Rapid Construction of HEP & JES (High Speed Element Pull & Jointed Element Structure) by Mechanical Excavation

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1. Introduction
In projects to construct a road tunnel that crosses below a railway line in service, the HEP & JES method is usually used. This technique consists in inserting rectangular steel components with small section (called "elements") successively into the ground, and joining the elements with each other to make a tunnel tube, then excavating inside the tube. As a general rule, the elements are inserted in the order: ceiling slab, side walls and floor slab. During placement of the ceiling slab element in a site with a thin overburden, where the work is likely to adversely impact the railway track, the railway is closed. In a construction site where it is difficult to close the railway, ceiling slab elements must be placed during short periods when tracks are closed, resulting in longer construction period. Speeding up the element placement has been therefore a high-priority.

This paper gives a description of an underpass construction project that used the HEP & JES method, below the JR Tohoku Honsen Line, in an attempt to shorten the length of time required for the project.

![Fig. 1 Schematic diagram of the HEP Method (by mechanical cutting)](image)

The plan of the project is shown in Fig. 3. The construction zone allotted to East Japan Railway Company spanned 58.6 m, of which 12.0 m length below the conventional railway tracks was constructed by the HEP & JES non-open cut method. In the sections adjacent to this zone, a box culvert and a U type retaining wall were constructed by the open cut method. The cross section of the HEP & JES zone is shown in Fig. 4.

![Fig. 2 JES Method](image)
2. Construction conditions
The construction zone has a railway double track. During placement of the ceiling slab element, a speed limit on railway operation of 45 km/h was imposed. The track closure durations are shown in the diagram of Fig. 5, 180 minutes in the track bound to Tokyo (hereinafter called “southbound track”) and 114 minutes in the track bound to Tohoku (hereinafter called “northbound track”). However, the duration of closure in both tracks at the same time was only about 40 minutes. The track crossing width was 10.0 m.

As a rule, the work was to be performed during track closure, in a zone where the excavator cutter casing position was within 1.5 m on either side from the center of the southbound or northbound track (Fig. 6).
The length of an element was, as a general rule, 11.6 m long spanning the whole length of the project structure (therefore no longitudinal joints were necessary). The vertical shaft was 20.0 m long. Of 23 ceiling slab elements, 14 elements were placed by mechanical cutting and 9 elements by manual cutting (one reference element (A), two at both ends (G and E), and 6 at sections interfering with a water channel). The overburden was about 1.0 m deep. The geology was cohesive soil.

<table>
<thead>
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<th>Time</th>
<th>22</th>
<th>23</th>
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<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<td>Start side</td>
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<td>End side</td>
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<tr>
<td>Track closure Southbound</td>
<td>41 minutes</td>
<td>27 minutes</td>
<td>Ballast removal/Temporary rail support</td>
<td>Element pull</td>
<td>Ballast restoring/ Tamping</td>
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<td>(31 minutes)</td>
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**Fig. 5 Track closure schedule**

3. HEP & JES method and pull speed
3.1 Conventional pull speed in the HEP & JES method
The HEP & JES method needs no temporary members since the elements are used as a permanent structure. Therefore, a mere pulling completes the placement. For element pulling in a zone with a shallow overburden, East Japan Railway Company requires track closure for ensuring safety, thus limiting time available for construction.

The pull speed by mechanical cutting recorded in preceding projects were 40 to 65 mm/min on the average and 80 to 90 mm/min at maximum, and usually 4 to 6 m during one night. The pull speed is limited empirically so that no heaving or settlement of the track may be induced by pulling, and no time loss may occur due to jamming of soil at the cutter casing and belt conveyor.
3.2 Setting the target pull speed
The target set for the present project was to complete the placement of an element during one night (cutting the steel sheet pile, element pulling, cutter casing recovery). To achieve this goal, for the northbound track, it is necessary to pull a length of 4,560 mm in 84 minutes with a time margin of 30 minutes. The pull speed necessary for this purpose is at least 55 mm/min. The target pull speed was set at 100 mm/min that is about double the minimum necessary speed, in order to accelerate construction.

4. Issues for achieving rapid construction – performance of mechanical equipment
4.1 Soil intake volume
In dense cohesive soil as with the present project, the higher the pull speed, the soil intake volume tends to be insufficient, which may heave the surface.
Conventionally, in the HEP & JES method, the cutter rotation rate is kept almost constant, and adjusted observing the impact upon the surface and pull force. Therefore, when increasing the pull speed, the cutter casing geometry should be so designed that soil intake efficiency is optimized.

The present construction used the cutter casing geometry with an open side. In addition to the conventional cutter casing (photo 1), the improved cutter casing (Photo 2) was used, which is provided with a ribbon screw elongated one pitch ahead for preventing track heaving. Of 14 elements placed by mechanical cutting, 5 elements on the starting side were placed using the improved cutter casing, while 9 on the ending side with the conventional cutter casing.

4.2 Transport capacity of the ribbon screw
Soil excavated by the cutter casing is carried by the ribbon screw in the excavator to the belt conveyor installed in the element. The ribbon screw and cutter casing are rotated by the same driving shaft at the same rotation speed. With a pull speed of 100 mm/min, the conveyed muck volume is 7.52 m³/hr. At this speed, the section filling ratio of the ribbon screw is 0.31, demonstrating a sufficient margin of the capacity even if the pull speed is increased to 100 mm/min.

4.3 Transport capacity of the belt conveyor and measures against breakdown.
A unit-type belt conveyor was used for mucking. Its transport capacity was 15 m³/hr. The capacity was sufficient with a margin to handle muck of 7.52 m³/hr at a pull speed of 100 mm/min. However, breakdown of the belt conveyor was mainly caused by non-uniform distribution of soil falling from the ribbon screw onto the belt conveyor and split soil due to fluctuation in muck volume jammed the belt conveyor.

As a result of the study on this issue, protection panels were installed to prevent soil from spreading outside the belt conveyor width.
To make muck easy to detach from the ribbon screw, the excavator was designed with a structure capable of spraying water into the cutter casing. In addition, since muck is prone to spill when transferring from the conveyor inside the element to another conveyor below the element, a worker was assigned to monitor the status of mucking.
5. Measures against track deterioration during rapid construction
5.1 Measures against track heaving due to element pulling
To prevent the track from heaving, ballast was removed in the range of two to three tie intervals just above element being pulled to make a clearance of 50 to 100 mm below the ties ("sleepers" in British expression).

When a train passes by, the track is temporally supported with short ties, and after pulling is complete, the track is restored. Since the work was done during the season when rail temperatures are high (April 1 to July 19), an anti-buckling plate was placed at an interval of one per three ties, and the ballast was restored during the last track closure at night.

5.2 Measures against track alignment irregularities due to element pulling
Fig. 8 shows the measures taken for reducing friction between elements and the ground, to prevent irregularities in track alignment during element pulling.
For this purpose, a 6 mm thick steel plate (FC plate) was installed on the upper surface of the element. The FC plate was fixed by welding to the starting side steel sheet pile, after the cutter casing passed the southbound track, thereby preventing the southbound track from being displaced when the element was pulled below the northbound track.
In addition, lubricant was applied to the upper surface of the element and the steel plate to reduce friction with the ground during element pulling.
5.3 Installation of rail stiffening girders
For underpass construction below railway tracks, installing rail stiffening girders is the standard practice of the JR Tohoku Construction Office to prevent roadbed cave-in. In the present project, rail stiffening girders 30 m long were placed both for the southbound and northbound tracks (Fig. 9, Photo 3).

Fig. 9 Cross section of the stiffening girder

Photo 3 Stiffening girder installed

6. Construction results
6.1 Number of elements pulled per day
Of the 14 elements placed by mechanical cutting, except for two elements in places where electric pole foundations interfered, the initial target of one element pulling/one night was achieved.

6.2 Pulling speed
Fig. 10 shows the relationship between pull speed of the conventional cutter casing (B9) and improved cutter casing (F1), and the pull distance.
The pull speed of the conventional cutter casing (B9) was about 70 mm/min up to the point below the southbound track and about 85 mm/min below the northbound track.
The pull speed of the improved cutter casing (F1) was about 70 mm/min up to the point below the southbound track and about 100 mm/min below the northbound track.
The reason why the pull speed was low below the southbound track is that there is a relatively large time margin for track closure, and therefore, even if the pull speed would have increased to a level equal to that below the northbound track, waiting would not have been eliminated.
Fig. 11 shows the average and maximum pull speeds for each element below the northbound track. The average speed was 77 mm/min with the conventional cutter casing, and 90 mm/min with the improved cutter casing. As demonstrated by this result, the pull speed was higher with the improved cutter casing below the northbound track. In addition to the difference in the geometry of the cutter casing, different geology between the starting side and ending side may be another cause of speed difference.
6.3 Maximum pull force
Fig. 12 shows the pull force of the elements with the conventional cutter casing (B9) and the improved cutter casing (F1). The design pull force was 835 kN, whereas the maximum pull force was 599 kN with the conventional cutter casing (B9) and that with the improved cutter casing (F1) was 455 kN. With the improved cutter casing capable of taking in cut soil, the pull force was smaller by about 10 percent than that with the conventional cutter casing.

6.4 Track displacement
Fig. 13 illustrates the track displacements (vertical and alignment) of the southbound track, caused by pulling with the conventional cutter casing (B9). Displacement was determined every 30 minutes by analyzing the image on the mirror installed beside the rails by the total station. Since the element was pulled after removing the ballast just above the element, no track displacement occurred due to pulling below the southbound track. When the cutter casing passed below the northbound track after the ballast of the southbound track was restored, both vertical and alignment displacements of the southbound track (4:52 to
5:45) were less than 1 mm. As demonstrated by this result, no significant impact on the track was caused by the effects of the rail stiffening girder and friction reducing measures.

![Graph of Pull Force](image1)

**Fig. 12 Pull force (B9/F1)**

![Graph of Displacement](image2)

**Fig. 13 Displacement of the northbound track (when placing B9 element)**

7. Conclusions
The ceiling slab elements must be placed during track closure. This is one of the major reasons work on an underpass below railway tracks takes longer. The project discussed in this paper attempted to shorten the project, by using improved machinery and taking measures to prevent railway track from deteriorating, and achieved placement of one element 12 m long per night. Increasing the progress rate of HEP & JES work while ensuring safety as with the present project will reduce the length of construction and cost of construction of underpasses below tracks. In the design phase it is preferable to configure a single element spanning the whole length of the project structure and a longer shaft for ease of work. In the work planning phase, it is important to establish a plan enabling continuous work, that will minimize necessity of work rearrangement, by rational mucking and reduction of fault risk of the belt conveyors.