the center where the load was loaded, and the lower part of the curvature on the left and right sides; the inside steel outrigger was measured to exhibit a greater compressive stress increase at the center where the load was loaded.

The maximum stress change in the concrete block was evaluated to be 0.97% in Load Case 1 and 0.43% in Load Case 2, compared with its design strength of 35 MPa. The maximum stress change in the steel outrigger was evaluated to be 1.52% under the eccentric loading condition and 2.01% under the center loading condition compared with its yield strength of 450 MPa. In the measured displacement in Load Case 1, horizontal displacement occurred to the

Table 2 Measured displacement results for loading tests (mm)

Measure point		Load case 1		
		1st row	2nd row	Average
L5 (Left side block)	Horizontal displacement	0.984	0.032	0.508
	Vertical displacement	-0.525	-0.638	-0.581
Center of arch	Horizontal displacement	0.044	0.05	0.047
	Vertical displacement	-0.066	-0.029	-0.0475
R5 (Right side Block)	Horizontal displacement	0.025	0.181	0.103
	Vertical displacement	0.17	0.391	0.2805
Measure point		Load case 2		
		1st row	2nd row	Average
L5 (Left side block)	Horizontal displacement	-0.393	-0.273	-0.333
	Vertical displacement	-0.083	-0.102	-0.0925
Center of arch	Horizontal displacement	-0.034	0.039	0.0025
	Vertical displacement	-0.02	-0.358	-0.189
R5 (Right side Block)	Horizontal displacement	0.065	0.345	0.205
	Vertical displacement	-0.129	-0.103	-0.116

opposite side of the loading position relative to the arch center at all measurement positions due to change in the soil pressure under the eccentric loading condition of the arch; downward vertical displacement occurred at the center and the loading position, and upward displacement occurred in the opposite side. In the measured displacement in Load Case 2, horizontal displacements occurred in the outward direction relative to the center of the arch at the left and right measurement positions. From the loading test results, the proposed arch system can resist the external load based on the interaction of the outrigger and the deformation that occurred by the concrete blocks determined by the load position. The maximum displacement was evaluated to be extremely small compared with the overall size of the modular arch specimen, with a horizontal displacement of 0.014% for Load Case 1 and 0.005% for Load Case 2, vertical displacement of 0.013% for Load Case 1 and 0.007% for Load Case 2, respectively. The results of the loading test also show that it appears according to the load transfer acting on the modular underground arch and the flexible behavior of the arch system, such as the behavior of the underground arch in the construction stage (Jeon et al. 2021b). In addition, since the culvert structure can behave flexibly, it was judged that there would be no problem even if asymmetric displacements and stresses occurred in the working load state.

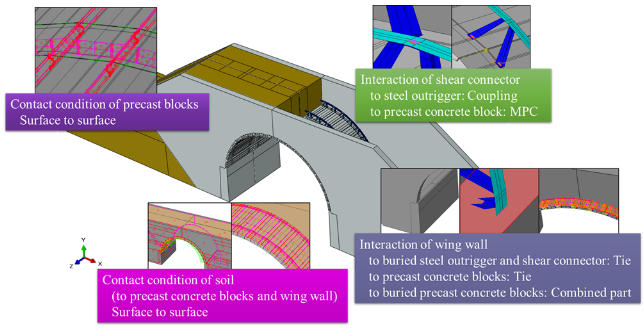
3.3 Structural analysis of modular underground culvert specimen with improved height

3.3.1 Structural analysis model

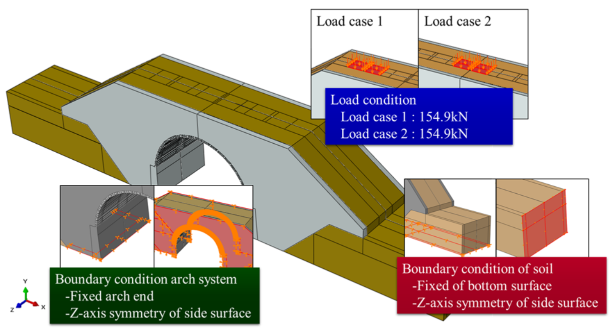
A three-dimensional structural analysis model was constructed for examining and comparing structural behaviors and structural responses of a modular underground arch culvert specimen with improved height using the finite element analysis program ABAQUS, as shown in Fig. 13. In the structural analysis model, the precast concrete block, wing wall, reinforcement wall, and earth soil were applied as solid elements(C3D8R) to consider the connection between concrete blocks and friction force, and the shear connection and outrigger were applied using shell elements(S4R). Additionally, according to the test results, it was confirmed that each member would behave within the elastic range in the construction process and load conditions. Thus, for each material property, only material properties in the elastic range were considered, an elastic modulus for the concrete with the 35 MPa design strength was applied, and an elastic modulus of 205,000 MPa was applied to steel. For earth soil for the modular underground arch, the cap plastic model was applied with an elastic modulus of 50 MPa, considering material nonlinearity (Drucker and Prager 1952). The connection and contact conditions of the precast concrete block and outrigger were considered.

In addition, in the case of the construction stage analysis model, since the wing wall and reinforcement wall are installed simultaneously and lead to rebars, their behavioral characteristics are assumed to be the same and integrated. The concrete blocks that are buried in the reinforcement wall were also integrated. Particularly, for steel outriggers, since a part of it is buried in the reinforcing wall, the end of the steel outrigger that is not buried when the wing wall and the reinforcement wall are installed is configured, such that the same behavior is exhibited under the applied TIE conditions (ABAQUS 2014).

Fig. 13 shows the interaction between members, boundary conditions, and contact conditions considered in the structural analysis model for the underground arch culvert specimen. The surface-to-surface function was used for each contact condition between members including concrete blocks (ABAQUS 2014, Jeon et al. 2021a, b). The structural analysis model for loading tests was used structural analysis model made through the construction stage analysis, as shown in Fig. 13. The load position and

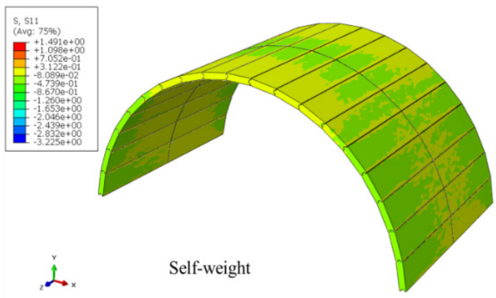


(a) Interaction between structural members

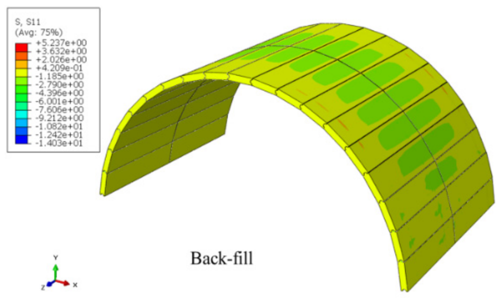


(b) Boundary condition and loading condition

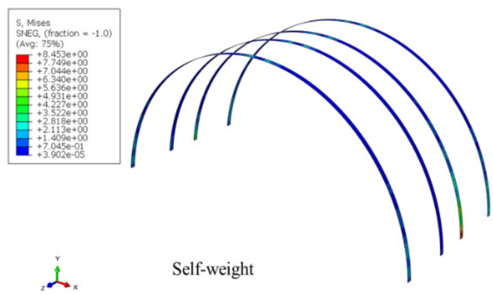
Fig. 13 Structural analysis model of modular underground arch culvert specimen



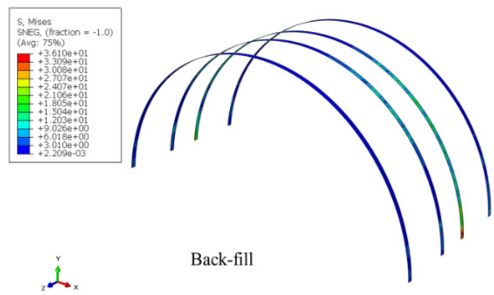
(a) Concrete block stresses for 1st back fill



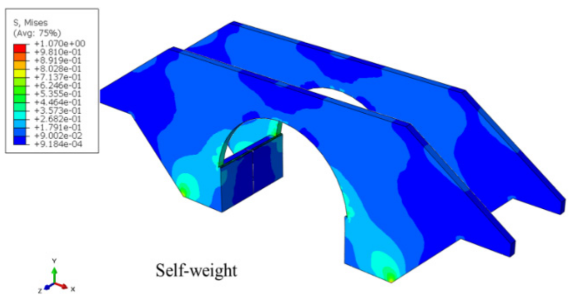
(b) Concrete block stresses for back fill completion



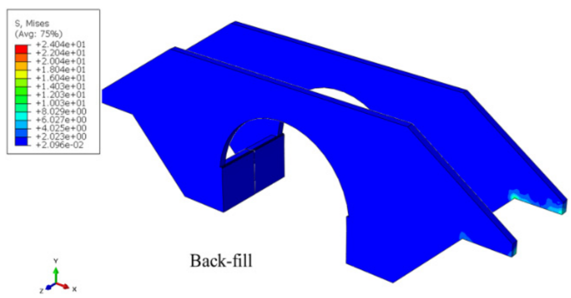
(c) Outrigger stresses for 1st back fill



(d) Outrigger stresses for back fill completion



(e) Wing wall stresses for 1st back fill



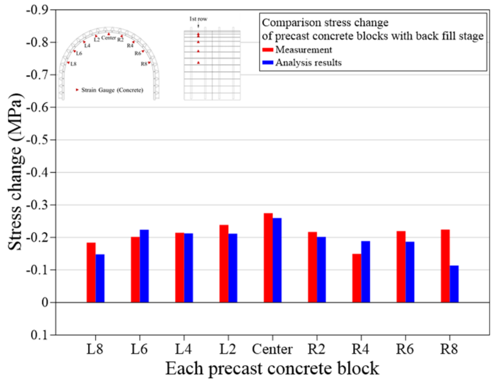
(f) Wing wall stresses after back fill completion

Fig. 14 Structural analysis results for construction stage

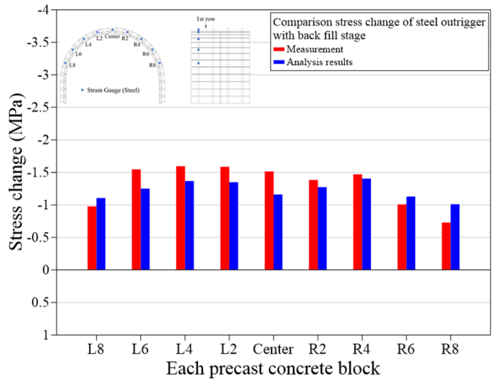
load level on the modular underground arch culvert specimen were considered as same with loading test conditions.

3.3.2 Structural analysis result comparison for construction stage

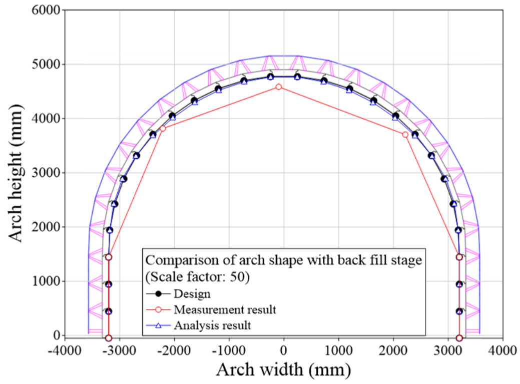
From the structural analysis of the construction stages of the modular underground arch culvert specimen, the deformation shape and stress changes are presented in Fig. 14. As shown in Fig. 14, as a result of the structural analysis, the average stress change generated in the precast concrete block of the modular arch culvert in the construction stage is 0.08~0.87 MPa in the self-weight stage after the wing wall is installed and 0.42~6.00 MPa in the completion stage; the average stress change of the outrigger was evaluated to be 1.4~3.5 MPa in the self-weight state



(a) Concrete block stress changes



(b) Steel outrigger stress changes



(c) Displacements

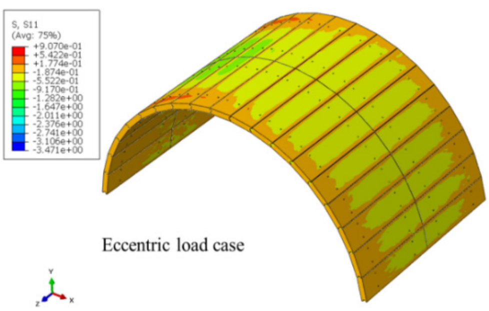
Fig. 15 Comparison of test results and structural analysis results for construction process

and 6.0~15.0 MPa in the completion stage. Upon comparing the stress changes of the concrete block and outriggers in the final state, the final stress changes were evaluated to be less than 20% for the concrete block and less than 1% for outriggers against its design strength.

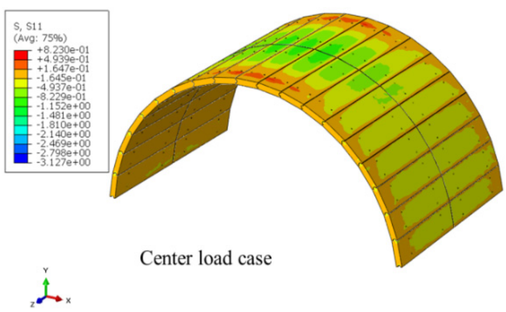
To compare the measurement results in the construction stage of the modular underground arch specimen with the structural analysis results, the strain rate and displacement measurement results were compared in Fig. 15 with the structural analysis results. The stress of the precast concrete block and the steel outrigger appearing in the final construction stage are similar, as shown in the tendency of the structural analysis results and the measurement results, and the difference is not relatively large. The deformation shape and displacement were evaluated to be extremely small relative to the overall scale of the modular arch culvert specimen, and its deformation shape was shown to be similar to each other; however, the displacement in the experiment is relatively larger than that in the structural analysis result. This is attributed to the rotation between the concrete block connections not being completely integrated between the members and a change in the stiffness of the modular arch system from assemble errors and block spacing changes in the modular arch specimen, unlike those in structural analysis.

3.3.3 Structural analysis result comparison for loading tests

Furthermore, the results of the loading test on the modular underground arch culvert specimen were compared

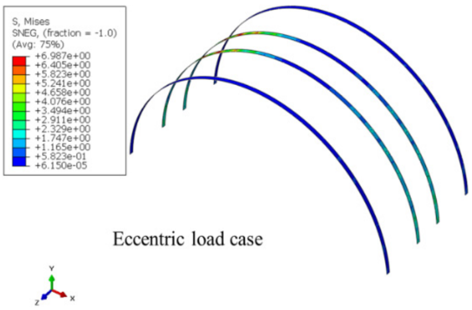


(a) Concrete block stresses for Load case 1

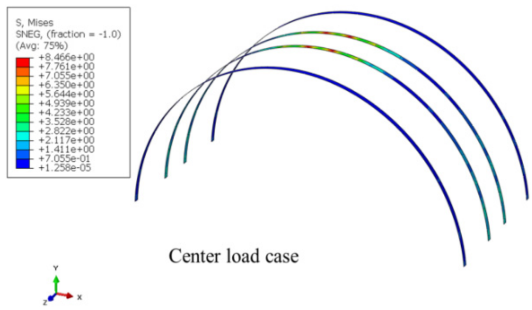


(b) Concrete block stresses for Load case 2

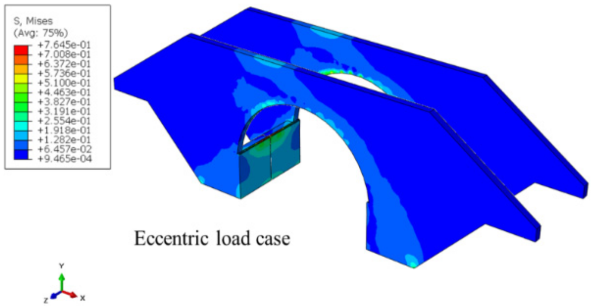
Fig. 16 Structural analysis results for Loading tests



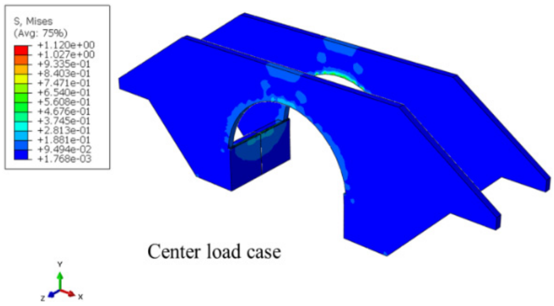
(c) Outrigger stresses for Load case 1



(d) Outrigger stresses for Load case 2



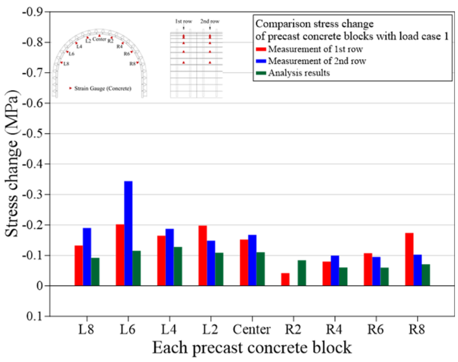
(e) Wing wall stresses for Load case 1



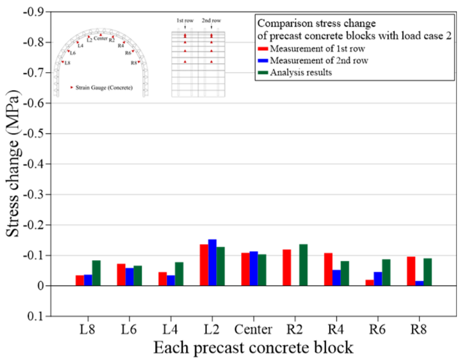
(f) Wing wall stresses for Load case 2

Fig. 16 Continued

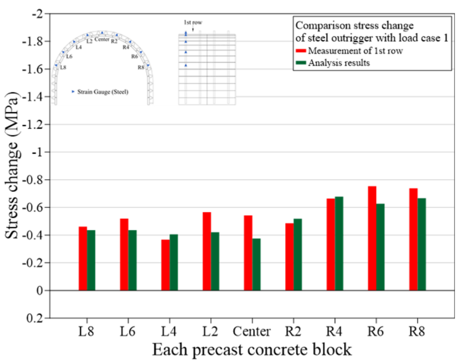
with the structural analysis results, and its deformation shape and stress changes according to the loading condition are shown in Fig. 16. As a result of the structural analysis shown in Fig. 16, the stress change of the precast concrete block is found to be 0.18~1.64 MPa on average for Load Case 1 and 0.16~1.81 MPa for Load Case 2, and the average stress change of the steel outrigger is 0.58~3.49 MPa for Load Case 1 and 0.70~4.23 MPa for Load Case 2. The stress change generated in the precast block and the outrigger was shown to be relatively larger in the loading position according to the load-resistant behavior of the modular underground arch culvert, and the stress change



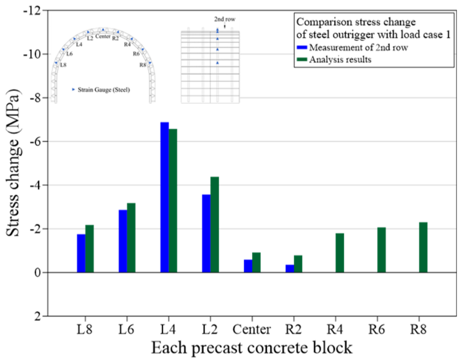
(a) Concrete block stresses for Load case 1



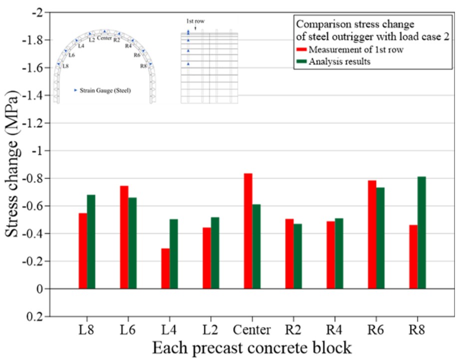
(b) Concrete block stresses for Load case 2



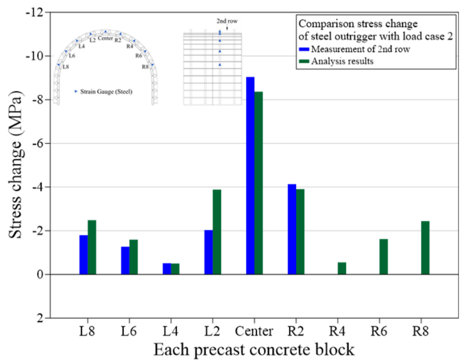
(c) Outrigger stresses for Load case 1



(d) Outrigger stresses for Load case 2



(e) Wing wall stresses for Load case 1



(f) Wing wall stresses for Load case 2

Fig. 16 Continued

was small in the opposite member of the loading position and the side member of the arch culvert. This is similar to the general load-resistant behavior of modular underground arches.

The stress and deformation of each member evaluated via structural analysis for the loading test were compared with the test results in Fig. 17. Since the uncertainty of the soil and interaction with the soil considered in the structural analysis may be different from the actual behaviors, the difference in the load transmitted through the soil is possible. In addition, due to the loading condition such as the perfect loading positioning and the verticality of the loading block, the difference between the structural analysis results was judged to have occurred due to the same reason underlying the measurement result difference between the first and second rows in loading tests. Even considering these errors, the compared stresses were analyzed to be similar in terms of the value and tendency exhibited. When the measured displacement was compared with the structural analysis result, the measured displacement was shown to be relatively larger than that of structural analysis results because of the assembling error of the modular arch member in the construction step, different contact surface conditions between the precast concrete blocks, and local gap and rotation at the block end, etc. However, when considering these characteristics, the difference in displacement relative to the overall scale of the culvert specimen is extremely small, and its tendency against loading is considered to be similar. Therefore, the proposed modular underground arch culvert shows stable behavior, and its structural behaviors can be predicted through structural analysis.

4. Conclusions

In this study, an improved modular underground arch culvert system with the lower arch space composed of a precast concrete arch block and an outrigger and the vertical wall composed of precast concrete blocks was designed by adjusting the placement spacing of concrete blocks to form an arch shape, and the system's applicability and structural behaviors were confirmed by examining its construction process and loading test results of the full-scale modular underground culvert specimen fabricated. In addition, the construction process and loading test results of the modular underground culvert specimen were compared with the three-dimensional structural analysis results to confirm its structural predictability and safety.

As a result of comparing the construction process results and load test results of the manufactured modular precast arched culvert specimen, the stress change of each structural member and the displacement of the arched culvert system were found to be similar to the flexible arch behavior of the previously studied modular arched system. In addition, the stress level generated in the structural member was lower than the design stress, and the member's deformation and displacement were found to be at the considered level upon comparing with the dimensions of the fabricated modular arch specimen. Upon comparing the test results with the structural analysis results, the stress change of the structural members was found to be similar to the structural analysis results, and the deformation characteristics exhibited a similar tendency in the construction process and under the loading condition. Thus, the structural characteristics of the improved modular underground arch culvert were evaluated to be similar to those of the previously studied modular arch structure, and its structural safety and applicability were confirmed.

In the future, the long-term reliability and economic efficiency of the proposed modular underground arch culvert should be investigated through analysis of the effect on the constructability and design of the arch culvert with various spans and lengths.

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