

Development of Slab Tracks for Hokuriku Shinkansen Line

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Thirty years have passed since the world's first use of slab tracks by the former Japanese National Railways. It is recognized that they have excellent performance for maintaining good track geometries and reduce track maintenance costs through this experience. However, there were still some points to be improved. This paper describes the present condition of slab tracks, development of a new structure on earthworks and reduction of construction costs for the Hokuriku Shinkansen line.

Keywords : Slab track, settlement, maintenance, noise, fastening, cement asphalt mortar

1. Introduction

Thirty years have passed since the world's first use of slab tracks by the former Japanese National Railways. Until now, slab tracks have been laid both on Shinkansen lines and narrow gauge lines for over 2,700 km including undersea tunnels and oversea bridges where natural environments are severe. The slab tracks are considered indispensable for Shinkansen and have been adopted for about 2,200 km, which accounts for about 55% of the total length of five Shinkansen lines. The slab tracks have brought about great changes in the maintenance of railway tracks, especially on Shinkansen lines because of its excellent performance for maintaining good track geometries and reduction of track maintenance costs. However, there were still some points for the slab tracks to be improved. So, the authors solved such problems of slab tracks during the last decade.

This paper describes the present condition of slab tracks, development of a new structure on earthworks, reduction of its construction costs for the Hokuriku Shinkansen Line. The contents of this paper were originally presented at the 8th World Conference of Transport Research¹⁾ in Antwerp in 1998 and International Conference²⁾ on railway track in Delft in 1999.

2. Outline of Slab Tracks^{3) 4)}

2.1 Background and Shinkansen network

The Tokaido Shinkansen from Tokyo to Shin-Osaka was inaugurated in 1964 just in time for the Tokyo Olympics. It ushered in a new era of high-speed train services. During the early years of Shinkansen operation, damage frequently occurred on conventional ballasted tracks with the increase of traffic intensity. The high-

rate economic growth and reduction in working hours, labor shortage and limited interval time for track maintenance created the need to introduce a new low-maintenance track. As a result, the former Japanese National Railways (JNR) started a study on slab tracks in 1965 and introduced those widely used on the Sanyo, Tohoku and Joetsu Shinkansen lines. After that, the Hokuriku Shinkansen line from Takasaki to Nagano was constructed and opened in 1997 to coincide with the Nagano Winter Olympics. Now, several new Shinkansen sections are under construction or in advanced planning stages, and the network of high-speed routes is being expanded.

2.2 Slab track structures

Fig. 1 (a) and (b) show typical types of slab track structures for the Shinkansen open sections and tunnel sections, respectively. The slab track consists of rails, fasteners, track slabs and a Cement Asphalt Mortar (CAM) layer. On the roadbed concrete on viaduct or in tunnel, circular upstands, 400 - 520 mm in diameter and 200 mm in height, are provided at intervals of 5 m. These upstands prevent the track slab from moving either in the longitudinal or lateral directions.

The track slabs are made of Reinforced Concrete (RC) or Prestressed Reinforced Concrete (PRC) in factories.

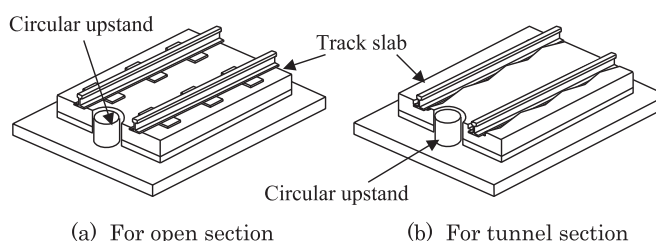


Fig. 1 Slab tracks

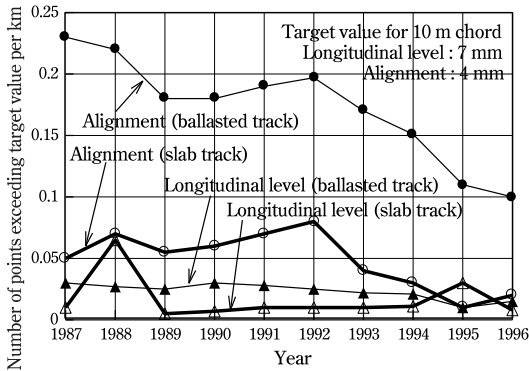


Fig. 2 Track irregularities in Sanyo Shinkansen⁵⁾

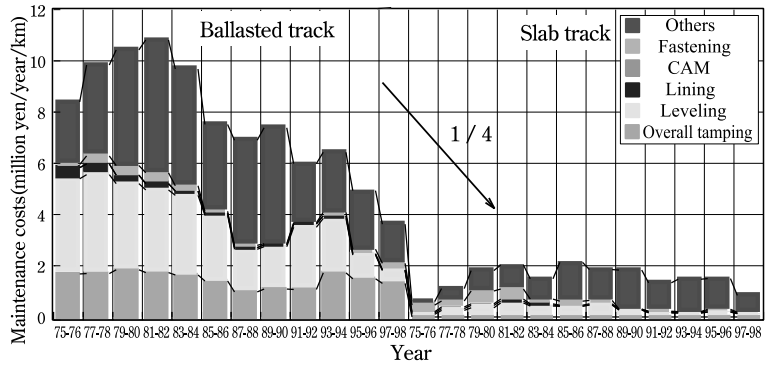


Fig. 3 Maintenance costs of tracks on Sanyo Shinkansen

The track slab for Shinkansen is 2,220 - 2,340mm wide, 4,900 - 4,950mm long and 160 - 200mm thick. One track slab weighs approximately 5 tons.

2.3 Present status of slab tracks and economic comparison⁵⁾

Changes in track irregularities on the Sanyo Shinkansen are shown in Fig. 2⁵⁾. This figure means the number of irregular points per km (length) which exceeds the target value for riding comfort of Shinkansen. Thus slab tracks keep the track in better condition than ballasted tracks do. A comparison of the maintenance costs between slab tracks and ballasted tracks on the Sanyo Shinkansen line is shown in Fig. 3. The ratio of maintenance costs, the slab tracks versus the ballasted tracks, is about 1:4 for Shinkansen lines. Thus the slab tracks have made greater contribution to reducing maintenance and labor costs. In planning a new railway line, important factors in deciding the track structure are economy, durability, environment and construction workability. For example, the construction costs of slab track laid for Sanyo Shinkansen were 1.3 - 1.5 times those of ballasted track.

It had been estimated that the extra investment would be redeemed in about 2 - 6 years of commercial operation. Therefore, it is in the area of maintenance planning that slab tracks realize a full value over ballasted track.

3. Some improvements on slab tracks in the last decade⁴⁾

As mentioned above, the slab tracks have excellent performance for maintaining good track geometries and reduce track maintenance costs. However, there were still some points to be improved, including the following, before the construction of the Hokuriku Shinkansen line.

- (1) Use of slab tracks were limited on viaducts and in tunnels to satisfy severe maintenance standards applied to the Shinkansen lines.
- (2) Construction costs of slab track are still higher than those of ballasted track.
- (3) Some plug collars of fasteners were damaged.
- (4) The noise level on slab tracks is higher than that of ballasted tracks when trains run.

To solve these problems, some improvements on slab tracks had been made based on the experience of the Tohoku and Joetsu Shinkansen lines, as explained below.

3.1 Development of slab track on earthworks^{2) 4)}

3.1.1 History of Development

JNR organized a committee on the slab tracks in 1965. The Slab track type RA with asphalt pavement on earthworks (RA-slab) was proposed in 1968 (Fig. 4). It was experimentally installed at twelve sites in total for about 1.8 km extension as of 1974. However, a further study on the settlement and durability of pavement was demanded to meet the severe maintenance standards applied to the Shinkansen lines. Therefore JNR decided to forgo installing the RA-slab on the Sanyo and Tohoku Shinkansen lines.

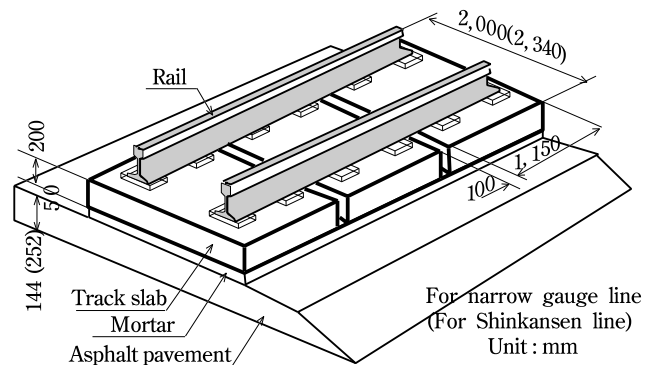


Fig. 4 Slab track type RA with asphalt pavement

Slab tracks on earthworks may provide the same result as when they are used on viaducts or in tunnels, provided that the geological and ground conditions are good. The settlement of roadbed has direct influence, of course, on whether the track can be maintained at relatively low cost. Standards for constructing slab track on earthworks have therefore been established as shown in Table 1. Final settlement is decided from the adjustable vertical tolerance limit of fastening (30 mm). Deflection and angular bending are stipulated mainly for riding comfort, and bearing capacity is derived to restrict settlement and on the basis of the structural design of slab track.

3.1.2 Development of new structure

To achieve a so-called low-maintenance track, it is important to spread imposed loads effectively over earthworks and control cumulative settlement. So the authors proposed a reinforced concrete roadbed for slab

Table 1 Standards for laying slab track on earthworks

Items	Standard
Final settlement (estimated)	≤ 30 mm
Deflection	$\leq 1/1800$
Angular bending	$\leq 3/1000$
Bearing capacity of bank & cutting bed	$K_{30} \geq 110$ MN/m ³

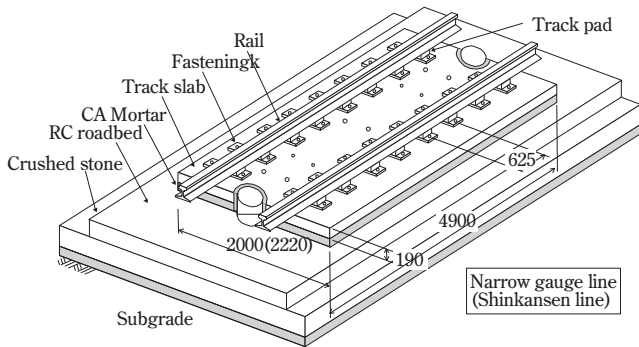


Fig. 5 Slab tracks with concrete roadbed on earthworks

tracks (RCRS) shown in Fig. 5. The RCRS is expected to be superior to RA-slab on asphalt pavements in terms of settlement and durability. The ordinary track slab used for viaducts and tunnels can also be used for earthworks.

(1) Basic studies at Test Site of RTRI

In order to confirm the performance of RCRS, a test track was laid at the Civil Engineering Test Site of Railway Technical Research Institute (RTRI). A subgrade soil layer of test track was laid 1.2m in thickness by replacing the original soil with sand. The average of K_{30} -values by the plate load test method for roads (plate diameter :30 cm) was 114 MN/m³ at the surface of original soil (supporting ground) which consisted mostly of conglomerate. The special sand was compacted four times in layers by rolling with a vibration roller. The plate loading test confirmed that K_{30} -values averaged 114 MN/m³ and the degree of compacting was 94.8% at the upper layer.

First of all, a static loading test was carried out to confirm the behavior under static wheel loads and lateral forces. The measured displacement and stresses showed almost elastic behavior under 80 kN static wheel loads. When the wheel loads of 80kN were imposed on the rails, the maximum displacement of RCRS was about 0.4 mm, fiber stress of the RCRS was about -0.5 MPa and the stress in the reinforced bar about 3 MPa. According to the Japanese concrete criteria, the bending strength was expected to be 3.1 MPa for this concrete roadbed. The possibility of cracking on RCRS is low. The average track spring constant K (wheel load / rail displacement) was 72.6 MN/m. It was approximately one half that of slab track on viaduct. Fig.6 shows the theoretical deflection and stresses of RCRS compared with experimental values. Even though the thickness of roadbed and bearing properties were not consistent with the design, theoretical results approximately correspond to experimental values.

(2) Full scale testing at Kashiya section

To study whether the RCRS is appropriate as a low-maintenance track for the Hokuriku Shinkansen line, a full-size test track was laid on the site known as the Kashiya section. A 60 m stretch comprising both an

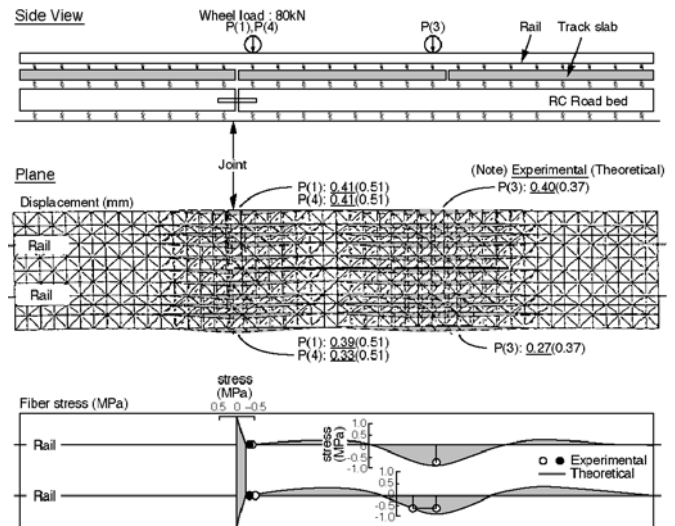


Fig. 6 Theoretical deflection and stresses of RCRS compared with experimental ones

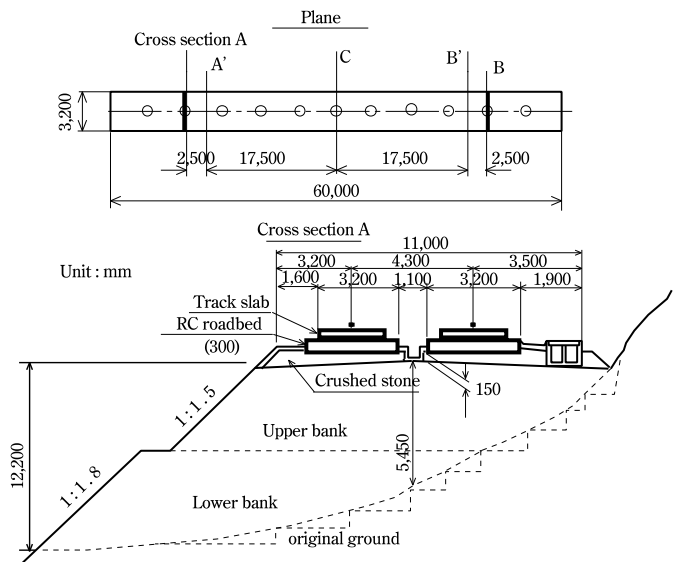


Fig. 7 Test track structure at Kashiya section of Hokuriku Shinkansen

embankment and cutting was selected as a test site.

Fig. 7 shows the test track structure which consisted of embankment, reinforced concrete roadbed, cement asphalt mortar, slab tracks, fastenings and rails. The construction of embankment was completed in December, 1991 and left as it was for three months. Next, a reinforced roadbed was constructed in March, 1992. After the track slab was laid, static and dynamic loading tests were carried out in April to May.

The Group-A materials composed of sand and gravel were used for banking. They were compacted twice in layers by a 10 t vibration roller followed by four passes with a 15.5 t tired roller. To ensure that the rolling met standards, a plate loading test was carried out to confirm that the K_{30} -value of embankment was 143 MN/m³ for the lower layer and 186 MN/m³ for the upper layer, achieving the degree of compacting between 95.0-99.0%. These test

results satisfied the standards for embankments shown in Table 2.

Table 2 Standards of materials and geological conditions for RCRS

Items	Embankments	Cuttings
Bank materials	Upper layer: Group-A (sand & gravel) Lower layer: Group-A or B (sand & gravel including fine sand less than 30%)	
K_{30} -value	Upper layer: $K_{30} \geq 110 \text{ MN/m}^3$ Lower layer: $K_{30} \geq 110 \text{ MN/m}^3$	On subgrade: $K_{30} \geq 110 \text{ MN/m}^3$
Degree of compacting	$D \geq 90\%$	
Supporting ground	Sandy: $N\text{-value} \geq 20$ Loam: $N\text{-value} \geq 4$	Not including a soft & fine alluvium deposit within 3 m beneath formation

The test results confirmed that the fiber stresses and reinforced bar stresses of the roadbed were at low levels from the viewpoint of durability, and that the settlement caused by dynamic loading is extremely small. Fig. 8 shows the relation between the embankment height and its settlement at the test section. These tests demonstrated that a consolidation settlement (GA2) was about 4.2 mm after the slab track was laid. The sum of ground settlement (S2) and GA2 was 6.2 mm, which practically tended to converge. It was possible therefore to restrict settlement to within 10 mm, which is well below the targeted 30 mm.

3.1.3 Practical Application⁴⁾

(1) Laying and structure

The Japan Railway Construction Public Corporation (JRCC) is currently constructing several sections of Shinkansen on three routes. The Hokuriku line from Takasaki to Nagano was laid to a 1435 mm gauge track, and opened to traffic in 1997. Based on the earlier test

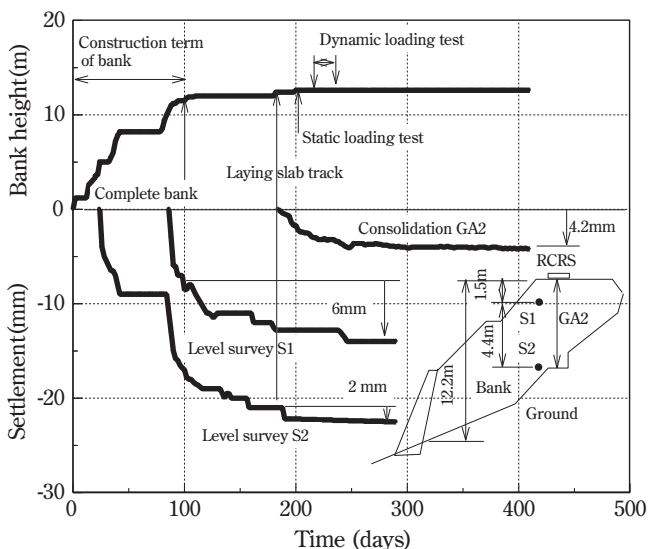


Fig. 8 Relation between bank-height and its settlement

results, JRCC decided to apply the RCRS in 1993 and laid it for about 10.8 km on the Hokuriku Shinkansen line, which accounts for 4% of its total length (Fig. 9). It corresponds to one fourth of all earthwork sections. Henceforth, JRCC is going to use the RCRS for about 11 km on Tohoku Shinkansen line from Morioka to Hachinohe and for about 13 km on Kyushu Shinkansen line from Shin-Yatsushiro to Nishi-Kagoshima. Fig. 10 shows the RCRS laid on a cutting along the Hokuriku Shinkansen line. A crushed stone layer for mechanical stabilization is introduced under the RCRS to facilitate drainage through the roadbed, and distribute the train load evenly.

(2) Transition to bridge

Embankments approaching bridge abutments or culvert supporting tracks are one of the weakest points of the track, because the settlements of these sections tend to progress faster when compared with those in ordinary sections, and track supporting conditions tend to change before and behind these sections. Approach blocks shown

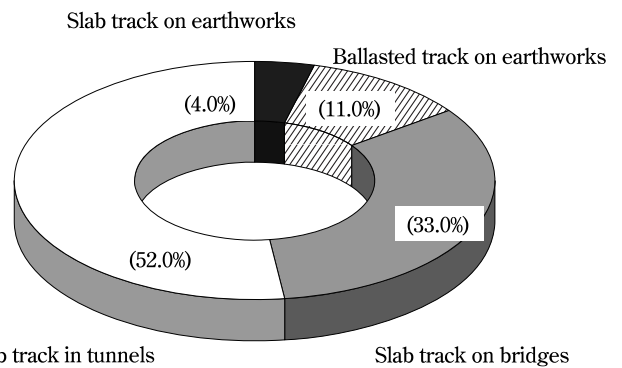


Fig. 9 Applied rate of RCRS at Hokuriku Shinkansen line



Fig. 10 RCRS laid on cutting in Hokuriku Shinkansen line

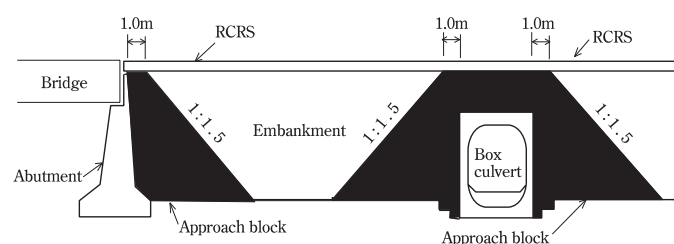


Fig. 11 Approach block structure

in Fig. 11 were contrived to deal with such problems. They are made of crushed stone bound with cement. The minimum strength is set at the unconfined compression value of 2 MPa. Each 150 mm-thick layer must be compacted to the K_{30} -value of 150 MN/m³ or over, and the degree of compacting to 95% or over. In addition, the end part of the RCRS is placed on the crown to prevent excessive deflection at the transition between the RCRS and the bridge.

(3) Noise

Generally speaking, the average noise level of slab track under train-running is 5dB (A) higher than that of ballasted track. The slab tracks from Takasaki to Nagano, with their concrete roadbed on earthworks, were in mountainous sections through sparsely populated areas. Except ordinary sound-protection walls, therefore, special countermeasures for reducing noise were not considered necessary.

(4) Earthquake

Not only viaducts but also embankments were seriously damaged by the Hyogo-ken Nambu Earthquake in 1995. The embankments along the Hokuriku Shinkansen line, therefore, were reinforced against earthquake shock by the insertion of geosynthetics (nets) into bank-layers. The embankments are expected to avoid fatal damage by this method.

(5) Economic comparison

The initial construction cost of slab track on earthworks, including typical subgrade, is higher than that of ballasted track by 18% for cuttings and by 24% for embankments. Fig. 12 shows an example of comparison of the total costs between the two tracks. These costs include personal expenses, maintenance costs, municipal property tax and depreciation costs. In this case, the extra investment might be redeemed in about 12 years of commercial operation.

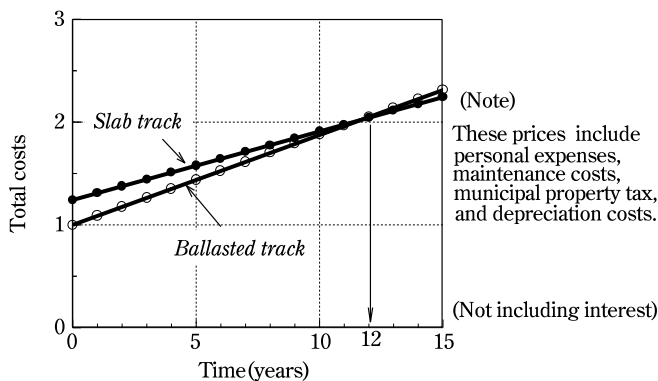


Fig. 12 An example of comparison of total costs between slab track and ballasted track

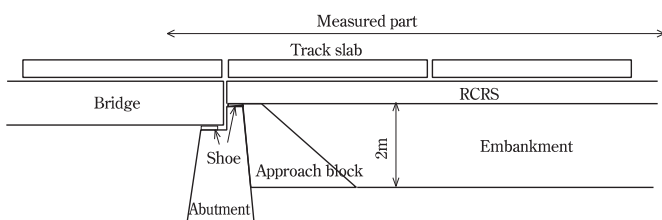


Fig. 13 The structure of Saku section

3.1.4 Performance tests by live loads ⁴⁾

(1) Test at the Kashiyama Section

Performance tests under train running were carried out to confirm the running stability of slab track on embankment and cutting at the Kashiyama Section in December 1996. Along a straight track section, wheel loads, displacement and stresses were measured under train running up to 250 km/h. Stresses were recorded at low levels in terms of durability. As the test results indicate, there were no problems in running trains at high speed.

(2) Test at the Saku Section

The purpose of the test along the Saku Section in June 1997 was to confirm the running stability at high speed on tracks near an approach block. Fig. 13 shows the structure of the Saku Section. The height of the embankment is about 2 m. As for the alignment of test section, the track has a curvature of 3500 m, cant of 200 mm and gradient of 30/1000. Wheel loads, displacement and stresses were measured under train running up to 260 km/h. The wheel loads on the approach block section were roughly equal on an average when compared with those on ordinary sections. As the test results indicate, there were no problems for high speed train operation.

3.2 Practical use of frame-shaped slab track and other components ⁴⁾

3.2.1 Frame-shaped slab track

When JNR started studying of slab tracks in 1965, one of the targets of development was that its construction cost should not exceed twice that of ballasted track. The construction costs of slab track for the Sanyo Shinkansen line were 1.3 to 1.5 times those of ballasted track. Thus the target had been achieved sufficiently. In

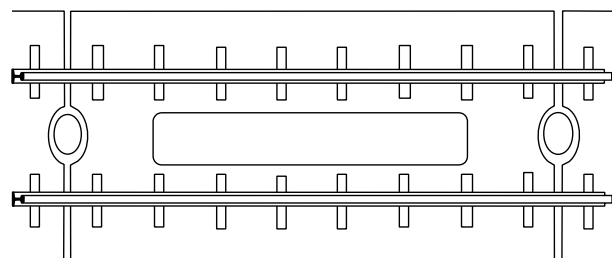


Fig. 14 Frame-shaped slab track in tunnel

Table 3 Construction costs of tracks at Hokuriku Shikansen line.

Tracks	Construction Cost		Design	low-noise	with nets*	with ballast mat	Note
Frame-shaped Slab track AF-55T	0.92	1.19	RC				For tunnel & viaduct
Frame-shaped Slab track AF-57	0.86	1.12	RC				For tunnel
Ordinary Slab track A-55M	1.00	1.30	RC				For viaduct in warm area
Slab track A-55C	1.10	1.43	PRC				For viaduct in cold area
Slab track A-55MN	1.16	1.51	RC	○			For viaduct in warm area
Slab track A-55CN	1.26	1.64	PRC	○			For viaduct in cold area
Ballasted track A	0.77	1.00	PC	○		○	
Ballasted track B	1.03	1.34	PC	○	○	○	For $V \geq 160\text{km/h}$ & snow area
Ballsted track C with resilient ties	0.84	1.10	PC	○			
Ballsted track D with resilient ties	1.11	1.44	PC	○	○		For $V \geq 160\text{km/h}$ & snow area

(Notes *) Nets prevent ballast from dispersing by snow-balls falling from vehicles

addition, when the construction cost of viaducts is included, the slab track on viaducts is more superior to the ballasted track. However, in planning the recent Shinkansen network project, further reduction of construction costs is required. One of the countermeasures is to use frame-shaped slab tracks shown in Fig. 14. This type was laid for 130 km in tunnels of the Hokuriku Shinkansen line.

Table 3 shows the construction costs of tracks which were adopted for this line.

The construction cost of frame-shaped slab track is 8 to 14 per cent lower than that of ordinary slab track. The recent construction costs of slab tracks are 1.1 to 1.6 times that of ordinary Ballasted track A. However, ballast had to be prevented from dispersing by snow-balls falling from vehicles at a large number of sections of the Hokuriku Shinkansen line, where the train speed was 160 km/h or over and located in a snow area. So, Ballasted track B or the Ballasted track D with nets on ballast were fundamentally used. Their costs are 1.3 to 1.4 times that of Ballasted track A. Thus, there are virtually few differences in the construction costs between slab tracks and ballasted tracks.

3.2.2 Cement asphalt mortar pouring

Ordinary slab tracks are generally laid by the following method.

- ① Precast track slabs are transported and unloaded on the roadbed concrete.
- ② After adjusting their positions, they are supported

temporarily by slab supporting bars.

- ③ Then forms are installed along the track slab sides for preventing CAM from leakage.
- ④ The gap between the track slab and the roadbed concrete is filled with CAM for stabilizing the track slabs.
- ⑤ Next, rails are laid on the track slabs.
- ⑥ Finally, they are adjusted to the correct position by variable pads.

As for the frame slab track, forms must be installed not only along slab sides but also inside the frame. To improve workability and reduce costs for CAM pouring, a long-tube method is adopted for the construction of the Hokuriku Shinkansen line. This method does not require installation of forms. The CAM is injected into the long tubes made of non-woven fabrics (geotextiles) which are laid between the track slab and the roadbed concrete. By using this method, the construction cost of CAM was saved about 10% from that of the ordinary method for the above line.

3.2.3 Rail fastening

The Type-8 Fastening shown in Fig. 15 (a) were widely used for slab track in Japan. This fastening consists of a track pad with stainless steel plate, a variable pad for fine height adjustment, a shoulder-equipped tie plate, an insulation plate, bolts and plate springs and so on. In low-temperature (cold) areas, some plug collars were damaged because of inadequate component quality or retightening of plate springs. In addition, an anti-rust protection oil in collars decreased because of the cracks of track slab in some cases. To improve this problem, embedded inserts are adopted instead of plug collars as shown in Fig. 15 (b). This Improved Type-8 Fastening was widely used at the construction of the Hokuriku Shinkansen line.

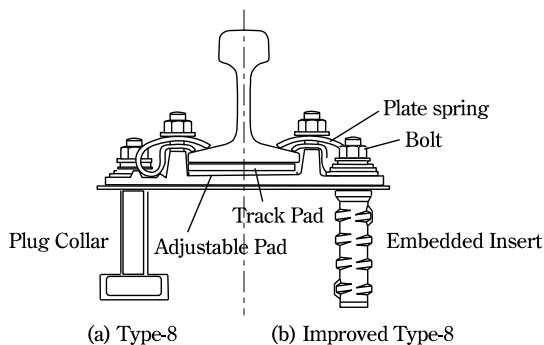


Fig. 15 Fastening for slab tracks

4. Conclusion

Thirty years have passed since the world's first use of slab tracks by the former Japanese National Railways. It is confirmed that slab tracks have excellent performance for maintaining good track geometries and reduce track maintenance costs. However, there were still some points to be improved before the construction of the

Hokuriku Shinkansen line. In the last decade, some improvements had been made on slab tracks based on the experience from the Tohoku and Joetsu Shinkansen lines. The following conclusions can be drawn from this study.

- (1) A concrete roadbed structure has been developed for slab tracks that can be laid on embankments and cuttings. As the test results indicated, there were no problems as a track for high speed railways. Now the application of slab track is being extended to earthworks.
- (2) A frame-shaped track slab and a long-tube pouring method for CAM were developed to reduce the construction costs of slab track. In the construction of Hokuriku Shinkansen line located in a snow area, there were few differences in the construction costs between slab tracks and ballasted tracks.

The authors' future subjects are to confirm the performance in commercial operation and save construction costs further.

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