Strategy for Constructing Environment Vibration Control System for High-Speed Railway

Zhenxing He, Guangtian Shi, Xiaoan Zhang, Nengneng Bao, Shuzhen Wang and Jiangang Xu

Abstract With the acceleration of urbanization and the rapid development of rail transit, more and more high-speed railways are built and connected with urban rail transit of the big cities. It is the trend to deduce the train-induced environmental vibration of the high-speed railway by using vibration damping tracks, but it is still in the exploration stage for using damping tracks in the high-speed railway. After more than 10 years of rapid development, urban rail transit has established an environment vibration control system. Because of the great difference between the high-speed railway and the urban rail traffic which exist in the speed of train and the maintenance standard, the problems of whether the vibration damping measures widely used in the urban rail transit are applicable, how to determine the key dynamic parameters of the vibration damping tracks, could not be avoided in design, construction, and operation of the high-speed railway vibration damping track. This study investigated the construction of environmental vibration control system for high-speed railway based on the experience of environmental vibration control of urban rail transit.

Keywords High-speed railway · Environmental vibration · Control system · Dynamics · Long-term service

1 Introduction

Reducing train-induced environment vibration is an important measure to reflect the friendly environmental characteristics of rail transit. With more and more attention been paid to environmental protection and "green development," the vibration reduction track has been widely adopted in urban rail transit. At present, the cases of high-speed railway entering densely populated urban areas and connecting with

Z. He (✉) · G. Shi · X. Zhang · N. Bao · S. Wang · J. Xu
School of Mechanical Engineering, Institute of Vibration and Noise Control, Lanzhou Jiaotong University, Lanzhou, China
e-mail: 383645442@qq.com

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urban rail transit network are increasing. In order to reduce the vibration and noise, using the vibration reduction track has been the trend of high-speed railway development [1–3].

After more than 10 years of engineering practice and theoretical investigation, the environmental vibration control system of urban rail transit was established. The empirical formula method is used to predict the vibration superscalar of the vibration-sensitive point [4–6]. Various types of vibration damping tracks are adopted, and the vibration damping layers or components are usually arranged at three positions (the rail fastener, the sleeper, and the track bed) of the track system [7–9]. According to the damping effect, the vibration damping track is divided into three levels. Based on the results of the environmental vibration evaluation and the usage of the damping track in the entire network, the type selection design of the vibration damping track for a certain line is carried out [10]. The actual effect of the vibration damping track is usually tested and evaluated before the line is officially put into operation [7].

When the vibration damping track is used for the high-speed railway with heavier axle load and higher speed grade, how to draw on the experience of urban rail transit and establish the environmental vibration control system suitable for high-speed railway has become an unavoidable engineering problem for the design, construction, and maintenance of high-speed railway.

2 Characteristics of Rail Transit Environmental Vibration Control

Environmental vibration control of rail transit is a systematic project, which includes three aspects. The first is to determine the sensitive point of vibration and predict the vibration's superscalar; the second is to choose the appropriate track vibration damping measures according to the vibration's superscalar, and the third is to maintain the safety, stability of train running, and vibration damping performance of track in a long term. According to Table 1, the above three aspects of jobs worked throughout the whole process of the design, construction, and operation of rail transit. A reasonable control system is needed to efficiently support the environmental vibration control of high-speed railway.

The design and construction stages of rail transit generally continue for four to six years, and the process needs the participation of many units such as management, design, construction, and manufacturing. Correspondingly, the participation of each unit in every period is different. The determination of the vibration-sensitive point and the prediction of the vibration superscalar are completed by the environmental impact assessment (EIA) specialty in the stage of the feasibility study of the rail transit project, and the cost of vibration damping measures is taken into the track construction cost. The EIA report must be submitted to the competent department of environmental protection for approval after being reviewed by

Table 1 Time sequence and implementation units of environmental vibration control

Design and construction units	Design unit							Construction unit		Manufacturing unit	
	EIA major	Driving major	Line major	Track major	Civil engineering major	Stray current protection	Relevant interfaces	Track laying	Civil construction	Core components manufacturing	Auxiliary components manufacturing
Engineering feasibility study	★	◆	◆	◆							
Preliminary design		◆	◆	★	◆	◆	◆				
Construction drawing design				★	◆	◆	◆	★	◆	★	★
Construction				◆							
Operation				◆				◆		◆	◆

★ High degree of participation; ◆ Low degree of participation experts. The EIA reports, appraisal opinions, and approval documents formed as the basis of the subsequent design phase.

In the preliminary design stage, the major track carries out the type selection design of vibration damping track and the second interface design according to the above research results. The possibility of line adjustment in the initial design stage can lead to the vibration superscalar changes of the environmental vibration-sensitive points. Generally, the track major is in charge of predicting the vibration superscalar according to the principles and prediction methods provided by the EIA report. In order to ensure that different specialties have the same prediction results for environmental vibration in different construction periods of rail transit, the prediction method must be unified, the evaluation scale must be clear, and the influence of the subjective factors must be eliminated as much as possible.

3 Research Status of Environmental Vibration Control of High-Speed Railway

Recently, the research on the environmental vibration control of high-speed railway is mainly focused on the law of vibration propagation, and the engineering application research vibration damping track is still in the exploratory stage.

3.1 Vibration Propagation Characteristics of High-Speed Railway

The theoretical research methods of environmental vibration propagation characteristics of high-speed railway can be divided into time-domain method and frequency-domain method [11–16]. The representation of time-domain method is a numerical simulation method based on the theory of vehicle-track coupling dynamics [13]. This method has developed rapidly in recent years, its main characteristics are: Through model expansion, the track foundation and the structures around the line can be considered together [16]. In the study of the influence of vibration on and structures, the dynamic influence factors of the main components of vehicles and all kinds of track structures can be taken into consideration by the dynamic interaction model of wheel and rail.

In China, a large number of field measurement studies have been carried out on the environmental vibration of high-speed railway. China Railway Corporation has issued guiding opinions on the value and governance principles of noise and vibration sources for environmental impact assessment of railway construction projects (revised 2010) basing on the field test results of Beijing–Tianjin, Shijiazhuang–Taiyuan, Wuhan–Guangzhou, Zhengzhou–Xian, and other high-speed railways. This document provides a prediction formula for environmental vibration similar to urban rail transit.

$$VL_z = \frac{1}{n}\sum_{i=1}^{n}\left(VL_{z0,i} + C_i\right)$$

$VL_{z0,i}$ is vibration source intensity, C_i is the vibration correction term, including velocity correction, axle load correction, line type correction, classification of the track, geological correction, distance adjustment, and building modification.

Unlike urban rail transit, the distance between vibration source reference point and the center line of the track is 30 m, and the vibration source intensity grade is decided by different speed levels and line conditions. According to the construction and operation experience of urban rail transit and high-speed railway, the above prediction formula is simple and easy to use by engineers. It can meet the needs of environmental vibration prediction of high-speed railway.

3.2 Engineering Application of Vibration Reduction Track in High-Speed Railway

The vibration damping track used in high-speed railway is mainly used to reduce the dynamic influence on the track foundation. To prevent the underwater tunnel soft soil liquefaction risk, The Guangzhou–Shenzhen–Hong Kong high-speed railway has adopted vibration-reducing slab track in the Lion Ocean large section tunnel. In order to adapt to the stiffness difference between the subgrade and the bridge foundation, the elastic mattress is used at the bottom of the track at the second double line of Lanzhou to Xinjiang.

In recent years, some application research of vibration reduction track has been carried out in national railways with higher speed. For example, the Chengguan express railway line has tried to lay an elastic mattress in the speed range below 80 km/h. “Engineering research of unballasted track vibration and noise-reducing engineering in environmentally sensitive areas” is being studied as one of the fifteen engineering test projects of Chengdu–Lanzhou railway. The Guangzhou–Foshan Loop and the Guangzhou–Zhuhai line underpass the Foshan Museum, and relevant departments have carried out special research on environmental vibration problems.

It can be seen that the prediction mode of environmental vibration of high-speed railway has been formed, but the research on vibration damping track is not sufficient, and the relationship between the vibration prediction and the application of vibration reduction track has not been established. After the vibration damping track is adopted, the influence on the running stability of train and maintenance of track during the long-term operation is not clear. There is an urgent need to carry out research on the formation of a high-speed railway environmental vibration control system.

4 The Key Technical Issues of High-Speed Railway Environmental Vibration Control

The construction of a high-speed railway environmental vibration control system may reference urban rail transit experience. Based on the mature experience of vibration damping track in urban rail transit, and combining the operation speed, vehicle characteristics and track foundation structures of the high-speed railway, the key dynamic parameters of vibration damping track should be studied, grade vibration damping strategy is established, and the principle of classifying vibration damping track is determined.

4.1 The Availability of the Existing Typical Vibration Reduction Tracks

In view of the fact that the vibration damping track has been widely used in urban rail transit, the usability of the existing typical vibration damping track in high-speed railway should first be studied theoretically to provide theoretical support for the engineering test study.

The typical vibration reduction measures which are representative and have good comprehensive performance in urban rail transit are selected as the research object among the fastener vibration reduction measures, sleeper vibration reduction measures and track bed vibration reduction measures. The study should be carried out by combining theory with engineering test, and the theoretical study should precede the engineering test study. The dynamic calculation model established by theoretical analysis should be able to reflect the dynamic interaction between the vehicle and the track system and the characteristics of vibration propagating through the track to the periphery of the line. The vehicle dynamic response, track dynamic response, and vibration damping effect corresponding to typical vibration damping track and the common track should be comprehensively compared and analyzed. The influence of the existing vibration damping track on the dynamic response of the vehicle and track system when it is used in high-speed railway should be studied clearly. The quantitative evaluation results of the availability of the existing typical vibration damping track could be given.

4.2 Value Range of Key Dynamic Parameters of Vibration Damping Tracks

Since the vibration source intensity of environmental vibration prediction formula of the high-speed railway is based on different speed grade and line condition, the value of the key dynamic parameters of the vibration damping track should also be studied according to different speed grade and line condition, so that a corresponding relationship is established between the reasonable range of key dynamic parameters of the vibration damping track and the prediction results of environmental vibration.

According to the application and research experience of urban rail transit, the following key parameters should be studied in depth. For fastener vibration reduction measures, the key dynamic parameters are node stiffness and damping. For sleeper vibration reduction measures, the key dynamic parameters are sleeper mass, the stiffness, and damping of the sleeper support pad. For track bed vibration reduction measures, the key dynamic parameters are the mass of track bed, the stiffness, and the damping under the track bed. Figure 1 shows the influences of the dynamic parameters of the vibration track in urban rail transit.

The mass unit of the sleeper damping track is the sleeper mass. As for the track bed damping measures, the mass units are track bed. The influence trend of the mass units on the vibration damping effect and stability of train-track system should be studied, and the reasonable value range is determined according to the

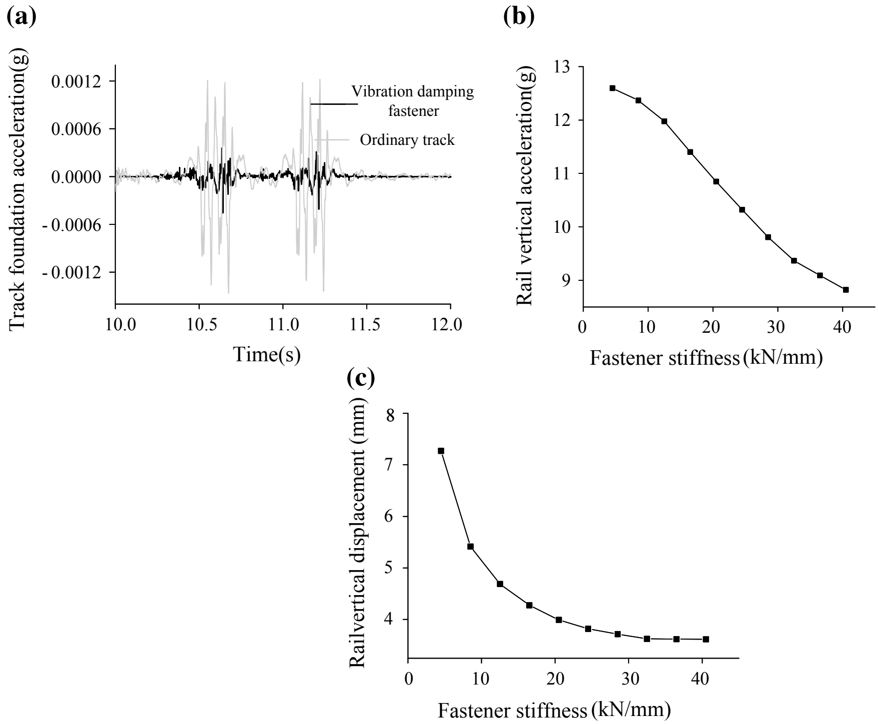

Fig. 1 Influence of the key dynamic parameters of the vibration damping track: **a** comparison of acceleration; **b** rail acceleration trend; and **c** rail displacement trend

characteristics of different rail foundations. Similarly, the reasonable value ranges of stiffness and damping of the vibration damping tracks could be determined according to different train speeds.

4.3 Graded Vibration Damping and Performance Classify

Urban rail transit generally divides the vibration damping track into three grades according to the vibration damping capacity. Usually, damping requirements below 5 dB are called mid-level, damping requirements within the scope of 5–10 dB are called high level, damping requirements more than 10 dB is called special level; mid-level measures mainly refer to the vibration damping fasteners. The high-grade measures mainly include elastic sleepers. The track bed vibration damping measures such as steel spring floating slabs are generally are the representative of special level. Whether the classification principle of vibration damping measures established by urban rail transit is applicable to high-speed railway needs further study. The main factors to be considered in the study include the type of vibration damping track, train running speed, required vibration damping capacity, and the maintenance mechanism of high-speed railway.

Therefore, we can draw from the experience of urban rail transit on the basis of the research on the availability of vibration damping track and the key dynamic parameters of the track, then putting forward the classification strategy of high-speed railway vibration reduction track and defining the principle of reasonable vibration damping level classification and the specific vibration damping track measures at all levels. The above is the foundation of establishing environment vibration control system for high-speed railway.

4.4 Research Strategy of High-Speed Railway Environment Vibration Control System

The research on the availability of the typical vibration damping track in high-speed railway and the key dynamic parameters of the vibration damping track is the basis of formulating the classification principle of the classified vibration damping strategy. In order to ensure the reliability and usability of the above research results, the two key scientific problems must be solved.

The first is to comprehensively consider the dynamic response evaluation index of the vehicle system, track system, and the vibration damping effect and to carry out the multi-index comprehensive evaluation. The theoretical model needed to be established for the calculation of dynamic evaluation index is huge and has many factors to consider. Different indexes in the dynamic response evaluation system have different sensitivities to various kinds of excitations. The trend of growth and decline of some indicators is even diametrically opposite, as shown in Fig. 2. On the same issue, using different evaluation indicators may lead to diametrically opposite conclusions. Therefore, a reasonable multi-index evaluation method should be selected for comprehensive evaluation [17].

The second is the close connection between theoretical calculation and engineering application. It means a unified model and evaluation scale are adopted to systematically study the availability and key dynamic parameters of the typical vibration absorption track. It means a unified model and evaluation scale are adopted to systematically study the availability and key dynamic parameters of the vibration damping track. At present, there is a lack of a unified evaluation scale in the study of the value range of key dynamic parameters of high-speed railway vibration damping tracks and the analysis of stiffness transition between different track structures. It is difficult to obtain measured data to compare the response of deterministic irregularity excitation. However, the corresponding evaluation scale can be obtained through dynamic calculation according to the rules and standards for deterministic irregularity excitation. That is to say, parameter analysis and comprehensive evaluation are carried out under the principle of dynamic response equivalence. Based on the above analysis, a theoretical research mode of an environmental vibration control system for the high-speed railway is put forward in this paper, as shown in Fig. 2.

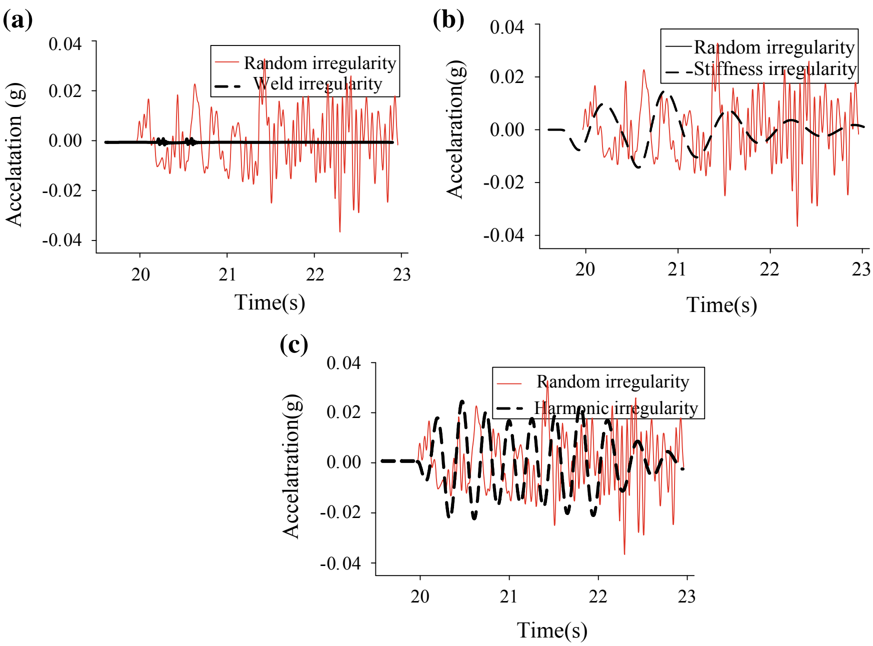

Fig. 2 Vehicle dynamic response corresponding to track irregularities: **a** corresponds to weld irregularity; **b** corresponds to stiffness irregularity; and **c** corresponds to harmonic irregularity

Firstly, the mature and reliable theory is adopted to establish a complete theoretical calculation model for the interaction of vehicles, tracks, and foundations. The model is used to calculate the evaluation parameters, including the running quality of the vehicle system, the interaction between train and track, the stability of the track system, vibration propagation, and damping effect. The calculated evaluation parameters can be compared with the commercial software and the measured data of urban rail transit and high-speed railway to ensure the reliability of the calculation results.

The interaction between vehicle and track is caused by the irregularities between wheels and rails. Although the dynamic response of the vehicle and track system caused by the single deterministic irregularity is difficult to be obtained through the field measurement, it can be accurately calculated by the dynamic model. In the design, acceptance and operation specifications and standards of urban rail transit and high-speed railway, there are clear limits for certain geometric irregularities such as weld irregularities and harmonic irregularities. Therefore, the irregularities between wheels and rails used in the dynamic calculation model can be determined depending on the engineering specifications.

In order to construct a multi-index comprehensive evaluation method, using the above dynamic calculation model, the evaluation scale and evaluation object is determined by calculation. The multi-index comprehensive evaluation method based on gray theory can give a quantitative evaluation of the availability of existing typical vibration damping tracks in high-speed railways. It is also possible to determine the reasonable range of key dynamic parameters of high-speed railway vibration damping track. Then, combined with the experience of an urban railway and the test results of high-speed railway, the classified vibration damping strategy of the high-speed railway can be determined (Fig. 3).

The above research method is characterized in that the evaluation index calculation and evaluation process are based on the same model and the same evaluation scale, which can eliminate process errors.

The wheel–rail irregularity originates from the engineering standards. The theoretical model is verified by engineering measured data. The formulation of the grading vibration damping strategy takes into account the experience of the urban railway and the test results of high-speed railway vibration damping track. Through the above steps, the theoretical research process and engineering practice are closely combined to ensure the reliability and usability of the research conclusions.

5 The Property Maintenance of the Vibration Damping Track

Under the long-term loading, the components of the vibration damping track will gradually age, and the damping capacity will recede. The daily inspection of the railway maintenance department can hardly find the performance change of the

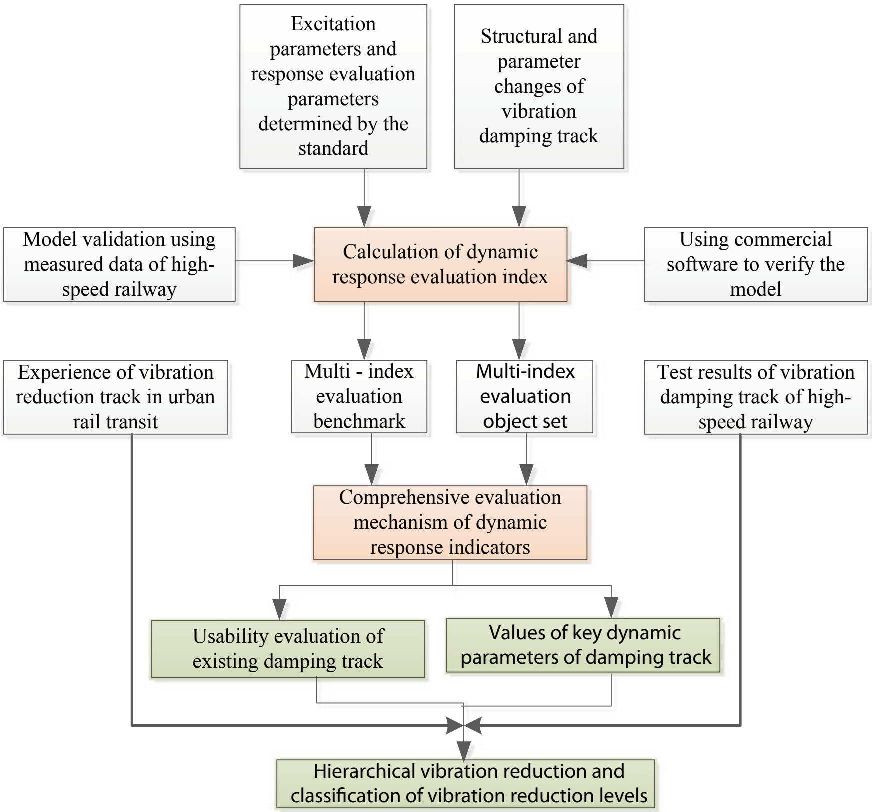

Fig. 3 Research model of key issues in high-speed railway environment vibration control system

vibration damping track. When the vibration reduction capability reduced to a certain degree, the vibration of the sensitive points will exceed the standard and cause the complaint event. In recent years, there are more and more complaints caused by environmental vibration around urban rail transit.

The railway maintenance department will investigate the performance attenuation of the vibration damping track after receiving the complaint report. It is usually to replace vibration absorber parts or upgrade vibration damping measures to solve the problem of excessive vibration at sensitive points. The above method of resolving vibration complaints is a passive process, as shown in Fig. 4. Although the complaint of over vibration can be solved, the vibration may have caused

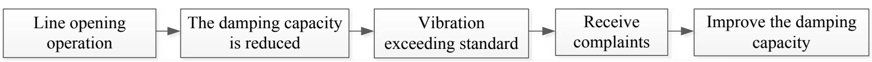

Fig. 4 Passive upgrade process of vibration damping track

damage or loss to vibration-sensitive points and it affects the reputation of rail transit. Therefore, the damping effect of vibration mitigation measures should have a certain amount of redundancy when selecting the type of vibration damping track. Generally, it can be considered about 3 dB in urban rail transit.

For the large-scale applications of vibration damping track in urban rail transit, the dynamic problems have also aroused widespread concern. Abnormal wave grinding, poor train running comfort and increased noise are common in vibration damping track areas. Compared with the urban rail transit, the trains in high-speed railway have larger axle loads and higher speed. Thus, in order to avoid the above problems of vibration damping track in long-term service, the experience of urban rail transit should be used for reference to research the environment vibration control system in high-speed railway. Of course, the high-speed railway engineering test results of the vibration reduction track are also of the important reference value.

6 Conclusion

For the environment vibration control, the characteristics are summarized in rail traffic and the research status is presented in high-speed railway. Thus, the key points and research models of establishing environment vibration control system in high-speed railway is put forward.

The environment vibration control of high-speed railway is a systematic project. Based on a large number of on-site tester search, simple and feasible prediction formulas have been established. However, the application of vibration damping tracks in high-speed railway is still in an exploratory stage. The establishment of environment vibration control system needs to be studied. In the vibration control system of high-speed railway, the key issues are that the study of the availability of existing typical vibration damping track seeks the reasonable value range of key important dynamical parameters of the damping track and formulates the strategies and the classification principle of graded vibration reduction.

The research method of the environmental vibration control system in high-speed railway is constructed in this paper. The dynamic response of train and track systems, the dynamic response of foundations, and structures can be considered comprehensively. The multi-index comprehensive evaluation method should be considered in future dynamic response research. The quantitative analysis of the availability and key dynamics parameters of the typical vibration reduction track can be carried out based on a unified model and evaluation scale.

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