Innovations in Structural Technologies to Create Spaces Near Railways

Shinichiro Nozawa

General Manager, Structural Engineering Center, East Japan Railway Company

1 Introduction

When building structures near railways, much construction work is done taking into account the impacts on train operation classified as "construction near commercial lines." Construction costs are on the increase due to time constraints of construction needing to be done at times when trains and passengers are not passing through the site and spatial constraints of avoiding the structure gauge for rolling stock and building in places that do not obstruct passengers. Construction near commercial lines involving work done on artificial ground and viaducts may incur costs more than double those of construction in ordinary places.

Moreover, since the 1995 Great Hanshin-Awaji Earthquake, seismic motion that structures are designed to withstand has become large, and this is another factor leading to increased costs when building structures.

We will not be able to build quality social infrastructure at low cost by simply following conventional design and construction methods in work to build and renovate. We are hence making efforts in innovating structure technologies to create new spaces.

2 Situation Expressed in One Photograph

Fig. 1 shows the condition of Shinkansen and conventional line viaducts near Nagamachi Station on the Tohoku Line south of Sendai, taken a week after the March 2011 Earthquake off the Pacific Coast of Tohoku. Both are reinforced concrete (RC) viaducts. Columns for the Tohoku Shinkansen viaduct (left side of photo, approx. 8.5 m span), which opened in 1983, had heavy damage. Those of the conventional Tohoku Line viaduct (right side of the photo, approx. 17 m span), which came into use in 2006, were almost undamaged with only some minor cracking.

Tohoku Shinkansen (1983) Tohoku Line (2006)

Fig. 1 Viaduct Column Damage (between Shiroishi-Zao and Sendai)

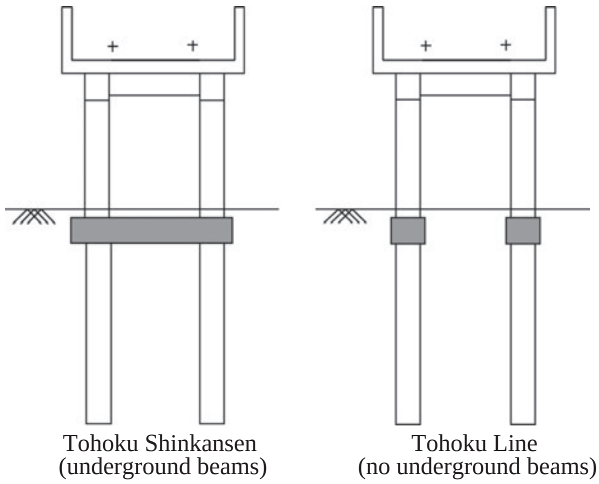


Fig. 2 Structural Forms of Viaducts

The structural form of Shinkansen viaducts has underground beams, the same as with RC railway viaducts across Japan, but the viaduct of the conventional line on the right side of the photo does not have underground beams. Fig. 2 shows a summary cross section of that difference. The Shinkansen viaduct was already in place when the conventional line viaduct was built adjacent to it, and protection would have been necessary if excavating to install underground beams, so a structure with those underground beams omitted was adopted. Fig. 2 shows a cross section, but if there were underground beams in the direction parallel to the track, much time and money would be required to install underground beams on the side adjacent to the Shinkansen (left side of conventional line viaduct in the figure). In the case of elevating tracks near Akabane Station employing the same construction near commercial lines, underground beam construction expenses made up 49% of total structure construction expenses, and it has been reported that cost reduction effects of omitting underground beams when building viaducts near existing track is large.[1]

Moreover, steel tubing is used to make the joints for columns and piles smaller. Spans in the direction parallel to the track (interval between columns) are double the ordinary size, and a larger space can be provided under the track. Resistance to earthquakes has been demonstrated even while being a structure where much lower costs than with past structures could be achieved and the value of the space under the viaduct increased. This is an example of innovation in structure technologies combining improvements such as prevention of uneven settling of the foundation and enhancing resilience by increasing the number of ties hoops in columns and piles.

3 Construction Near Commercial Lines

Railways in Japan have a more than 140-year history since the laying of the first line, and they advanced by making improvements. More than 100 years ago, the Shineikan Construction Office, predecessor to today's Tokyo Construction Office, changed the alignment of the Tokaido Line by relocating it on a viaduct, and it has put efforts into construction for improvements up to today. Construction is constantly underway at large stations such as Tokyo and Shinjuku, whereby we are working to improve convenience for passengers.

(1) Considerations at time of planning

Costs can sometimes be reduced by constructing in locations that will not impact trains or tracks. When building bridges over tracks, overall construction costs can sometimes be kept down by constructing in a manner where bases and piers are placed a bit away from the track for lower impact on trains and tracks, even if extra materials costs are incurred due to slightly longer girders.

Moreover, considerations at time of planning, such as rerouting trains and layouts taking into account construction work, can greatly affect construction costs.

Viaducts without underground beams were introduced in the previous chapter, but employing similar constructions in construction on artificial ground as well often can demonstrate effectiveness. Ordinarily, underground beams, which are effective at providing stability for the structural system as a whole, also pose a risk of deforming track in construction near lines and involve large time constraints and greater installation expenses than other members. If the structure has no underground beams both parallel and perpendicular to the tracks, some piles and columns may need to be thicker to distribute the performance ordinarily exhibited by underground beams in supporting safety and limit displacement, but overall artificial ground expenses are reduced. Since the construction of artificial ground upon which the Omiya Station Ecute commercial space (opened in 2005) was built, most artificial ground constructed by JR East in places such as Tachikawa, Nippori, and Higashi-Nakano stations has had a structure without underground beams.

(2) Modifications for size reduction

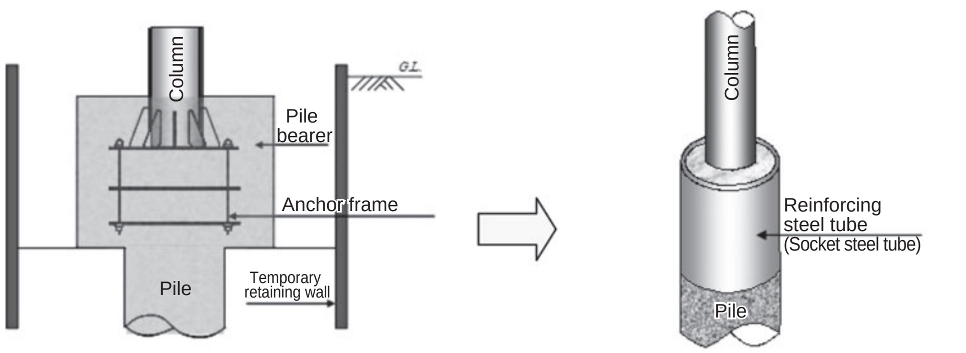
Narrow columns and thin girders help when building structures without obstructing the structure gauge and when building in places such as inside stations where many passengers move about. In order to make columns narrow, structures called concrete-filled tubes (CFT, using steel tubes) are often used. On the other hand, in locations between tracks where steel tubes cannot be transported, reinforced concrete (RF) structures may be advantageous. With those, reinforcement is brought in and assembled and concrete then poured.

Joints between columns and piles usually have members called anchor frames or they form footings to assure transmission of force between two members (Fig. 3 (a)). However, building those in narrow spaces between tracks would involve excavating the ground over a wide area and attachment would take time, so costs would be higher due to space and time constraints.

We thus developed a structure as shown in Fig. 3 (b) where a small-diameter steel tube is inserted to a set length in a large-diameter steel tube integrated with a pile. The joint load bearing mechanism and factors influencing ultimate strength were identified by model tests conducted at JR East, and an ultimate strength evaluation formula for generic and simple joint parts was put together. This is called a socket joint. Similarly, joints for piles and columns in narrow spaces using steel tubes became possible when columns are RC as well. Since 2000, this method of joining using steel tubes has been used in many viaduct and artificial ground pile and column joint parts.

(3) Construction while operating trains

In order to assure safety in construction near commercial lines, work in types of construction that could have a major impact on safety is done at night when trains are not running. Construction with relatively small impact is done between train runs. If the technical basis for performing some types of construction at



(a) Conventional jointing method
(Anchor frame method)

(b) Jointing method developed
(Socket type joint using reinforcing steel tube

Fig. 3 Column and Pile Joints

night when trains are not running could be clearly identified and safety confirmed to allow work to be done while running trains, costs could be reduced. This is introduced in "Construction Methods Developed to Enable Work Near Tracks in Times with Train Operation" in this edition of JR EAST Technical Review.

4 Structures Safe Even in Large Earthquakes

(1) Changes in seismic performance requirements and evaluation of structures

Aseismic design was introduced in Japan long ago due to the lessons learned from damage suffered in the 1923 Great Kanto Earthquake. Judgment of ground liquefaction and handling of that in design was prescribed after the 1964 Niigata Earthquake; consideration for structures on soft ground was prescribed after the 1968 Tokachi Earthquake; and installation of devices to prevent bridge collapse, adoption of round/square steel rod stoppers, design with resilience for RC members, and conditions for RC bridge piers with terminated reinforcement and the like were prescribed from lessons learned from damage suffered in the 1978 Miyagi Earthquake. However, it was the 1995 Great Hanshin-Awaji Earthquake that had the greatest impact on designing. That near-field earthquake with a magnitude of 7.3 saw the collapse of viaducts at 32 locations on eight lines of five railway operators, including eight locations on the Sanyo Shinkansen. Calculating back from elements such as the amount of reinforcement showed that many of the RC viaducts that collapsed were structures that tended to allow shear failure to occur first. The Imazu Line overbridge on the Sanyo Shikansen with prestressed concreter girders, which collapsed, had damage where cracking stemmed from shear cracks on rigid frame pier columns.

Fig. 4 shows allowable shear stress of RC structures in different ages. With scientific progress, it became clear that allowable shear stress becomes smaller with larger structures, and that was reflected in technical standards as well. At the same time, seismic motion tended to be larger after each major earthquake experienced. So, as shown in Fig. 5, design came to be implemented so structures would not collapse by giving structures resilience against large seismic motion. Ductility factor is a parameter used to express how much resilience there is, and that parameter is defined as how many times the yield displacement a load can be supported at yielding.

In railways, a ductility factor of 4 or greater was secured after the 1978 Miyagi Offshore Earthquake, and a ductility factor of 10 or greater was secured after the 1995 Great Hanshin-Awaji Earthquake. Even using the currently clarified allowed shear failure, seismic motion can now be countered with column and pier resilience.

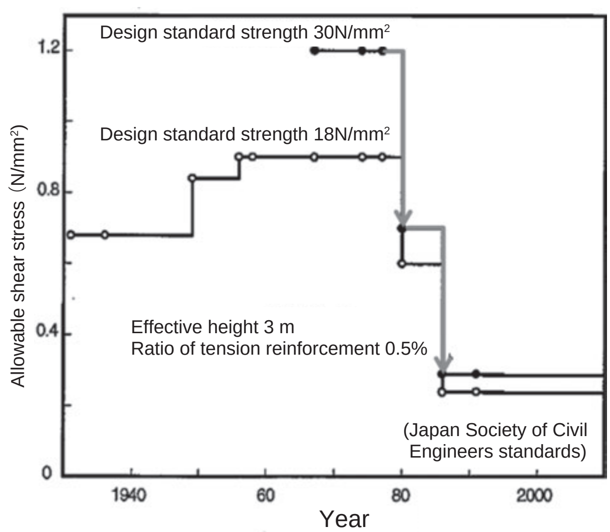


Fig. 4 Changes in Allowable Shear Stress of RC Structures

(2) Requirements for giving resilience to a structure

From about 2000, JR East has employed inner spiral reinforcement with fewer ties hoops in viaduct columns. Fig. 6 shows an overview of inner spiral reinforcement, and Fig. 7 shows the load vs. displacement curve when cyclic loading tests were performed on columns using inner spiral reinforcement. It has excellent deformation performance as can be seen in the figure by retaining loads even if deformation of 20 times yield displacement progresses shown. There were viaducts that used inner spiral reinforcement in the eastern Japan area affected by the 2011 Earthquake off the Pacific Coast of Tohoku, but none of them suffered damage. There may not have been large deformation to an extent that inner spiral reinforcement exhibits its inherent performance, but we can rest assured on the point that leeway is maintained in seismic performance of columns even if an earthquake larger than anticipated strikes. Adoption of inner spiral reinforcement, which can handle even large seismic motion at cost not much different than previous construction methods, it thus increasing.

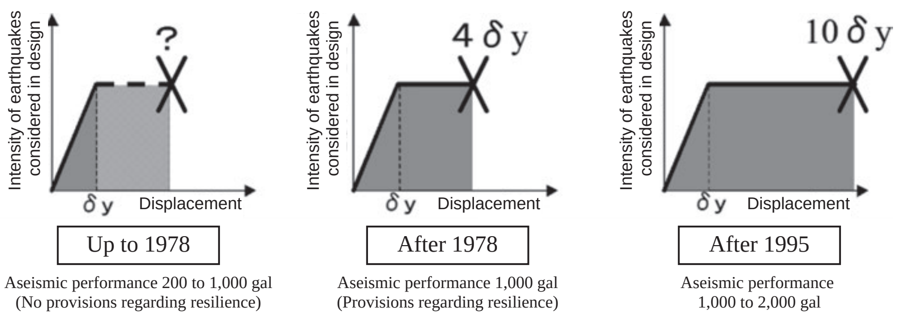


Fig. 5 Changes in Aseismic Design

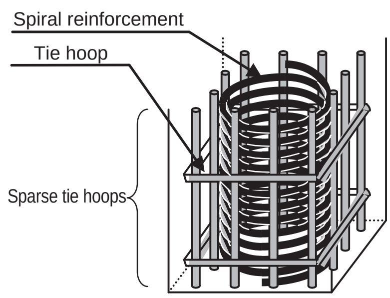


Fig. 6 Schematic of Inner Spiral

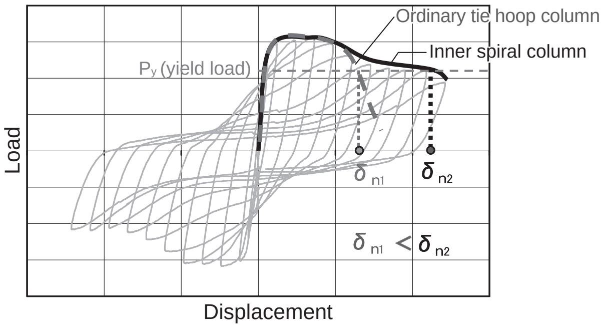
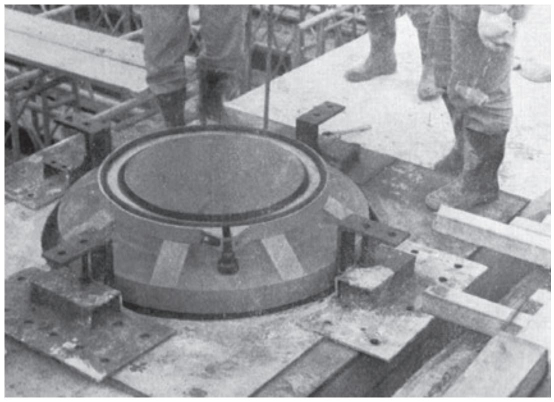


Fig. 7 Load vs. Displacement Curve for Inner Spiral

Fig. 8 Tohoku Shinkansen Kanagase Bridge
(between Shiroishi-Zao and Sendai)



Bottom shoe

Top shoe

Fig. 9 Sliding Bearing[2)]

For existing viaduct columns, steel plates are wrapped around the surface to increase deformation performance. Results of technical development to allow installation in places with obstructions and in narrow spaces, are introduced in “The Present State of Seismic Retrofitting Methods for RC Viaducts.”

(3) Seismic isolation structure

While adopting seismic isolation structures where seismic motion from the understructure to superstructure can be cut off has effects of securing safety for superstructure, costs incur for securing running stability of trains and separation from nearby structures. An example of adopting seismic isolation structures that reduces displacement in historical brick buildings is introduced in “Preservation and Restoration of Tokyo Station Marunouchi Building.”

The value of this structure is exhibited when the ground is particularly soft. Fig. 8 shows the Kanagase Bridge built between Shiroishi-Zao and Sendai, one of the areas of softest ground on the Tohoku Shinkansen. Taking into account large deformation of the ground in earthquakes, vertical forces of the weight of the bridge itself and the load of trains are shared by the piers and abutments. Horizontal force applied to the superstructure, generated by inertia in an earthquake, is made to be transmitted to and supported by the robust abutments fixed to bedrock at both ends by the lateral stiffness of concrete girders. The calculated value of ground displacement in an earthquake is as much as a few tens of centimeters. The superstructure uses RC continuous three-cell box girders for a girder length of 221 m (20 m × 11 spans). In order to withstand the bending moment generated in an earthquake, there are 116 D32 main reinforcements located at both ends of the girders.

Taking into account the large displacement at the top of piers in an earthquake, round special sliding bearings that can slide freely are used in the horizontal direction. Fig. 9 shows the top and bottom shoes of the sliding bearings before being placed at the head of a bridge pillar.

5 Conclusion

Structures in the future will likely become increasingly difficult to build in terms of time and space. We will thus work to innovate structure technologies to be able to reduce construction costs while securing safety of railways, including in times of earthquakes.

Reference:

1) Isao Oyu, Kazuhiro Obara, “Design and construction of the viaduct which eliminated underground beam in the track direction. Track elevation work near Akabane Station.”, *The Journal of Japan Railway Civil Engineering Association* (October 1996)

2) Structure Design Office, Japanese National Railways, Ed., *Kozobutsu Sekkei Shiryo* No. 61 [in Japanese] (March 1980)