Automation and Operation Record of Large Overhead Crane for Segment Transportation

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Abstract –

The wall of the shield tunnel body is made by assembling panels called segments into a ring shape. For the segment transportation in this site, quick, accurate and safe operation is required in each device mainly using a crane. However, in recent years, it is difficult to secure human resources due to the aging of skilled workers, and automation of segment transport equipment has become an urgent issue.

In this paper, we decided to work on automation of a 40t large overhead crane. The focus of this effort was to investigate an automatic gripping device that can handle various types of segments with different shapes, to study the selection and arrangement of sensors that achieve both high-precision positioning and fail-safe functions, and to efficiently use segments in narrow spaces. This is the construction of a management system using a color code for transporting to a computer.

As a result, the number of workers was reduced by automatic operation, and rework due to human error in selecting the carry-in / carry-out segment was eliminated, and productivity was improved through labor savings. In addition, it eliminates damage to the segments due to erroneous operations and contributes to ensuring quality.

Keywords –

large overhead crane (load limit:40t); Autonomous conveying technology; underground expressway construction site

1 Introduction

In this work, the main line tunnel is being constructed from the intersection of the Tomei Expressway and the Nogawa River in Okura, Setagaya-ku to Inokashira-dori, Kichijoji, Musashino-shi, as part of the Tokyo Outer Ring Road extending from the Kan-Etsu Expressway to the Tomei Expressway, by the EPB shield tunneling method (Figure 1). This work is characterized by a large section (outer diameter: 16.1 m), long distance (9 km), and high-speed excavation.

The walls of the shield tunnel body are made by assembling panels called segments in a ring shape. At the construction site, segments are carried mainly by using cranes, which requires quick and accurate operation. In recent years, however, the aging of skilled workers has made it difficult to secure human resources, so there is an urgent need to automate the cranes. Therefore, this project worked on the automation of 40t large overhead cranes to be used for carry-in, storage, and carry-out of segments in the segment stockyard. This paper reports on how this project was planned and the actual operation results.

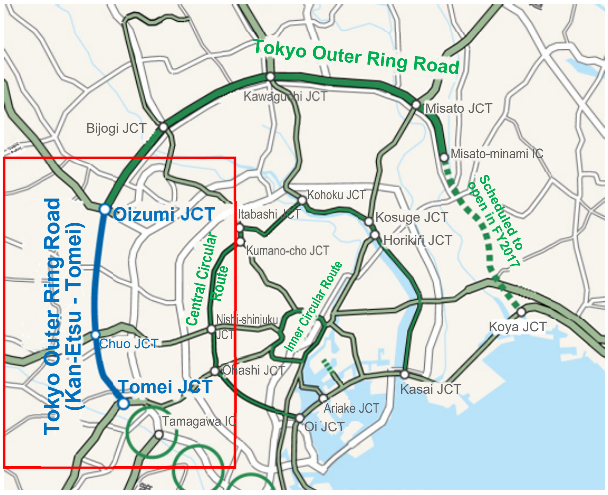


Figure 1. Map of construction location

2 Construction Overview

2.1 Overall Construction Overview

Construction name: Construction Work of the Tokyo Outer Ring Road Main Line Tunnel (Southbound) Tomei Expressway North Route

Orderer: Tokyo Outer Ring Road Construction Office, Kanto Branch, East Nippon Expressway Company Limited

Contractor: Specific Construction Work Joint Venture of Kajima, Maeda, Sumitomo Mitsui, Tekken, and Seibu
Construction area: from Okura, Setagaya-ku, Tokyo to Kichijoji Minami-cho, Musashino-shi, Tokyo
Construction outline

- Section size
  Outer diameter of tunnel: φ15.8 m
  Inner diameter of tunnel: φ14.5 m
  Outer diameter of shield machine: φ16.1 m (largest in Japan)
- Excavation length: 9,155 m
- Construction method: EPB shield tunneling method
- Horizontal alignment: R = 643 m (minimum)
- Earth covering: 38.3 (at the riverbed of Nogawa River) to 55.7 m
- Longitudinal slope: 0.3 to 1.5%
- Cross Passage: 5 locations
- Underground junction: 1 location

2.2 History of Introduction of Automated Overhead Cranes

A multi-shelf automated warehouse is an example of equipment that automatically carries segments in and out. Such warehouses are well-proven and technically established, but if used in construction work that handles large segments such as this project, the following problems arise:

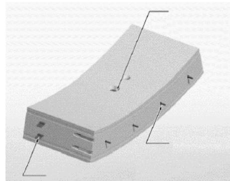
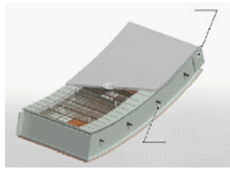
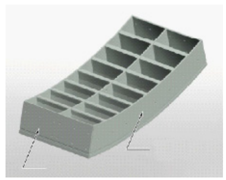
1. The multi-shelf warehouse for large segments requires a large frame structure and consequently large support piles, which increases the construction period and cost.
2. The large frame structure also reduces the advantage of a small footprint of the multi-shelf warehouse.
3. The equipment (a stacker crane) cost is also high (about 2.5 times that of an overhead crane) because it handles heavy loads.

An overhead crane can move freely in three dimensions and function equivalently to a multi-shelf warehouse. Since the overhead crane does not require any special structure, it can shorten the construction period and reduce the cost, and is highly applicable to other similar construction works. Therefore, although it was an unprecedented attempt, this project worked on the automation of overhead cranes as equipment that can automatically carry in and out even large segments instead of a multi-shelf automatic warehouse.

2.3 Segment Overview

In this project the tunnel is constructed by using segments of different materials and widths depending on the purpose and conditions at each location. Over 70,000 segments must be brought in to construct a total of 5,676 rings over the total tunnel length of 9,155 m (Table 1)

Table 1. Segment overview

RC segment		◆ Reinforced concrete structure ◆ Has high rigidity and excellent compression resistance and durability; Used for standard sections across the entire tunnel Number of rings: 4,247 Number of divisions: 13 pcs/ring Weight: Approx. 10 ton/pc
Composite segment		◆ Hybrid structure of steel and concrete ◆ Used in areas where high-rise buildings causing high loads may be constructed Number of rings: 628 Number of divisions: 13 pcs/ring Weight: Approx. 11 ton/pc
Steel segment		◆ Box structure made of steel plates ◆ Used for lateral connecting galleries requiring openings and underground widened sections that need to be cut to be removed Number of rings: 801 Number of divisions: 13 or 14 pcs/ring Weight: Approx. 5 ton/pc

2.4 Overview of Segment Stockyard

Figure 2 and 3 show the workflow from carry-in to carry-out in the segment stockyard.

Segments are transported by trailer, and then picked up, carried in, and stored in the segment stockyard by the overhead cranes. In order to prevent the load from collapsing during transportation, the segments are stacked in only two tiers. In the stockyard, however, segments are stacked in four tiers in principle, and so three rows are used for one ring. In the tunnel, since a precast RC invert is to be installed when assembling segments, it is efficient to also carry in and store RC inverts in the segment stockyard and carry one out together with segments. Therefore, a RC invert storage area is also provided in the segment stockyard. The stockyard as a whole can store segments for 10 rings and RC inverts for eight rings (Figure 4).

Segments stored in the segment stockyard are picked up by the overhead cranes and placed on a temporary receiving pedestal (hereafter, "temporary receiving setter") to be carried out. The segments placed on the temporary receiving setter are transferred to a transport carriage to be carried into the tunnel. Once the segments are carried out of the segment stockyard, their order cannot be changed in the tunnel. Therefore the segments must be carried out in the order of assembly.

Table 2 shows the mechanical specifications for the overhead crane body. Two overhead cranes are installed in order to shorten the cycle time by alternately carrying in and out segments, eventually enabling high-speed excavation (Figure 5).

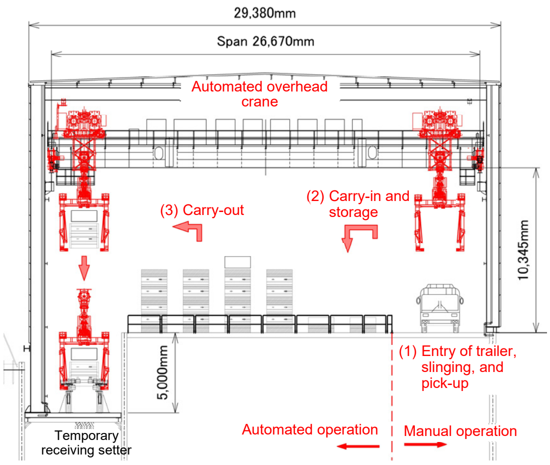


Figure 2. Carry-in/out of segments using overhead cranes

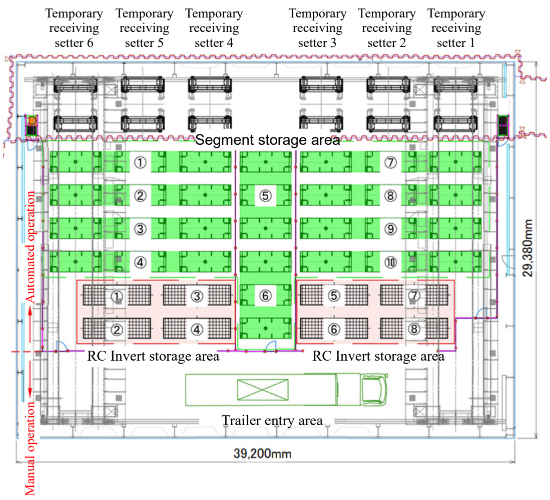


Figure 4. Plan view of segment stockyard

Table 2. Mechanical specifications for overhead crane

Item		Specifications
Rated values	Load	40 t
	Hoisting speed	0.172 m/s
	Traverse speed	0.417 m/s
	Travel speed	0.417 m/s
Wire rope		Type B: IWRC 6 × Fi (29) 8 hooks × 20 mm
Construction	Span	26.67 m
	Crane girder length	27.17 m
	Lifting height	14.25 m
	Crane girder height	10.345 m
Motor	For hoisting	2 × 45 kW
	For traverse motion	2 × 2.2 kW
	For traveling	2 × 5.5 kW
Drum	Hoisting drum	PCD φ540 mm
Sheave	Hoisting sheave	PCD φ558, 400 mm
	Equalizer sheave	PCD φ400 mm

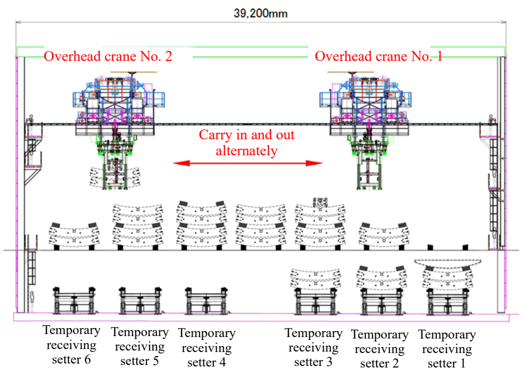


Figure 5. Vertical section of segment stockyard

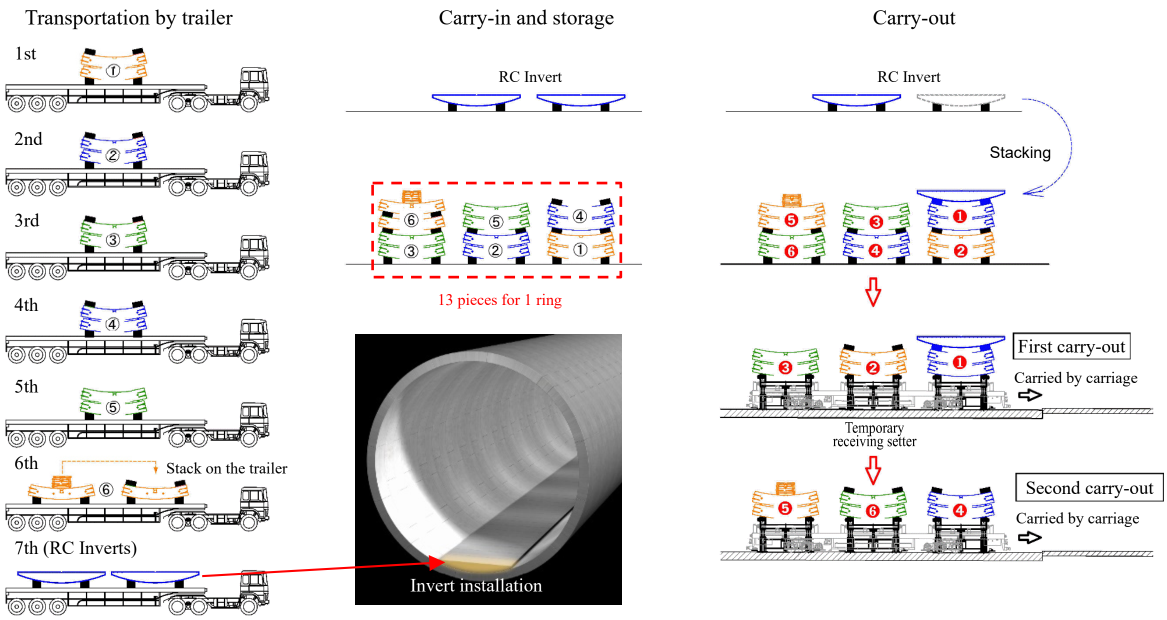


Figure 3. Workflow from carry-in to carry-out in segment stockyard (for one ring)

3 Automated Equipment

3.1 Overview of Automated Cranes

3.1.1 Scope of automation

This time, segments are picked up manually from trailers. This is because there are various shapes of trailers and segments and therefore positioning is difficult, and also the segments brought in by trailers must be checked for damage, requiring human intervention.

After segments are picked up and moved to the storage area, carry-in, inventory management, and carry-out are performed automatically.

3.1.2 System Configuration

Figure 6 shows the system configuration of the automated overhead cranes. The system consists of overhead crane and segment grabs equipped with various sensors and control devices necessary for automation, a management system that issues transport instructions, and a ground control panel that exchanges signals with each piece of equipment.

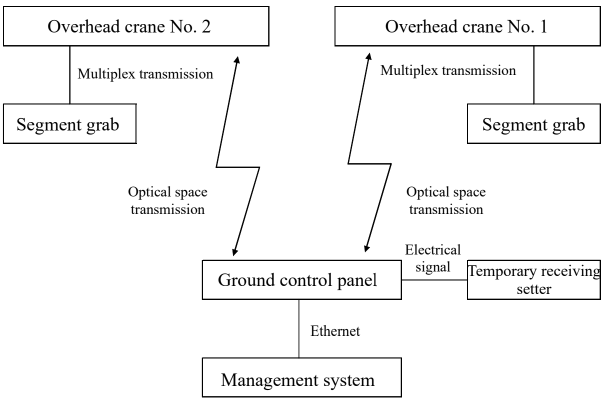


Figure 6. Configuration of automated crane system

3.2 Overhead Crane

3.2.1 Basic Configuration

Table 3 lists the sensors mounted on the overhead crane body for the purpose of automation, and Figure 7 shows the layout.

The position coordinates of the overhead crane were measured by using a laser rangefinder for the travel and traverse directions, and by using an encoder for the hoisting and lowering directions.

Table 3. List of overhead crane sensors

Intended use	Qty.	Model	Intended use of signals	Mounting position and specifications
Hoisting sensor				
Encoder for hoisting position detection	2	MRE-G160SP061FKB (NSD)	For hoisting position detection	Mounted on hoisting drum
Normal upper limit (for origin correction)	2	PSKU-110CO (YE CONTROL)	For correction of hoisting position detection encoder For automated operation control	Weight type
Upper and lower hoisting cam limit switch	2	Supplied with hoist		
Emergency upper limit	2	Supplied with hoist	For master interlock	
Load detector	2	DLS-5033A-1		
Traverse motion sensor				
Laser rangefinder for traverse position detection	1	DL100 (SICK)	For traverse position detection	Mounted on girder With reflector mounted on traverse grab Reflector: 0.5 × 0.5 m
Traverse limit	2	PIKU-110 (YE CONTROL)	Triggers emergency stop when open	
Magnetic proximity switch for traverse position detection	5 (3)	PSMM-R3E1H (YE CONTROL)	For speed monitoring before traverse limit and trailer area detection Triggers emergency stop upon detecting abnormal speed while open	Sensor: Mounted on girder (3 sensors for overhead crane No. 2)
Magnet for magnetic proximity switch for traverse position detection	1	PSMM-M450T (YE CONTROL)	For speed monitoring before traverse limit and trailer area detection Triggers emergency stop upon detecting abnormal speed while open	Magnet: Mounted on traverse grab
Travel sensor				
Laser rangefinder for travel position detection	2	DL100 (SICK)	For travel position detection	Mounted on girder With reflector mounted on soundproof house wall Reflector: 1 × 1 m
Travel limit	1	PIKU-110 (YE CONTROL)	Triggers emergency stop when open	
Magnetic proximity switch for travel position detection	9 (7)	PSMM-R3E1H (YE CONTROL)	For speed monitoring before travel limit Triggers emergency stop upon detecting abnormal speed while open	Sensor: Mounted on travel girder (7 sensors for overhead crane No. 2)
Magnet for magnetic proximity switch for travel position detection	9 (7)	PSMM-M450T (YE CONTROL)	For speed monitoring before travel limit Triggers emergency stop upon detecting abnormal speed while open	Magnet: Mounted on soundproof house wall (7 magnets for overhead crane No. 2)
Others				
Optical space transmission device	1 pair (2 units)	BWF-3EA/B (Hokuyo)	For overhead–ground transmission: 1 pair	Crane-ground transmission
Anti-collision detector	1	TCR-30L3 (Toyo Electric)	For collision prevention between cranes	Mounted on girder With reflector mounted on counterpart crane

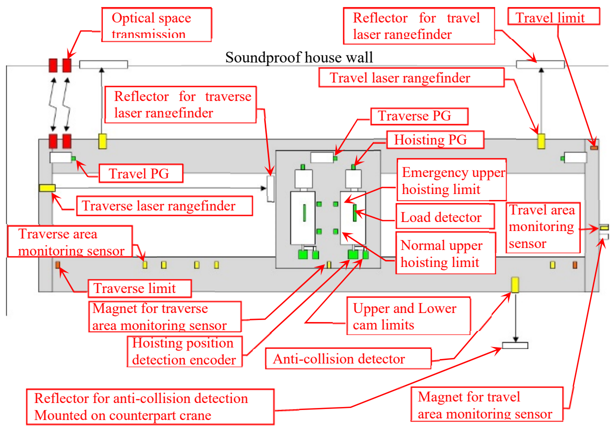


Figure 7. Layout of overhead crane sensors

3.2.2 Positioning Accuracy

The stopping accuracy of the overhead crane must be set to the target value ±50 mm, considering the possibility of interference between the segment to be carried into the tunnel and other equipment. Since high-precision positioning control is required, vector control with PG (pulse generator), which can output stable torque even at low speeds, is used to control the electric motor (Table 4).

Table 4. Specifications for overhead crane motor

Intended use	Qty.	Model	Output (kW)	Control method
Electric hoisting motor	2	For hoist 180Fr	45	Yaskawa Matrix Converter U1000 80 kVA Vector control with PG PG: MSK-510-1024 (1024 pulse/rev)
Electric traverse motor	2	CNVM3-6120-AP-B-21	2.2	Yaskawa Matrix Converter U1000 8 kVA Vector control with PG PG: ERN1330 (1024 pulse/rev)
Electric travel motor	2	CNVM8-6165-AP-B-25	5.5	Yaskawa Matrix Converter U1000 12 kVA Vector control with PG PG: ERN1330 (1024 pulse/rev)

3.2.3 Safety Functions

The following safety functions are provided so that the automated operation of the overhead cranes is stopped if the positions of the cranes cannot be measured accurately due to failure in the laser rangefinder or encoder measuring the positional coordinates of the cranes.

1. Positioning monitoring
   If the deviation between the integrated value of the vector control PG and the value measured by the laser rangefinder, for the travel and traverse directions, or the deviation between the command value from the management system and the value measured by the encoder, for the hoisting and lowering directions, exceeds a certain value during positioning, it is regarded as a position detection error and the overhead crane is stopped.
2. Area monitoring
   The area is monitored by magnetic detection sensors to prevent the overhead cranes from continuing automated operation after deviating from the predetermined area. These sensors are installed near the boundary between the manual and automated operation areas and that between the working areas of the two overhead cranes.Figure 8 shows the area monitoring plan diagram.
   A magnetic detection switch for monitoring deceleration is installed in front of the segment storage area at the end of each area. If the overhead crane is traveling or traversing faster than the rated speed when detected by the sensor, it is judged to be abnormal and the crane is stopped. This ensures that overhead cranes approaching an area boundary are decelerated without fail.
   If the overhead crane continues traveling or traversing even after reaching the segment storage area at the end of each area, the limit magnetic detection switch (or the limit switch for the travel and traverse ends) judges it as an overrun and stops the crane. The limit magnetic detection switch acts as an electric stopper and is set to the position such that the overhead crane stops before hitting against the mechanical stopper.

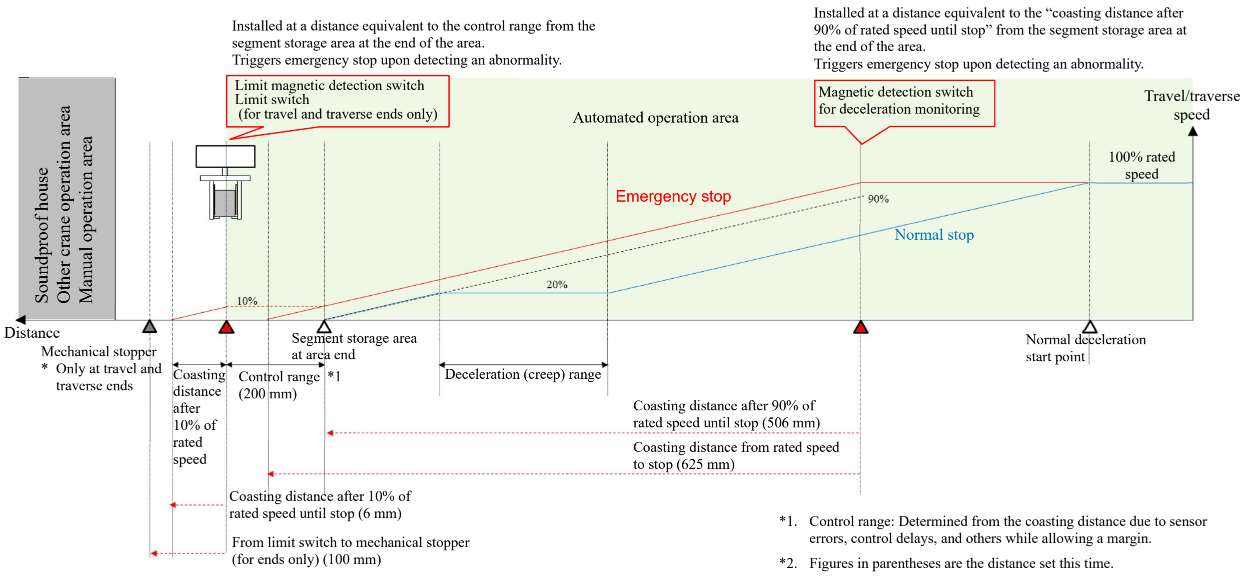


Figure 8. Area monitoring plan diagram

3.3 Segment Grab

Transportation of segments using a crane used to be performed by manually slinging the segments on a sling or the like. This time, a segment grab was newly developed as an automated segment slinging device.

Figure 9 shows the mechanical drawing and Table 5 lists the mechanical specifications for the segment grab. The segment grab is used as a slinging tool by hanging it on the hook of the automated overhead crane. However, the hook would rotate freely if left as it is, so it is pinched with plates to prevent rotation.

In order to align the center of gravity between the segment grab and the segments even for those with different widths, the segments are sandwiched by two arms in the lateral direction and then placed on the grabbing jaws. The grabbing jaws that support segments are fitted with rubber plates, and the arms and the grabbing detection bar that come into contact with the segments are fitted with MC nylon plates (friction reducing plates), in order not to damage the segments during lifting. Photo 1 shows the segment grab grabbing segments.

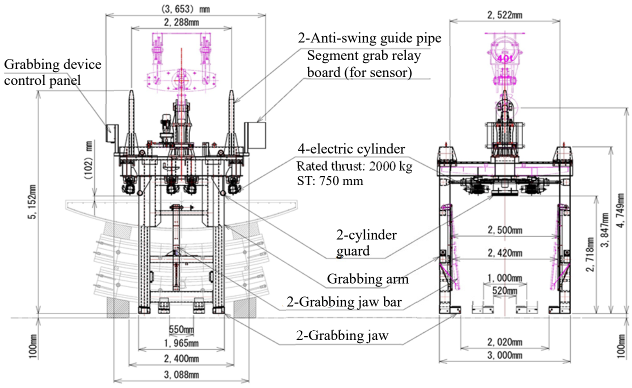


Figure 9. Segment grab drawing

Table 5. Mechanical specifications for segment grab

Item		Specifications
Rated load		33 t
Opening/closing speed		75 mm/sec × 2 (9.0 m/min)
Arm opening		520 to 2,020 mm
Arm length		3,547 mm
Arm width		1,950 mm
Jaw length		240 mm
Own weight		6,800 kg
Electric cylinder	Power supply	3-phase, 400 V, 50 Hz
	Stroke	750 mm
	Motor capacity	2.2 kW × 2 units × 2 arms
	Rated thrust (per piece)	2,000 kgf
	Accessories	Thrust detector Rotary encoder Stroke adjustment LS

In addition, anti-swing guide pipes are installed on the segment grab, which fit into the sheath pipes on the overhead crane when the grab is hoisted to the upper limit, preventing the load from swinging during traverse motion. Although it is necessary to hoist up the grab to the upper limit each time before making traverse motion, this enables high-speed traverse motion and highly accurate positioning.

Table 6 lists the sensors mounted on the segment grab, and Figure 10 shows the layout.

The grabbing sensors detect that the segments are sandwiched by the arms, and the loading sensors detect that the segments are engaged with the jaws. Both types of sensors work together to detect that the segments are securely grabbed.

The pocket collision and bottom collision detection sensors are provided to prevent contact between the segment grab and the segment, RC invert or any obstacle in the event of an abnormality in positioning or an unexpected incident.

The grab opening detectors are provided to detect the cylinder strokes of the left and right arms and are used for positioning correction in the traverse direction (Figure 11). In particular, when picking up segments from a trailer by manual operation, the center cannot be aligned precisely between the segment grab and segments, causing a difference in the strokes of the left and right arms. If the segments are carried in such a state, the center of the segments will deviate from the target position because the positioning is performed using the center of the segment grab as the reference. In order to prevent this, the strokes of the left and right arms are detected when grabbing the segments, and the traverse distance is corrected during positioning by the difference between the strokes.

Photo 1. Segment grab grabbing segments

Table 6. List of segment grab sensors

Name	Qty.	Model	Intended use of signals	Notes
Electric cylinder	4	LPTC2000H7.5V LRIJF-TK (Tsubaki E&M)	For opening/ closing the grab	With thrust detector, rotary encoder, and stroke adjustment LS
Hole detection photoelectric switch	6	PEY-155C (Hokuyo)	For detecting obstacles when opening/closing the grab	Light projector/receiver
Loading detection proximity switch	2	E2E-X3D1 (Omron)	Loading detection	
Grabbing detection proximity switch	2	E2E-X10D1 (Omron)	For grabbing detection	
Bottom collision detection photoelectric switch	16	PZ-G41N (Keyence)	For detecting obstacles under the grab	
Pocket collision detection photoelectric switch	16	PD5-1MC (Hokuyo)	For detecting obstacles when lowering the grab	

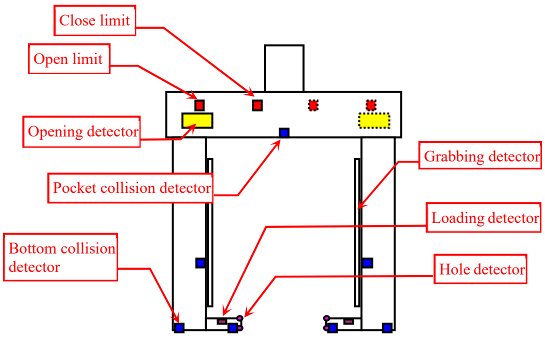


Figure 10. Layout of segment grab sensors

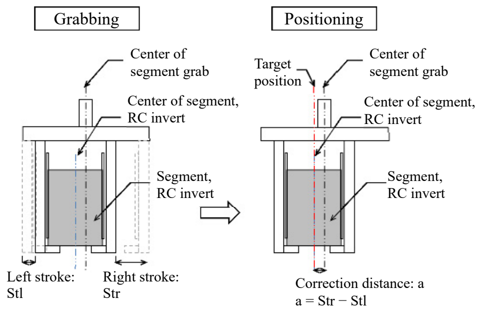


Figure 11. Positioning correction in traverse direction

3.4 Picking Up and Attitude Detection of Segments

It is impossible to position the trailer strictly at right angles to the overhead crane or load segments exactly parallel to the trailer, and consequently, segments are angularly misaligned with the segment grab. As the segment grab is suspended by wires, it rotates to align with the segments upon grabbing the segments, but when the grab is hoisted up to the upper limit, the guide pipes on the grab fit into the anti-swing sheath pipes, so that the angular deviation is corrected (Figure 12).

3.5 Management System

The management system consists of a survey system and an ordering system. The configuration of the management system is shown in Figure 13.

The survey system plans the allocation of future segments based on the survey results of the tunnel alignment and the design alignment plan.

The ordering system orders the factory to ship the segments planned to be allocated by the survey system, and at the same time, specifies the loading order of the segments onto the trailer according to the types of segments, and is also able to check whether the segments are loaded onto the trailer in the specified order at the time of shipment from the factory.

The automated overhead crane automatically determines where to store the segments in the stockyard from the information on the segments brought in by trailers and that on the inventory in the stockyard. In addition, it automatically selects the segments to be carried out according to the allocation plan and transports them from the stockyard to the temporary receiving setter.

The color code shown in Figure 14 was adopted as a marker to identify each segment and RC invert. A color code sticker which identifies the segment type is attached to the side of each segment at the factory, and the color code is read by the camera on a tablet terminal at the site so that the automated overhead crane recognizes the type of the segment brought into the stockyard. Unlike barcodes and QR codes, multiple color codes can be read from a distance at a time, which is ideal for identifying stacked large segments such as those in this case.

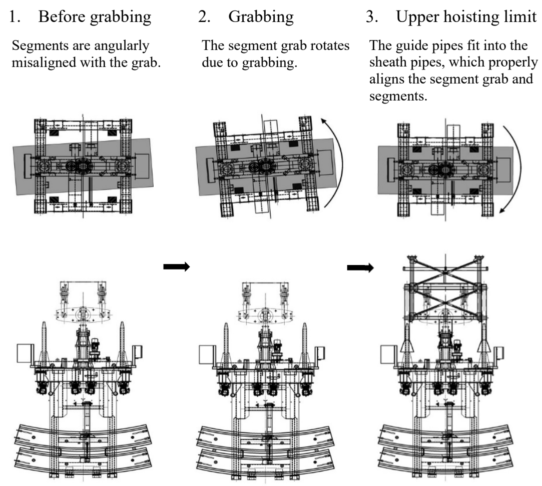


Figure 12. Angular misalignment correction flow for segments

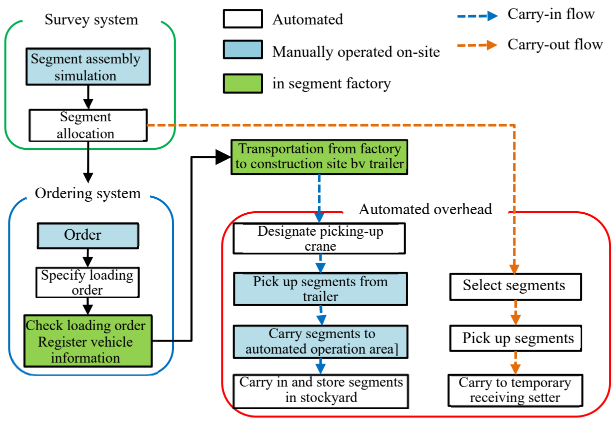


Figure 13. Configuration of management system

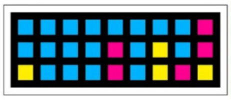


Figure 14. Color code

3.6 Safety Measures

In order to prevent accidents such as people getting caught in the overhead crane during automated operation, fences are installed at the boundary between the automated and manual operation areas. However, to allow people to enter the automated operation area for maintenance, open/close doors are provided at some points of the fences. A lockable open/close detection sensor is also mounted on each door in order to prevent people from accidentally entering the area during automated operation (Figure 15). If any door opens during automated operation, the overhead cranes are stopped. Furthermore, to ensure safety, people entering the automated operation area are obliged to carry the key of the open/close detection sensor with them so that the automated operation of the cranes cannot be restarted until they leave the area.

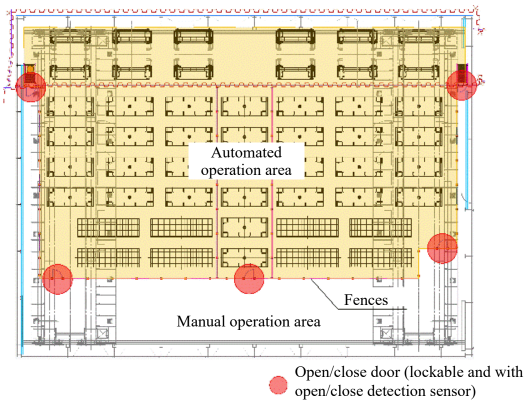


Figure 15. Layout of fences and doors with open/close sensors

4 Actual Operation Results

4.1 Productivity Improvement

4.1.1 Labor saving and reduced dependency on personnel

As a result of the introduction of automated overhead cranes, all the segment stockyard operations were automated except unloading of segments from the trailer, which required only two operators. Before these cranes were introduced, it had been assumed that a total of six operators would be required, two for each of the two overhead cranes and two for the temporary receiving setter. Thus, the use of automated overhead cranes improved productivity by saving labor.

This project significantly improved productivity also by reducing labor hours due to the reduced thinking time required for determining where to store segments and identifying the segments to be carried out, and by reducing the dependency on personnel so that even operators without specialized knowledge or advanced skills can perform the operations.

4.1.2 Reduction of losses due to rework

If a wrong segment is carried into the tunnel, the segment must be replaced, requiring shield excavation to be stopped. This would cause various losses, such as the stand-by hours of excavation operators and cancellation of materials and vehicles. In the case of a large-scale construction work like this, the cost incurred would be enormous.

The segment selection function of the automated overhead crane has been working without requiring any rework until now.

4.2 Quality Assurance

While ensuring a positioning accuracy of ±50 mm, this project achieved automated transportation, and prevented malfunctions by means of various sensors and prevented erroneous operation by humans. The system has not caused any damage, such as cracking and chipping, to segments until now. The project has successfully built equipment that can make a significant contribution to quality assurance.

4.3 Improved Safety

In automated operation, the overhead cranes (machine) and segments and RC inverts (load) are completely separated from humans, eliminating the risk of man-made disasters and contributing to improved safety.

5 Conclusion

This project introduced automated transportation using overhead cranes, which was unprecedented in the carry-in/out of segments for shield construction work. The system improved the on-site productivity and safety, and also contributed to quality assurance. The automated overhead crane we developed can handle segments of different widths and shapes, and is highly applicable to other similar construction works.

We will continue to work on improving the efficiency of construction work on-site in order to address the shortage of human resources due to the declining birthrate and aging population.