Research on the Protection Level Transformation and Upgrading Technology of the W-beam Barrier on Highway

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Abstract: After 20 years of rapid development of highway in China, the w-beam barrier is the most widely used form of barrier. Recycling and reusing of old barrier are often involved in daily maintenance and expansion project. This paper established the actual protection grade calculation model of the old W-beam barrier through investigation on old W-beam barrier. Considering previous research experience and theoretical calculation, five kinds of barrier structure are put forward which can enhance barrier protection ability. Two design schemes are selected through the computer simulation analysis comparisons and are tested through the full-scale impact test with real vehicle. Test results show that the protection level of selected two design schemes meet the level A protection requirements of the current assessment standard.

Introduction

In early years, the w-beam barrier of highway constructed in China is based on "Specification for Design and Construction of Expressway Safety Appurtenances (JTJ 074-94)", of which the protection energy is 93kJ.Withthe changes of traffic flow characteristics in freeway, the protection level of original barrier cannot meet the safety and security requirement. Therefore, using the existing structure of the old w-beam barrier and enhancing the protection level energy from the 93kJ to the current "Specification for Design of Highway Safety Facilities (JTG D81-2006)" requirements of 160kJ, can not only enhance safety, but also reflect the new conception of saving, low-carbon and environmental protection.

The protection of w-beam barrier is a system function. Old w-beam barrier protection system includes column system and w-beam plates system. The protection level of the w-beam barrier is related to the sum of absorbed deformation energy of columns and w-beam plates. The factors which affect the protection energy of column and w-beam plates include the following aspects [1], as shown in Figure 1.
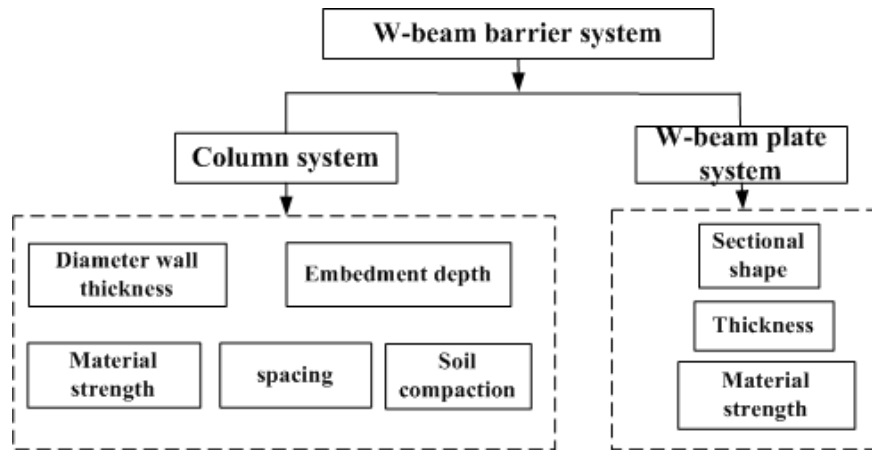
Fig.1   W-beam barrier protection level factors

The calculation model of enhancing the protection level of old w-beam barrier

Model

Here use the standard Gr-A-4E barriers reference to estimate the protection energy of the w-beam barrier. The deformation resistant of barrier systems is used to calculate the actual barrier protection energy. Based on this, basic assumptions are as follows:

(1) Vehicle impact energy of the across-road direction on the barriers mostly absorbed by the deformation of columns and beams;

(2) The deformation energy of columns and w-beam plates is equal to the protection level of barrier.

(3) Under the standard conditions of the vehicle impact, the length of barrier section which absorbs energy is within a certain range.

(4) The barrier column and the w-beam plates are steel-plastic material.

(5) The protection level of the barrier is mainly influenced by the performance of energy absorption of columns and w-beam plates [2] [3] [4].

Barrier calculation model of actual protection energy is shown in equation (1):

$$E_2 = k \times (\sum_{i=1}^{m} D_i + \sum_{j=1}^{n} D_j) = k \times (\sum_{i=1}^{m} k_P k_h k_l M_{pi} |\theta_i| + \sum_{j=1}^{n} M_{pj} |\theta_j|) \quad (1)$$

In the equation

E_2 - Actual protection level of barrier (kJ);

k - Correction coefficient (considering barrier system energy consumption, corrosion, etc.), (0.8-1.0);

D_i - Absorbed deformation energy of column(kJ);

i - Numbers of deformed column;

D_j - Absorbed deformation energy of W-beam plate (kJ);

j - Numbers of deformation W-beam plate;

k_p - Coefficient of soil compaction;

k_h - Coefficient of depth of column embedment;

k_l - Column spacing coefficient;

M_{pi} - Ultimate plastic bending moment of column (N • m);

θ_i - Relative angle at the plastic deformation area of the NO.i column;(rad)

M_{pj} - Ultimate plastic bending moment of w-beam plate (N • m);

θ_j - Relative angle at the plastic deformation area of the NO.i plates[5];

Main Parameter Value

1) Main range of energy absorbed section of w-beam barrier

According to the theoretical analysis, for grade A w-beam barrier under the impact conditions, the average length of total deformation section is 12.21m. Thus, Numbers of deformed columnis4, the Numbers of deformation W-beam plate j is 3. Figure2 shows the main energy-absorbing area of w-beam barrier before and after deformation.
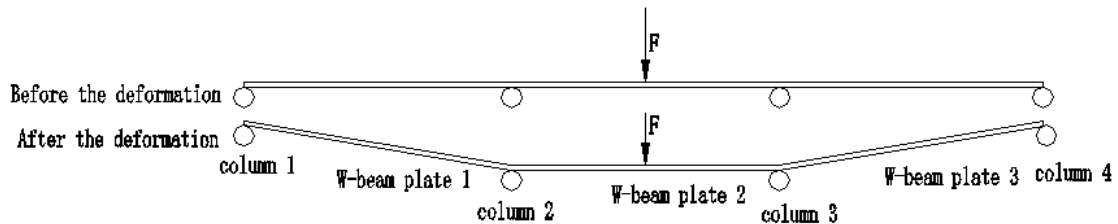
Fig.2   W-beam barrier energy deformation range diagram

2) Analysis of energy-absorbing of column

According to the research and barrier material performance test of expressway w-beam barrier, column is circular and typical sizes are mainly Φ114mm × 4.5mm and Φ140 mm× 4.5mm. Factors affecting energy absorbing of barrier column include the following aspects: the column section modulus, strength, column embedment depth, subgrade compaction, relative plastic deformation bending angle of the column.Figure3 shows the schematic diagram soil foundation cracking and measurement parameter[6].
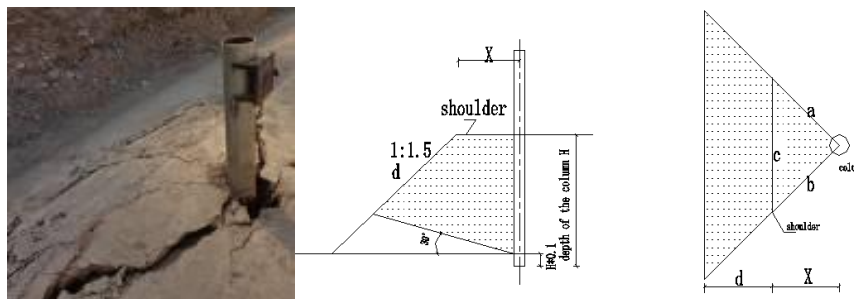
Fig.3Soil foundation cracking and measurement parameter schematic diagram

With the same degree of compaction of soil and distance between column and road shoulder, the ratio of the ultimate strength, of which between different embedded depth and the embedded depth which is less than 1.1m, is in a small range. When embedded depth is larger than 1.4m, the ratio is 1.45-1.48, column 1.4m depth, the ratio is 1.21-1.23. This conclusion has high conformity with experimental coefficient of the column embedded depth test. Therefore, in the calculation of the maximum energy-absorbing column, column embedment depth coefficient uses the experimental values, but the coefficient of compaction uses the actual degree of soil compaction [7][8]. Table 1 shows the column energy dissipation with different conditions.

Tab.1   Column energy dissipation calculation under different conditions

Column Specifications(mm)	Type / Embedment depth(cm)	Embedment depth coefficients	Column spacing (m)	Column spacing coefficient	Soil compaction coefficient	Column energy consumption(kJ)
Φ114*4.5	Buried pile	0.94	4	1	0.95	38.98
	110	1		1	0.95	41.47
	125	1.36		1	0.95	56.40
	140	1.44		1	0.95	59.71
	Buried pile	0.94	2	1.5	0.95	58.47
	110	1		1.5	0.95	62.20
	125	1.36		1.5	0.95	84.59
	140	1.44		1.5	0.95	89.57
Φ140*4.5	Buried pile	0.94	4	1	0.95	65.06
	110	1		1	0.95	69.22
	125	1.36		1	0.95	94.14
	140	1.44		1	0.95	99.67
	Buried pile	0.94	2	1.5	0.95	97.60
	110	1		1.5	0.95	103.83
	125	1.36		1.5	0.95	141.20
	140	1.44		1.5	0.95	149.51

3) Analysis of energy absorbing of w-beam plate

According to the highway investigation, there are two w-beam thicknesses: 3mm and 4mm. the factors of w-beam energy consumption are the section modulus of w-beam, strength, relative bending angle of plate plastic deformation. Calculation of W-beam energy absorbing is shown in Table 2.

Tab.2 W-beam energy dissipation calculation

Thickness (mm)	Moment of inertia (cm^4)	Radius of gyration(cm)	Section modulus(cm^3)	Yield Strength(kN/cm)	Amount of plates	Relative angle(rad)	W-beam maximum consumption energy(kJ)
3	106.6	4.25	25.08	37.71	3	0.5	28.38
4	143.05	4.25	33.66	37.71	3	0.5	38.08

Old barrier reuse design and theoretical calculations

According to the actual situation of the reuse of the old barrier panels, combined with the experiences of research, design and renovation project of barrier, five kinds of recycling modification program is put forward [9] [10], which is shown in Table 3.

Tab.3　The retrofit scheme and protection grade calculation

Serial number	Description of original barrier structure	Description of Renovation or new part	Protection class calculated (kJ)
OptionⅠ: Replace with 4mm three-wave beam	Column Specifications:Ø140mm×4.5mm w-beam stickiness:3mm	Column :Keep the original column spacing, depth w-beam plate: Replace with 4mm three-wave beam	154.14
OptionⅡ: extra column, double w-beam plate	Column Specifications:Ø114mm×4.5 mm w-beam stickiness:3mm	Column :Add extra Ø140mm×4.5mmcolumn w-beam plate: Add extra 3mm w-beam plate(old w-beam plate can be used)	157.94
OptionⅢ:extra column, Add 3mm single wave beam	Column Specifications:Ø114mm×4.5 mm w-beam stickiness:3mm	Column :Add extra Ø140mm×4.5mmcolumn,Heightening the original column casing w-beam plate: Add 3mm single wave beam	186.18
Option Ⅳ:8-shape w-beam plate	Column Specifications:Ø140mm×4.5mm w-beam stickiness::3mm	Column: Add extra Ø140mm×4.5mm column w-beam plate: Add extra 3mm w-beam plate(old w-beam plate can be used)	197.9
OptionⅤ:extra column, replace 4mm thick channel steel	Column Specifications:Ø114mm×4.5 mm w-beam stickiness:3mm	Column: Add extraØ140mm×4.5mm column w-beam plate: replace 4mm thick channel steel	164.69

Computer Simulation Analysis of modification programs

The simulation model and simulation parameters

Based on the main features of small passenger cars, medium bus and medium trucks in China, the vehicle finite element model is established. For small car finite element model, there are totally 41,011 nodes elements, 42,185 shell elements, 340 body elements, 92 beam elements; The finite element model of medium-sized passenger car has totally 44,834 nodes elements, 43,564 shell elements, 16 beam elements, 24 the spring elements, and 784 other elements; the finite element model of medium truck has totally 52,681 nodes elements, 28,944 housing elements, 16,416 body elements, 66 beam elements,32 spring elements and 1930 other elements. Figure 4 are the model demonstrations.
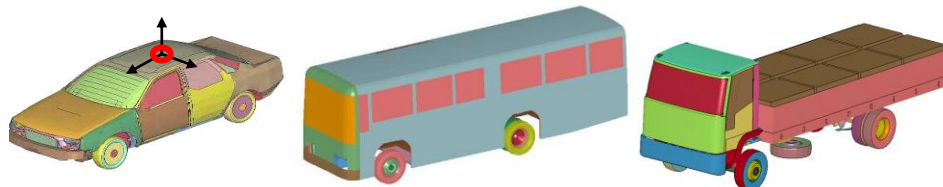
Fig.4 Finite element models of Small cars, medium bus and medium trucks

According to impact conditions of grade A barrier in "Standard for Safety Performance Evaluation of Highway Barrier" (JTG B05-01-2013),impact test conditions of small passenger cars, medium bus and medium trucks are shown in Table 4[11] [12].

Tab.4 Car, medium bus and medium truck collision simulation conditions

Type	Total mass(t)	Velocity(km/h)	Angle of impaction(°)	Energy(kJ)
Car	1.5	100	20	\
medium bus	10	60	20	160
medium truck	10	60	20	160

Simulation Analysis

According to "Standard for Safety Performance Evaluation of Highway Barrier" , for car, medium bu and medium truck, respectively, the barrier function, guiding function, buffering function, the maximum lateral dynamic deformation of the barrier, maximum lateral dynamic displacement of the barrier, maximum lateral epitaxial dynamic displacement value of the barrier, vehicle dynamic extraverted maximum value and the maximum dynamic vehicle extraverted equivalents are analyzed through simulation analysis, the evaluation results were shown in Table 5:

Full-scale impact test

According to simulations of finite element analysis, Option I (new 4mm three-wave beam) and Option II (extra column, double waveform w-beam), which were the optimum solution, were chose to pass a real vehicle impact test. The method of safety performance evaluation is in "Standard for Safety Performance Evaluation of Highway Barrier"(JTG B05-01-2013).

The results of full scale impact test with real vehicle of Option I (new 4mm three-wave beam)

The impact test of real car for minibus, medium-sized car and medium truck for the new modification program(4mm w-beam)are shown in Figure 5.

Fig. 5   Deformation of barrier collision of a car, medium bus and medium truck of optionⅡ

From the testing process, when a small car impacted, the collision between the vehicle tire and collided barrier column happened, but the collision did not affect the running attitude of the vehicle, the car could be relatively stably guided and the impact-side front tire blow out, when impact happened occupants suffered much larger acceleration, but acceleration did not exceed the requirements of specified limit values; when medium-sized bus impacted, vehicle rolling was large, the front portion of the vehicle had a tilt phenomenon, but after landing vehicle could still be driving normally, and did not leave exit box, the earth shoulder of the road was severely damaged and vehicle rolled over a collision zone column. Deformation of the column was large; When a medium truck impacted, vehicle rolled seriously, when rolling the vehicle steering wheel deflected, resulting in the truck cannot run along a straight line when the wheels landed, the vehicle ran against and rubbed the barrier until parking, deformation of barrier was large, and some part shads light tearing. According to the results, the safety performance of this design meet the Level A class protection requirements.

Tab.5　Evaluation of renovation option simulation

Evaluation items		Containment performance		Redirective performance		Buffering performance				Maximum dynamic lateral deflection (mm)	Maximum dynamic widening distance of lateral deflection (mm)	Maximum dynamic vehicle incline-out distance (mm)	normalized maximum dynamic vehicle incline-out distance (mm)	Meets the evaluation criteria or not
		Roll over or not	Components and detachment parts intrude vehicle occupant cabin	The vehicle roll over or not	The vehicle to meet the requirements of exit box	Occupant impact velocity(m/s)		Occupant ride down acceleration(g)						
						X	Y	X	Y					
I	Car	no	no	no	yes	5.1	7.7	7.7	8.6	659	1016	—	—	yes
	medium bus	no	no	no	yes	—	—	—	—	1296	1576	1498	1848	
	medium truck	no	no	no	yes	—	—	—	—	1012	1310	1482	2270	
II	Car	no	no	no	yes	3.2	5.9	6.9	8.2	585	1536	—	—	yes
	medium bus	no	no	no	yes	—	—	—	—	1188	1558	2268	2618	
	medium truck	no	no	no	yes	—	—	—	—	1195	1635	2574	3024	
III	Car	no	no	no	yes	11	7.7	16.7	7.8	419	1538	—	—	yes
	medium bus	no	no	no	yes	—	—	—	—	835	1739	914	1359	
	medium truck	no	no	no	yes	—	—	—	—	815	1821	1375	1820	
IV	Car	no	no	no	yes	9.7	9.3	11.1	8	422	1462	—	—	no
	medium bus	yes	no	no	yes	—	—	—	—	—	—	—	—	
	medium truck	no	no	no	yes	—	—	—	—	787	1499	1516	1961	
V	Car	no	no	no	yes	9.9	10	10.5	6.9	411	1504	—	—	no
	medium bus	no	no	no	yes	—	—	—	—	774	1047	765	1210	
	medium truck	no	no	no	no	—	—	—	—	792	1529	1588	2032	

Results of Option II (extra column, double waveform w-beam) of full-scale impact test with real vehicle

Real car impact test of modification option of adding extra column, double waveform w-beam of car, medium bus and medium truck are shown below respectively, in Figure 6.

Fig. 6　Deformation of barrier impact of a car, medium bus and medium truck of option II

From the testing process, when a small passenger car impacted the collision between the vehicle tire and collided barrier column happened, most of impact happened on the lower layer plate of barrier; large deformation took place on the lower layer barrier, while the lower column had weaker stiffness (diameter 114mm).After forming "string bag" phenomenon, the vehicle was guided due to the synergistic interception effect of column and high barrier plate and collision happened between the wheel and high column (diameter 140mm), the front side tire of the vehicle fell out, the vehicle was successfully exported.

When medium-sized bus impact, upper barrier deformation occurs firstly because the vehicle height, the wheels climb on the barrier. When the tire pressed on the barrier, the barrier deformation took place and the vehicle hit the vehicle directly on the lower short column, at this time the upper barrier deformed normally and the guiding function for the vehicle is formed, but at this time the lower barrier was completely deformed on the road. When the vehicle continued to move, the lower barrier plate fractured and the lower column fall down. Vehicle was successfully exported.

When a medium truck impact, vehicle rolled more seriously, in the rolling process, the vehicle

steering wheel deflected, leading to that vehicles cannot travel in a straight line when the wheel landing, the vehicle ran against the barrier and rub until the parking. Different from the situation of the medium-sized passenger car impacted, truck did not climb along the lower board of the barrier in the early stages. The main reason was the medium truck had different mass distribution between trucks and medium bus, and the impact force of the collision is less than the medium bus in initial period.

Conclusion

Based on the usage survey of old beam barrier, the calculation model of the old beam barrier actual protection level promotion was established, the factor of barrier protection level, of which the column section modulus, strength of steel, columns buried depth, soil base compaction, relative rotation angle of plastic deformation of the column and other factors, were analyzed;

Combined with previous research experience and theoretical calculations, the five kinds of barrier structure whose protection capacity were enhanced were suggested, and the theoretical protection level was calculated. Two final choice of barrier was chose through computer simulation analysis method and comparative analysis of performance of protection programs to conduct the full-scale impact test with real vehicle, the test results showed that the protection performance of the this two barriers program could meet the current level A requirements (160kJ)of the evaluate standard, and these two could be applied to the actual construction. But in practical applications, for the protection performance of the relatively lower height of the barrier due to overlays roads, as well as column force analysis with narrow soil shoulder width, further researches are needed.

Acknowledgements

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