Development and Practical Use of a Wire Rope Guardrail System for Two-lane Roads in Japan

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Abstract: Fatal high-speed head-on collisions often occur in limited spaces on two-lane roads without median strips. While the installation of such strips is permitted under the Road Construction Ordinance, their provision to date has been limited due to the high associated costs. Wire rope guardrail systems, which can be seen as an alternative to median strips, involve the use of thin posts, have a buffering function and require minimal width. The purpose of this study was to develop a wire rope guardrail system with a buffering function as a separator for two-lane roads. CG simulation and collision experiments using real vehicles were conducted to determine the characteristics of the fence, and performance tests were conducted in accordance with guard fence installation criteria. As a result, a wire rope guardrail system that satisfies Japan's Am performance standard criteria for expressway median strips was developed.

Keywords: road safety, wire rope guardrail systems, head-on collision, median strip

1. INTRODUCTION

Hokkaido's status as a snowy region with long intercity distances has led to the development of a geographically dispersed society. As road traffic speeds therefore tend to be high and traffic volumes low, most national highways in suburban areas are two-lane roads without median strips, meaning that head-on collisions often have fatal consequences. While the Japanese Road Construction Ordinance permits the installation of median strips as an exception, such work involves considerable installation costs because roadways must be widened so that emergency services can deal with accidents and disabled vehicles. An example of guard fence installation in the center of narrow roads is seen in the 2 + 1-lane road system adopted in Sweden. When median strip facilities are constructed in such sections in this Scandinavian nation, a wire rope guardrail system is also implemented as the lowest-cost option. The system involves the use of thin posts with a buffer function and does not require wide roads. This paper describes CG simulation and collision tests conducted to confirm the system's performance, examination to determine the applicability of Road Construction Ordinance guidelines, guard fence installation standards and other regulations, and development and practical use of wire rope guardrails as median strip facilities for two-lane roads in Japan.

2. OCCURRENCE CONDITIONS OF HEAD-ON COLLISIONS AND RELATED PROBLEMS

The number of traffic accident fatalities in Hokkaido has shown a recent decreasing tendency, reaching 218 in 2009 after peaking at 715 in 1990. This reduction is seen as a result of related measures and road improvements based on collaboration between road and traffic administrators. However, as the fatality ratio (i.e., the percentage of fatal accidents against all accidents) is approximately 1.6 times the national average, the situation remains serious. The majority of fatal accidents are head-on collisions, which account for 22% of the total, and this percentage is more than twice the national average (Figure 1).

In 2000, the Civil Engineering Research Institute for Cold Region launched the development of rumble strips (Figure 2), which are grooves cut on the center lines of two-lane roads as a measure against head-on collisions, and has promoted their practical use since then by Hirasawa (2005). Although the use of these strips has been shown to reduce the incidence of head-on collisions to some extent, it has also been found that their effectiveness decreases in sections with steep road alignments (such as longitudinal slopes in mountainous areas) and horizontal alignments. While it is necessary to physically prevent cars from leaving their lanes, the scope for installation of conventional median strips is limited due to the high cost of road widening and other modifications required.

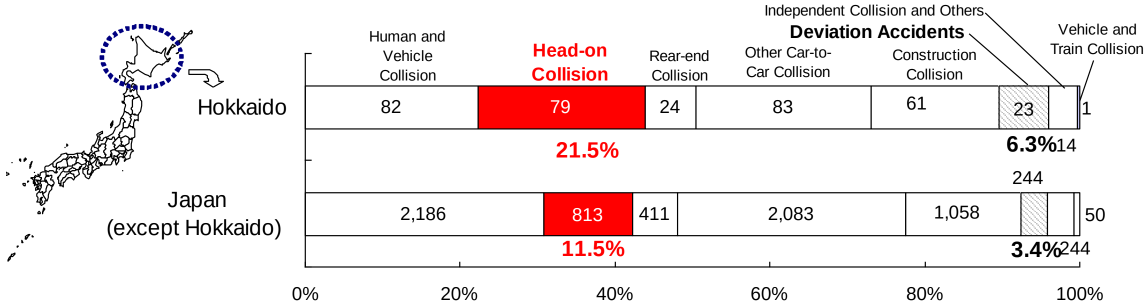


Figure 1. Accident types in Hokkaido and Japan (2003)

Figure 2. Centerline rumble strips (left: R237; right: R275)

3. WIRE ROPE GUARDRAIL SYSTEMS IN EUROPE AND THE UNITED STATES

An example of median strip usage on narrow roads is seen in the wire rope guardrail system widely used in Sweden on 2 + 1-lane roads, where the central lane of a three-lane road is used alternately as the overtaking lane (Figure 3).

The wire rope guardrail system is a type of flexible guard fence, and is categorized as a cable type. The major differences from the guard cables widely used in Japan lie in the use of thin intermediate posts that deform under vehicle impact and wire rope that absorbs and reduces impacts on vehicles (Figure 4). As guard cables are equipped with a block-out structure to prevent direct impacts on posts, a component known as a bracket is attached to each post, and cables and posts are spaced at certain intervals. Since the posts are stronger than those of wire rope guardrail systems, the impact of a car colliding with them is greater.

Figure 3. 2 + 1-lane road with a wire rope guardrail system (Sweden)

Figure 4. Guard cable (left) and wire rope (right) guardrail system

Hirasawa and Munehiro (2009) reported on wire rope guardrail systems introduced in Sweden on a trial basis in 1991 and 1992, and the overall installation length was increased in 1993 and 1994. Additionally, 13-m-wide two-lane roads were constructed in Sweden to allow space for overtaking. However, due to the frequent occurrence of serious accidents in the 1990s, studies on 2 + 1-lane roads with wire rope guiderail systems as median strip facilities were implemented as a low-cost measure. The cross-sectional composition of standard 13-m-wide 2 + 1-lane roads was set in 2001, and the distance covered by such roads with guard fences had reached 1,800 km by June 2008. In other European countries, the installation of guard fences in the center of 2 + 1-lane roads is limited to sections with steep alignments.

MacDonald and Batiste (2007) reported on a wire rope guardrail system featuring three lengths of low-tension wire rope that was first installed in the center of a road by the New York State Department of Transportation in 1968 as a measure against head-on collisions. In 2001, British company Brifen launched marketing activities in the US for its high-tension wire rope guardrail system approved by the Federal Highway Administration (FHWA), which subsequently also approved products by Blue System in Sweden and by Trinity, Gibraltar and Nucor in the US.

A major difference of wire rope guardrail systems in the US is their installation in sections where there are wide median strips and inbound and outbound lanes are separated, while those in Sweden are in the center of narrow roads (total width of 13 m) without median strips.

4. ADVANTAGES OF WIRE ROPE-TYPE GUARD FENCES

The main reason for the adoption of wire rope guardrail systems in Sweden is the low cost. The ratio of installation costs of standard median strip facilities in Sweden (wire rope, guardrail and concrete) is approximately 1:2:3. Wire rope guardrail systems also have high impact absorption ability because their posts deform more easily than guardrail and concrete fences (Figure 5). As a result, the number of fatalities and serious injuries in traffic accidents on 2 + 1-lane roads has decreased dramatically in Sweden. However, it was also reported that the total number of accidents, including those involving property damage, has increased.

When median strip facilities are installed on two-lane roads, the greatest challenge is traffic management in response to accidents or the presence of disabled vehicles. The costs of the road widening necessary to prevent stationary vehicles from interfering with the flow of traffic are enormous.

In Sweden, U-turn openings are provided for maintenance and management in snow removal and other work. Some products have wires and posts that can be removed (as shown in Figure 6) to partially open the median strip as a way of dealing with breakdowns, accidents and other emergencies. While wires can also be divided using a part called a Quick Lock or severed with a cutter, these methods are not used very frequently due to the time taken for restoration.

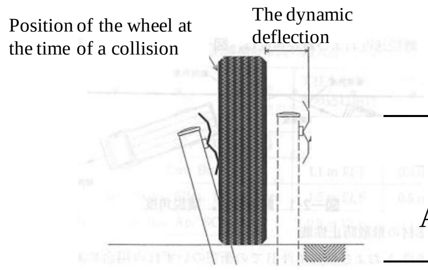
Figure 5. Crash test involving a wire rope guardrail system (from the CASS Cable Safety System Product Manual)

Figure 6. Median opening in emergency situations (from the Brifen website at http://www.brifen.co.uk/)

5. GUARD FENCE INSTALLATION CRITERIA IN EUROPE AND JAPAN

Wire rope guardrail systems introduced in Japan must meet performance standards set by guard fence installation criteria. Such fences are required to have particular strength, deformation and vehicle guidance characteristics, and function to prevent the scattering of components. Among these considerations, the most challenging standard to meet in wire rope guardrail systems is deformation performance, which is known as dynamic deflection in Japan. This is the maximum distance of the front or rear wheel of a vehicle from the original position of the outer surface of the guard fence at the time the vehicle collides with the fence (Table 1). Type B (1.1 m) and A (1.5 m) are mainly applied for national highways and expressways, respectively. In Sweden, where the European standard EN 1317-2 applies, the impact test condition is Level N2 and the working width is 1.7 m (W5 Class) for a 2 + 1-lane road (Table 2). The working width is the distance between the side facing the traffic before impact with the road restraint system and dynamic deflection. This differs for wire rope guardrail systems, which are characterized by deformable posts that absorb impact to meet the Japanese standards, and this has contributed to the delay in their introduction in Japan.

Table 1. Dynamic deflection of guard fences for median strips in Japan



Class	Dynamic deflection with posts buried in the ground (m)
C, B	1.1 m or less
A, SC, SB, SA, SS	1.5 m or less

Table 2. Working widths in EN 1317-2

Class	Level of working width (m)
W1	W ≤ 0.6m
W2	W ≤ 0.8m
W3	W ≤ 1.0m
W4	W ≤ 1.3m
W5	W ≤ 1.7m
W6	W ≤ 2.1m
W7	W ≤ 2.5m
W8	W ≤ 3.5m

As simple comparison of values in Japan and Europe is difficult due to differences in impact test conditions, the impact loads seen in these tests were calculated. The results revealed that the values adopted in Sweden were greater than those of Type B and less than those of Type A in Japan (Table 3). Although the accuracy of dynamic deflection values cannot be determined unless impact tests are actually conducted, the possibility of adopting wire rope systems in the form of Type B guard fences in Japan emerged. The degree of impact was calculated as shown in Figure 7.

Table 3. Impact loads seen in collision tests in Japan and Europe

	Level	Vehicle mass (kg)	Collision speed (km/h)	Collision angle (degree)	Degree of impact (kJ)
Guard Fence Installation Criteria and Instruction Manual in Japan	Type B	25,000	30	15	58.1
		1,000	60	20	16.2
	Type A	25,000	45	15	130.8
		1,000	100	20	45.1
EN1317	Level N2	900	100	20	40.6
		1,500	110	20	81.9

$$Is = \frac{1}{2} * m * \left(\frac{V}{3.6} * \sin\theta \right)^2$$

Is: degree of impact (kJ)
m: vehicle mass (t)
V: collision speed (km/h)
θ : collision angle (degree)

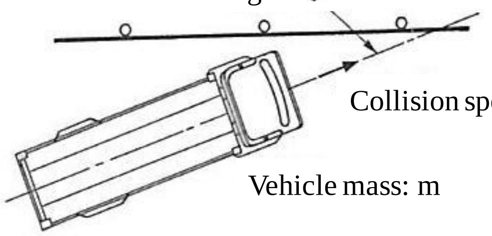


Figure 7. Equation used to calculate the degree of impact

6. DEVELOPMENT OF A WIRE ROPE GUARDRAIL SYSTEM

In October 2008, the Civil Engineering Research Institute for Cold Region launched the development of a wire rope guardrail system in conjunction with the Steel Barrier Association. A product of Trinity Industries, Inc. (Figure. 8) was imported in November of the same year, and the related construction method was checked. In March 2009, a performance test was conducted to determine whether the system satisfied the Bm performance standard for national highway median strips. The results showed that the maximum dynamic deflection of a large vehicle was 0.585 m, which satisfied the standard of 1.1 m or less (Figure. 9). The product also passed other tests and was found to meet Japan’s Bm performance standard. However, as no production license agreement with Trinity Industries, Inc. for usage in Japan could be established, it was necessary to develop a new model.

Figure 8. Wire rope guardrail system of Trinity Industries, Inc.

Figure 9. Collision conditions

Against this background, the development of a new wire rope guardrail system was commenced in conjunction with the Steel Barrier Association in September 2009. The system was required to meet Japanese guardrail standards and enable partial opening via manual detachment of wires and posts. The performance target was that of the Am standard, which can be applied to expressways and highways alike.

As a result of related examination, cylindrical posts were adopted with consideration of workability and impact from two-wheel vehicles. The posts also had cylindrical sleeves and plastic spacers. The wire ends were positioned linearly in the longitudinal direction of the road to minimize the installation width of the terminal bases (Figure. 10). The specifications were as follows:

- Post diameter: 89.1 mm
- Sleeve diameter: 114.3 mm; sleeve length: 70 cm
- Post height: 82 cm
- Post interval: 3 m
- Post material: STK540
- Wire rope heights: 75, 64, 53 and 42 cm


Figure 10. New wire rope guardrail system

In March 2010, a performance test was conducted for the new system. The test conditions for the Am standard are as follows:

- Large vehicle - weight: 20 t; speed: 52 km/h; collision angle: 15 degrees
- Small vehicle - weight: 1 t; speed: 100 km/h; collision angle: 20 degrees

It was found that the system did not meet the type Am performance standard because the large vehicle broke through it, although the results for the passenger vehicle satisfied the standard (Figure. 11).


Figure 11. Conditions of the new wire rope guardrail system upon collision and thereafter

In October 2010, the new system was improved with the following revised specifications based on analysis of the performance test results (Figure. 12):

- Post height: 92 cm
- Post material: STK400
- Wire rope heights: 86, 75, 64 and 53 cm
- Post slit shape: modified
- No. of straps: 2

Another performance test was conducted on the improved system in January 2011. The Am test conditions were the same as those in the previous test except for a change in the post bases from sandy soil to asphalt pavement.

Figure 12. Improved wire rope guardrail system

The test results for the passenger car satisfied the Am performance standard, but those for the large vehicle did not; the maximum dynamic deflection was 1.99 mm, which exceeded the standard value of 1.5 m or less, although the vehicle did not break through the guardrail (Figure. 13). The large vehicle penetrated significantly because three of the four wire ropes were pulled up by the rotating wheels and only the top one functioned (Figure. 14). The standards for all other test items, including the detachment speed (60% or more of the collision speed) and detachment angle (60% or less of the collision angle), were satisfied.

Figure 13. Collision with the improved wire rope guardrail system

Figure 14. Collision of the large vehicle

The Civil Engineering Research Institute for Cold Region and the Steel Barrier Association verified the results of the performance tests conducted in 2010 and 2011 and examined the guardrail specifications using CG simulation (Figure. 15). There is a tradeoff between many of the requirements for wire rope guardrail system specifications. For example, wire rope deflection helps to absorb impact, but also results in increased extrusion into the opposite lane (i.e., greater maximum dynamic deflection). Similarly, while it may be possible to increase post strength or adjust wire rope installation heights, this may lead to reduced detachment speed after impact from a passenger car or possible failure of wire ropes to catch the vehicle body. Accordingly, balanced specifications to satisfy such contrasting requirements are necessary.

CG simulation was conducted with conditions identical to those of the performance tests with variations in the post material and sheet thickness, the number of wire ropes, their height, the number of bands, tension specifications, post intervals and other variables. Two sets of specifications were determined in July 2011 based on the results for detachment speed, detachment angle and maximum dynamic deflection. The specifications were the same except for sheet thickness (4.2 and 3.2 mm) (Figure. 16).

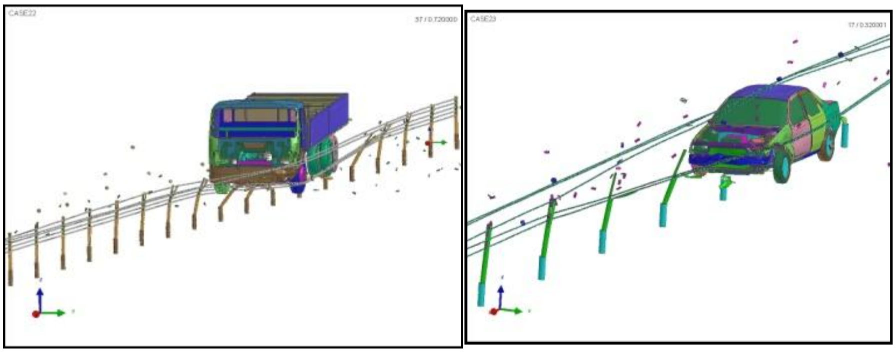


Figure 15. Example of CG simulation

Figure 16. Guardrail after the second round of improvements

In September 2011, two prototype guardrail systems were produced and a collision test with a large vehicle and a test driver was conducted. The results showed that the standards for all items, including maximum dynamic deflection and the detachment speed/angle, were satisfied. As post-collision analysis of vehicle swept path revealed that the type with a sheet thickness of 4.2 mm changed the direction of the vehicle more quickly and was more effective in guiding vehicles, it was decided use this set of specifications for a performance test (Figure. 17).

Figure 17. Conditions at the time of and after the collision

The specifications after the second round of improvements were as follows:

- Post height: 92 cm
- No. of wire ropes: 5
- Wire rope heights: 97, 86, 75, 64 and 53 cm
- Post sheet thickness: 4.2 mm
- No. of straps: 1

In January 2012, a performance test was conducted for the guardrail system after the second round of improvements with the following details:

- Test site: collision test facility of the National Institute for Land and Infrastructure Management (Tsukuba, Ibaraki, Japan)
- Guard fence classification: Am
- Guard fence form: cable-type flexible guard fence for vehicles
- Base type: ground (with anchors at both ends)
- Ground condition: asphalt pavement
- Collision condition A: heavy goods vehicle; test date: Tue. Jan. 18, 2011
  Test vehicle weight: 20 t; collision speed; 52 km/h; collision angle: 15 degrees; impact level: 140 KJ
- Collision condition B: passenger vehicle; test date: Jan. 12, 2011
  Test vehicle weight: 1 t; collision speed: 100 km/h; collision angle: 20 degrees

The test results indicated that the level of performance in preventing vehicle deviation was sufficient to stop a large vehicle from breaking through the guardrail, and that the level of passenger safety performance was sufficient to guide vehicles without them overturning (Figures. 18, 19). Although the front of the vehicle was damaged, its interior was intact and the maximum acceleration at the time of impact was 95.2 $m/s^2/10$ ms, which was less than two-thirds of the standard value of 150 m/s2/10 ms. Accordingly, the buffering capacity of the system was confirmed (Figure. 20). Concerning the deformation performance of the guardrail, the maximum dynamic deflection was 1.48 and 1.02 m for the large and passenger vehicles, respectively, which satisfied the standard of 1.5 m or less. The vehicle guidance performance standards were also met; the detachment speed was more than 60% of the collision speed (large vehicle: 83.1%; passenger vehicle: 66.1%) and the detachment angle was less than 60% of the collision angle (large vehicle: 0%; passenger vehicle: 35.7%). As a result, the system was found to satisfy all Am standard values.

Figure 18. Vehicle collisions

Figure 19. Post-collision swept path of the large vehicle

Figure 20. Post-collision vehicle damage

7. WIRE ROPE GUARDRAIL SYSTEM CONSTRUCTION METHOD

In the wire rope guardrail system, wire ropes are supported by posts inserted in sleeves in the post base. The sleeves of the system developed in this study are round steel pipes measuring 114.3 mm in diameter and 70 cm in length. Reinforcements to support posts are placed 40 cm from the top, and iron covers are welded to the sleeve bottoms to prevent contamination with dirt during construction and inflow of rainwater thereafter (Figure. 21). As the sleeve diameter was the same as that of existing guardrail and guard cable posts, a guardrail post driver was used for sleeve placement. However, since the driver could not drive sleeves down to the pavement surface, durable iron attachments and their ends were cut to match the shape of the bottom covers to prevent cover damage (Figure. 22). In test installation involving fixing 163 sleeves to attachments and driving them in directly, each sleeve took 25 seconds on average to fit (Figure. 23).

Figure 21. Sleeve and post support inside a pipe

Figure 22. Attachment and its end

Figure 23. Sleeve placement

8. EXAMINATION OF INITIAL TENSION UPON CONSTRUCTION

As wire rope guardrails absorb vehicle impacts mainly via rope tension, tension loss may impair function. It is necessary to control wire rope tension after construction, as stretching over time causes slackening. For wire rope guard fences at the center of two-lane roads, tension loss should be minimized because related measurement and re-stretching require traffic control. Accordingly, the prestretch method (in which rapid initial stretching of wire ropes is facilitated via the application of initial tension greater than the standard value) was tested.

In the prestretching process, a maximum tension of 33 kN (3,365 kg) was applied to stretch ropes manually, and the value was then adjusted to 22 kN (for winter construction), which is the initial tension value for guard cables as designated by guardrail installation standards. At this time, one of the five wire ropes was stretched without prestretching to verify the effectiveness of the method. Tensioning of 33 kN (3,365 kg) was applied for 1, 2, 3 and 18 hours to the remaining four ropes to determine the time for which prestretching should be maintained. The tension on the five wire ropes was adjusted to 22 kN (2,243 kg) on February 9, 2012 (Figure. 24), and tension was measured one, two, three and four days as well as one, two, three and four weeks later.

The results indicated that tension decreased from one day after stretching in the case without prestretch, and loss after four weeks was 18.3%. In the cases with prestretching for 1, 2, 3 and 18 hours, the figures for tension loss after four weeks were 5.8, 9, 1.3 and 4%, respectively. The effectiveness of the prestretching method was thus confirmed, but the relationship between the stretching time and tension loss varied. It was found that even an hour of prestretching was quite effective, although the optimal prestretch duration was not determined (Figure. 25). The tension of the prestretched wire ropes increased with reduced air temperature.

Figure 24. Stretching and tension measurement

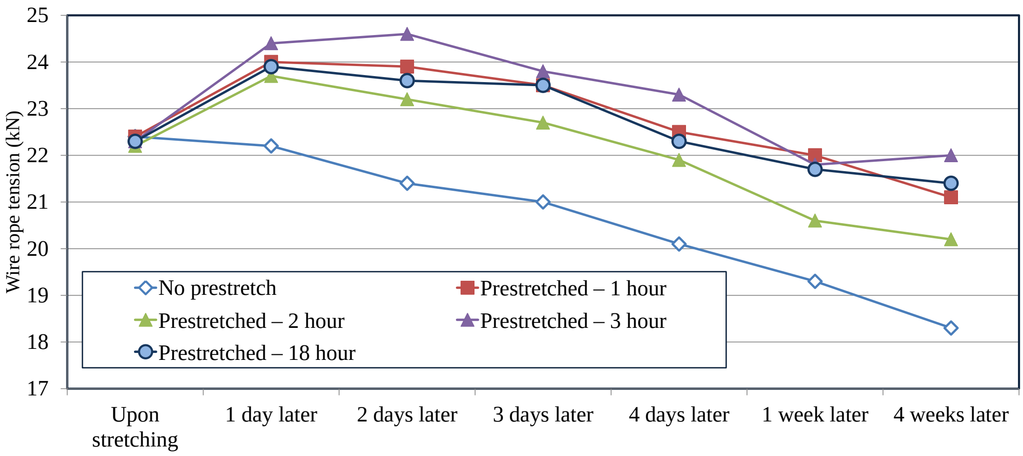


Figure 25. Tension measurement results

9. CONSTRUCTION OF THE WIRE ROPE GUARDRAIL SYSTEM

As the wire rope guardrail system was found to meet the Am performance standard, it was adopted on a trial basis for a 390-m section on the Ban-etsu Expressway (Figure. 26), a 1.6-km section on the Do-o Expressway (Figure. 27) and a 325-m section on Route 275 (Figure. 28) in 2012 and for a 128-m section on the Kisei Expressway (Figure. 29) in 2013. The Route 275 section has a steep alignment in a mountainous area and a curvature radius of 210 m. This corresponds to the purpose of the wire rope system's development, which is to physically prevent cars from leaving lanes as the effect of rumble strips decreases in sections with steep road alignments (such as longitudinal slopes in mountainous areas) and horizontal alignments.

Figure 26. Ban-etsu Expressway

Figure 27. Hokkaido Expressway


Figure 28. Route 275


Figure 29. Kisei Expressway

10. CONCUSION

Guard fence installation in the center of roads to prevent head-on collisions has been limited due to topographical and budgetary constraints. In this context, wire rope guardrail systems are expected to help reduce maintenance costs and improve safety because they require less width than conventional median-strip facilities. In this study, combinations of different post heights/hardness levels, shapes, numbers/heights of wire ropes, tension levels, post intervals and other values were examined to find the optimal specifications in order to solve the challenge of reducing the extrusion of vehicles into the opposite lane based on wire rope deflection to absorb impact. The results of the performance test conducted in January 2012 confirmed that the wire rope guardrail system developed satisfied the guard fence installation Am performance standard criteria for highway median strips. The system was introduced on a trial basis on sections of the Ban-etsu Expressway, the Do-o Expressway and Route 275 in 2012 and the Kisei Expressway in 2013. In the future, the authors intend to collect maintenance-related data (such as information on tension loss, accidents and the time and expense involved in restoration), conduct examinations and experiments on specifications to satisfy the type B standard, engage in detailed examination of structures and efficient construction methods in consideration of installation conditions (such as road alignment and positions of structures) to expand the use of the system, and develop a related construction and maintenance manual.

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