Recent Research and Development on Railway Geotechnical Structural Technology

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The Railway Technical Research Institute has been researching a variety of technologies related to railway structures. These include technologies for maintenance (inspection, diagnosis, prediction, repair, renewal), earthquake countermeasures, construction and environmental impact assessment. This review gives some overview of recent research and development trends in maintenance and construction technologies for “geotechnical structures” (earth retaining walls, soil structures and tunnels) conducted at the Railway Technical Research Institute.

Keywords: geotechnical structure, research and development trend, earth retaining wall, soil structure, tunnel

1. Introduction

RTRI has been pursuing R&D in a wide range of fields including railway structure maintenance in terms of inspection, diagnosis, deformation prediction and life prolongation (repair and reinforcement), aseismic reinforcement, renewal and environmental impact assessment as well as improving technical standards. This paper provides an overview of recent R&D trends at RTRI regarding earth retaining walls, soil structures and tunnels, all of which are geotechnical structures whose intended performance is maintained through interaction with the ground.

2. Inspection, diagnosis and deformation prediction

2.1 Overall trends

There are still many old railway structures in Japan that were built between the Meiji Era and the early part of the Showa Era (1880’s - 1940’s). As skilled engineers are retiring, the ongoing maintenance of these aged structures, to keep them in a sound state, is growing in urgency, in order to keep railway transport safe and ensure stable operations. Railway structures are mainly inspected through visual inspection and hammering, but there is a growing need for more objective and efficient inspection methods. RTRI has been developing alternative techniques (such as photographing and image analysis for tunnel lining etc.) and developing nondestructive inspection methods based on sounding and lasers to replace hammering tests. RTRI has also been advancing the development of diagnostics using impact vibration tests and deformation prediction methods. Work is also being conducted on a maintenance information network system utilizing rapidly growing IT and CIM.

Among the various R&D achievements related to geotechnical structures, this paper presents inspection and diagnosis methods for earth retaining walls, as well as inspection and diagnosis methods (deformation monitoring and roadbed diagnosis) and deformation prediction methods for tunnels.

2.2 Inspection and diagnosis methods for earth retaining walls [1]

Currently, the soundness of earth retaining walls is evaluated mostly by visual inspection. In an attempt to establish a quantitative soundness diagnosis method for earth retaining walls, applicability of the impact vibration test used for bridge foundations was examined.

Model experiments revealed that, as deformation progressed, the amplitude of the response speed increased in the impact vibration tests and responses in the low vibration frequency range became dominant. Following subsequent on-site experiments, a diagnosis method was developed that uses the significance of the speed amplitude spectrum in a specific frequency range and the dominance of responses in the low vibration frequency range, as indicators.

2.3 Inspection and diagnosis methods for tunnels

(1) Monitoring method for tunnel lining deformations using radio sensors [2]

Tunnel deformation monitoring typically uses manual convergence measurement and needs to be performed in the intervals between trains, restricting the frequency of measurement. As an alternative, automatic measurements with light waves and lasers can be used. However, this would require a large volume of wires and related maintenance. Therefore, a method was devised that can drastically reduce the labor and cost of collecting data by transferring automatic measurement data with a wireless sensor, which is now being used on site (See Fig. 1). In addition, a method was developed to remove any alteration due to temperature changes etc. in the vast amount of data collected by putting the it through a low pass filter.

(2) Method for diagnosing tunnel roadbed soundness [3]

Many existing tunnels in service are not equipped with inverted arches which often lead to roadbed settlement problems. Roadbed settlement is a phenomenon in which the ground becomes muddy due to the passing of trains, forming a cavity. As a result, the roadbed concrete sinks, causing track irregularity. Track irregularity can be detected through abnormal track measurements. How-
2.4 Tunnel deformation prediction methods

(1) Prediction methods for mountain tunnel deformation [4, 5]

In mountain tunnels, deformation such as displacement and/or upheaval sometimes occurs due to the action of ground pressure, which may occur over a long period of time. For that reason, geological surveys and long-term monitoring of convergences are conducted. Using those data, a numerical analysis method was developed whereby time dependency of the deformation is reproduced by reducing ground strength over the course of time, and the method’s applicability to existing tunnels for deformation prediction and measures planning was confirmed (See Fig. 3) [4]. Furthermore, based on this method, another method was developed that can reproduce tunnel behavior from the construction stage into the service stage, which can also be used for research into optimization of tunnel structures.

As deformation is allowed to progress, bending compressive failure and spalling of the tunnel lining will occur jeopardizing train operating safety. An analytical model was proposed which was capable of reproducing compressive failure and spalling due to bending of plain concrete, and a method was developed to accurately predict the behavior of the region which undergoes significant deformation. In addition, experiments were conducted on model linings made of plain concrete, fiber reinforced concrete, reinforced concrete and brick to identify the unique deformation characteristics of each of these materials. Furthermore, using the analytical method mentioned above, a convergence reduction ratio was proposed as an indicator of compressive cracks [5].

(2) Prediction methods for shield tunnel deformation [6]

In shield tunnels constructed in soft ground, deformation and cracks may develop and grow over a long period of time due to consolidation settlement of the ground, creating a need for deformation prediction methods.

Therefore, first, a method was developed to obtain convergence of the tunnel by Soil/Water Coupled FEM analysis, and to reproduce crack propagation of segment lining by nonlinear FEM using that value. In addition, a simple method was proposed whereby cracks are evaluated using a tunnel lining model test to express reduction in the ring rigidity. Then, by comparing the results of the evaluation with measurements taken of existing tunnels, the evaluation method was verified.

3. Life prolongation, aseismic reinforcement and renewal techniques

3.1 Overall trends

Along with these inspection and diagnosis techniques, there is also a growing need for sophistication of other techniques relating to life prolongation through economical repair and reinforcement, aseismic reinforcement and renewal. RTRI has been active in R&D in these areas as well.

Some R&D achievements in the field of geotechnical structures are: aseismic reinforcement and renovation of soil structures (an embankment resistant to tsunami
overflow, reinforcement of a widened embankment on soft ground, aseismic reinforcement of an earth retaining wall and evaluation of a ground anchor-reinforced slope), life prolongation of mountain tunnels and large-scale renewal of underground stations.

3.2 Aseismic reinforcement and renovation of soil structures

(1) Embankment structure resistant to tsunami overflow

(See Fig. 4) [7]

Tsunami damage to an embankment was reproduced using a model experiment. The experiment showed that: the embankment body and the slope protection were damaged by seismic tremors; then the embankment body and the supporting ground under the toe of slope on the land side were eroded by tsunami overflow, making the embankment unstable; and finally the embankment broke. As a result, it was found that; 1) the embankment body and the slope surface were damaged by shaking due to the earthquake first, 2) the erosion of the embankment body and the erosion of the toe of the slope were caused by the subsequent tsunami overflow, and 3) finally, the embankment broke. Therefore, a new embankment structure was designed with the following features:

1) The slope and body of the embankment were laid with strip reinforcement to improve earthquake resistance and resistance to erosion during overflow of the tsunami.
2) Cement-mixed gravel slabs were laid (the combination of grain-conditioned crushed stone treated with cement stabilization and planar reinforcement together) on the lowest layer of the embankment body.

(2) Reinforcement of embankment built for track widening constructed on soft ground (See Fig. 5) [8]

When an embankment constructed on soft ground needs to be widened to accommodate an additional railway track, the area of soft ground under the toe of the existing slope is normally reinforced, as it is difficult to reinforce the ground directly under the existing embankment. When the soft ground is deep, deep mixing piles, or similar ground improvements are used to achieve this. However, this method’s resistance to horizontal loads is not clear. A centrifuge model experiment was thus conducted to identify the deformation characteristics of the soft ground when the embankment constructed upon it is widened and also to develop a reinforcement method that is highly effective in stabilizing the soil. Based on the results of the experiment, a reinforcement method was proposed using deep mixing wall type ground improvements and cement-mixed gravel slabs. It was found that the proposed method halves the deformation rate of the embankment and surrounding ground with roughly the same rate of improvement as pile-type reinforcement. In addition, a design method based on the proposed method was developed.

(3) Aseismic reinforcement of an earth retaining wall [9]

A systematic method for the aseismic reinforcement of masonry retaining walls was developed that uses collapse prevention nets and ground reinforcement materials. In addition, another method was devised for when the working area is very restricted (small) (See Fig. 6).

3.3 Tunnel life prolongation and renovation

(1) Prolongation of mountain tunnel life through repair and reinforcement [10,11]

There are two types of life-extension measure: reinforcement against external factors and repair to prevent spalling.

a) reinforcement against external factors

RTRI has developed a method for selecting the optimal combination of reinforcement measures, after carrying out
tunnel lining model tests and simulations using the analytical method outlined in 2.4. These measures are backfill grouting, rock bolting, inner reinforcement and invert.

We also developed a Basalt fiber reinforced plate (BFRP) bonding method that offers the same levels of lining deformability as conventional inner reinforcements (such as the fiber sheet bonding method), but less convergence and therefore excellent workability and durability (See Fig. 7) [10]. The BFRP bonding method has since been utilized in several tunnels.

b) Repairs to prevent spalling

Fiber sheet bonding and nets are widely used to prevent spalling. However, fiber sheets are difficult to attach to rough lining surfaces and nets may allow small pieces of detached lining to fall through.

RTRI developed a method where polyurea resin, which has excellent elongation properties (more than 200%), is sprayed onto the lining. The method is currently being tested in existing tunnels [11].

(2) Large-scale renewal of underground station space (See Fig. 8) [12]

Underground stations are increasingly being widened by opening parts of their existing tunnels and connecting them with new tunnels to ease congestion and improve service. However, the increasing scale on which this type of work done has created the need for reinforcement of existing tunnels. Given that the section force borne by an opening in an existing tunnel is redistributed to surrounding members, it is necessary to have an accurate understanding of the forces at play.

As such, a three-dimensional FEM analysis was performed assuming that an opening had been made in the side wall of an existing disconnection tunnel, to understand the effect of three-dimensional stress changes in relation to the opening width. A method was developed where a reinforcement beam holds up the connecting section between the existing tunnels and new tunnels, which is further retained by horizontal and vertical anchors crossing each other. This configuration suppresses any increase sectional force in the existing tunnel: in the longitudinal direction because of the reinforcing beam and in the transverse direction because of resistance of the old and new tunnels acting as a unit. Results of a full scale model loading test of the beam in this connecting structure, confirmed that the new and old members behave integrally, and prevent collapse of the connecting section. A numerical analysis was used to verify that this connecting structure has the expected flexural strength. Compared to standard cut and cover tunnels with 2 layers and 2 spars, this connection structure reduces the amount of reinforcement work which has to be carried out on the existing tunnel, resulting in a cost reduction of approximately 10%.

4. Improvement of technical standards

4.1 Design standards revision into performance codes

RTRI has been preparing drafts for railway structure design and maintenance standards by commission from the Ministry of Land, Infrastructure and Transport. As part of this, the design standards for concrete structures were revised into performance codes in 2004, and subsequently other design standards were revised as well. Among the design standards for geotechnical structures, those for soil structures were revised in 2007 and those for earth retaining structures in 2012. Revision of the design standards for tunnels, the last of all required revisions into performance codes, started in 2013. The plan is to produce a four-part set of performance codes: Part 1 General, Part II Cut and cover methods, Part III Shield tunneling methods and Part IV Mountain tunneling methods.

4.2 Preparation of manuals

At the request of railway operators, RTRI has been preparing a range of manuals. As an example, two manuals relating to railway geotechnical structures are described below:

(1) Seismic diagnosis and reinforcement planning for soil structures [13]

Although soil structures account for the majority of railway line extensions, only a few have been subject to proper seismic reinforcement. Consequently, many soil structures have been damaged after past earthquakes and therefore seismic retrofitting will be considered in the future.

With that in mind, the “Seismic diagnosis guidelines for railway soil structures” (RTRI, 2016) were compiled as a reference to prioritize locations requiring seismic diagnosis and reinforcement. The key characteristics of the guidelines are as follows:

1) Local operator policy indicators are taken into account;
2) Occurrence probability of expected earthquake motion and magnitude can be considered;
3) Embankments can be prioritized according to potential...
tial size of deformation during an earthquake;
4) When a seismic countermeasure is required, it can be selected from a general countermeasure.

These guidelines were prepared with input from the “Meeting for consultation on earthquake countermeasures to be taken by railways in metropolitan areas” and from local operators.

(2) Selection and designing of transverse structures built beneath railway tracks

At the request of railway operators, research has been conducted by RTRI to design methods for predicting track irregularity occurring when transverse structures are built beneath railways. Using input from each railway operator, a set of guidelines are being drafted to facilitate the selection and design method to apply to transverse structures to be built beneath railways, based on existing research and the revised contents of the design standards for tunnels.

5. Conclusion

This paper presented some recent R&D achievements on geotechnical structures such as earth retaining walls, soil structures and tunnels. 80% of Japan’s rail network consists of soil structures, and 10% is tunnel. The ratio of tunnels is even higher for the projected Shinkansen and Chuo-Shinkansen lines currently under construction. These railway geotechnical structures however, are constructed in mountainous areas with complicated topography and geology and in urban areas on soft ground, exposing them to extremely diverse environmental conditions. RTRI believes that in future it will be necessary to deepen R&D into these kinds of geotechnical structure taking these conditions into account and considering the needs of railway operators.

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References

[1] Nakajima, S., Shinoda, M. and Abe, K., “Inspection of structural health of existing railway retaining walls,” Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013, pp.2059-2062, 2013.
[2] Tsuno, K., Hirata, R. and Kamachi, H., “Tunnel Monitoring Method Based on Wireless Sensor Network,” QR of RTRI, Vol.55, No.1, pp.27-32, 2014.
[3] Shinoda, M., Kubota, Y., Sakamoto, H. and Misaki, N., “Development of Inspection Methods of Roadbed Concrete in Tunnels,” RTRI Report, Vol.28, No.8, pp.17-21, 2014 (in Japanese).
[4] Shimamoto, K., Yashiro, K., Kojima, Y. and Asakura, T., “Prediction Method of Tunnel Deformation Using Time-dependent Ground Deterioration Model,” QR of RTRI, Vol.50, No.2, pp.81-88, 2009.
[5] Yashiro, K., Hirata, R., Okano N. and Kojima Y., “Study on Deformation and Failure Behavior of Mountain Tunnel Lining Which Consist of Various Materials,” Journal of Japan Society of Civil Engineers, Ser. F1 (Tunnel Engineering), Vol.71, No.2, pp.78-94, 2015 (in Japanese).
[6] Yakita, S., Tsuno, S., Nakayama, T., Komiya, K. and Akagi, H., “Prediction Method of Deformation of Shield Tunnels due to Construction,” RTRI Report, Vol.28, No.8, pp.23-28, 2014 (in Japanese).
[7] Watanabe, K., Matsuura, K., Fujii, K. and Kudo, A., “Development of Railway Embankment Structures Resistant to severe Earthquakes and Prolonged Overflows caused by Tsunami,” Japanese Railway Engineering, Vol.55, No.5, pp.13-16, 2015.
[8] Sato, T., Kudo, A., Shimada, T., Morikawa, Y. and Takahashi, H., “Proposal of Constructional Countermeasures for the Widening of Embankments with a Focus on Their High Stability,” QR of RTRI, Vol.5, No.3, pp.183-190, 2016.
[9] Nakajima, N., Watanabe, K., Koda, M., Fujiwara, T., Takasaki, H. and Ikemoto, H., “Development of Aseismic Countermeasure for Masonry Wall using Failure Prevention Net and Soil Reinforcement,” Journal of Japan Society of Civil Engineers, Ser. C (Geotechnics), Vol.71, No.4, pp.317-334, 2015 (in Japanese).
[10] Okano, N., Uemura, Y. and Kojima, Y., “Development of Internal Reinforcement Method for Tunnel Lining by FRP Plate,” RTRI Report, Vol.23, No.12, pp.41-46, 2009 (in Japanese).
[11] Shimamoto K., Yashiro, K. and Ito, N., “Spalling Prevention Method for Tunnel Lining Using Polyurea Resin,” QR of RTRI, Vol.58, No.3, pp.217-222, 2017.
[12] Nakayama, T., Tsuno, K., Yakita, S. and Muroya, K., “Investigation of opening at side wall of existent open-cut tunnel based on numerical calculation,” Journal of Japan Society of Civil Engineers, Ser. F1 (Tunnel Engineering), Vol.71, No.1, pp.29-40, 2015 (in Japanese).
[13]Railway Technical Research Institute (Ministry of Land, Infrastructure and Transport supervision), “鉄道土構造物の耐震診断の手引き (Seismic diagnosis guidelines for railway soil structures),” 2016 (in Japanese).

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