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DESIGN OF HIGHWAY PAVEMENT EARTHQUAKE DAMAGE PREDICTION METHOD CONSIDERING HORIZONTAL EARTHQUAKE FORCE

Diseño de un método de predicción para el daño del pavimento de carreteras por terremotos considerando la fuerza sísmica horizontal

Junlong PENG*

School of Traffic & Transportation Engineering, Changsha University of Science & Technology, Changsha 410114, China.

* pengjunlong2020@163.com

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Key words: Horizontal seismic force, seism prediction method, highway tunnels, power polynomial prediction.

ABSTRACT

Due to the influence of geographical environment and horizontal seismic force, it is difficult to predict the seismic damage of urban highway pavement. In addition, poor engineering characteristics will cause damage to the stability of the subgrade and extremely easy to deformation. The above situation has become an important problem in highway construction. To improve the accuracy of earthquake damage prediction of highway pavement, a method of earthquake damage prediction considering horizontal seismic force is proposed. This method is based on the fuzzy comprehensive evaluation, taking the highway bridge, subgrade and pavement, roadside environment and highway tunnel as the main factors, and establishing the post-earthquake damage evaluation model of the highway system. Based on the analysis of the relevant data, the power polynomial prediction model is proposed, and the feasibility and parameter determination method of the power polynomial are analyzed. The stability of highway pavement under earthquake is predicted. The results show that the design method can predict the seismic damage of highway pavement. In addition, the proposed surface model can also simulate the settlement value and predict the settlement law.

Palabras clave: fuerza sísmica horizontal, métodos de predicción de sismos, túneles en carreteras, predicción de polinomio de potencia.

RESUMEN

Debido a la influencia del entorno geográfico y la fuerza sísmica horizontal, es difícil predecir los daños sísmicos del pavimento de las carreteras urbanas. Además, las malas características de ingeniería dañarán la estabilidad de la subrasante y serán extremadamente fáciles de deformar. La situación anterior se ha convertido en un problema importante en la construcción de carreteras. Para mejorar la precisión de la predicción de daños sísmicos en el pavimento de carreteras, se propone un método de predicción de daños sísmicos considerando la fuerza sísmica horizontal. Este método se basa en la evaluación global difusa, tomando como factores principales el puente de la autopista, la subzona y el pavimento, el entorno de la carretera y el túnel de la carretera, y estableciendo el modelo de evaluación de daños post-terremoto del sistema de carreteras. Sobre la base del análisis de los datos pertinentes, se propone el modelo de predicción del polinomio de potencia y se analiza la viabilidad y el método de determinación de parámetros del polinomio de potencia. Se predice la estabilidad del pavimento de carreteras bajo terremoto. Los resultados muestran que el método de diseño puede predecir el daño sísmico del pavimento de carreteras. Además, el modelo de superficie propuesto también puede simular el valor de asentamiento y predecir la ley de asentamiento.

INTRODUCTION

With the deepening of the cause of socialist construction, the active fiscal policy of expanding domestic demand has been implemented worldwide. Especially in response to the global financial crisis, the intensity of infrastructure investment is increasing. The national economy has entered a period of rapid development. The economic cooperation and traffic volume between regions are increasingly close, and general low-grade highways cannot meet the requirements. Therefore, highway construction has become an urgent need for economic development (Jacobo et al. 2018). Highway construction has developed rapidly in this environment, and has gradually become an important aspect in the field of civil engineering construction.

Weiland and Muench (2018) proposed the life-cycle prediction of the Seattle Interstate Highway pavement reconstruction plan. Based on the life cycle assessment method, the Seattle experiment compared the use of life cycle schemes of Portland cement concrete pavement based on aging. They removed the aged pavement and replaced with Portland cement concrete (PCC) pavement; dismantled the aged pavement and replaced with hot-mix asphalt mixture pavement (HMA); chiseled and fixed the existing pavement and lay HMA overlay. Each project investigated in California included a detailed construction and repair plan, which had been analyzed within 50 years. The results showed that material production dominates energy use, emission and impact. Eul-Bum et al. (2018) proposed expressway longevity accelerated pavement of expressways, and the restoration of urban roads was a key problem faced by California department of transportation. This research introduced the innovative road repair technology proposed for the long-life road repair strategy project in the first asphalt concrete project. During the eight 55-hour weekend closures in Long Beach I-710, the previous section of 4.4 km of degraded concrete pavement was successfully repaired, using 230 mm thick asphalt concrete (AC) Overlay or 325 mm full Depth AC Replacement Layer. Pilot project proved that 55 hours of closure over the weekend reduced the overall construction time and mitigate the negative impact of construction in urban areas.

This paper proposed the impact assessment of highway pavement condition sampling on life cycle prediction management (Mishalani and Gong 2018). The experiment developed a new prediction method and applied it to a practical example facility. This method compared the decision-making framework that reflected the progress of interests with the decision-making framework that did not reflect the progress of interests (Lal et al. 2020). The basic idea of comparing the two frameworks was to generate the optimal strategy based on the specific assumptions they reflect. Then, these optimal strategies were simulated within the framework to reflect the truth of obtaining the closest realistic hypothesis (Zuo et al. 2020). The result of the evaluation method showed that the value of conditional sampling interest prepayment was considerable in the expected life cycle cost and agency cost.

Although some progress has been made in the above research, the geological and geomorphological conditions are complex and diverse (Osorio Rodriguez and Alberto Sanchez Quinonez 2018). A large number of high-grade highways are easily affected by horizontal seismic forces, and the geological conditions in soft soil areas are extremely complex. Therefore, based on the fuzzy comprehensive evaluation method, taking the highway bridge, subgrade and pavement, roadside environment and highway tunnel as the main factors, the experiment established the post-earthquake damage evaluation model of the highway system. Based on the analysis of relevant data, the power polynomial prediction model is proposed experimentally. The feasibility and parameter determination method of power polynomial are analyzed, and the stability prediction of seismic damage of highway pavement is realized. The experiment aims to provide help for accurately predicting earthquake damage.

BUILDING A MULTI-LEVEL COMPREHENSIVE EVALUATION MODEL OF EXPRESSWAY PAVEMENT

After an earthquake, the road leading to the earthquake area will be damaged to varying degrees and affect the transport capacity of the traffic line (Priddy et al. 2018). Therefore, it is required to evaluate the damage and transportation function of each section of the traffic line when studying the transportation problems after the earthquake (Lu et al. 2019). Considering that there are many factors affecting the transportation function of highway pavement, and the damage of highway pavement should be described by multiple states, it is vital to comprehensively analyze the multiple factors affecting the transportation function of highway pavement, so as to reasonably evaluate its function (Barkat et al. 2018, Corley-Lay 2018). The comprehensive evaluation model of highway pavement damage is applied to judge the state of highway pavement after earthquake, and a fuzzy number called damage index is used to describe the damage situation of road sections to evaluate the impact on its transportation ring (Tohver et al. 2018).

Set factor set and weight fuzzy set

Horizontal seismic force is the basic basis of seismic design of highway pavement as well as the premise of the perfect coordination effect of safety and economy in structural seismic design (Ghasemi et al. 2022). According to the principles of highway seismic dynamics and seismic engineering, it is one of the major problems faced by designers to determine the seismic action of highway according to many factors such as actual earthquake, geological conditions, site and structure (Chen et al., 2018). Statistical analysis shows that the damage of a section of the transportation system after the earthquake is mainly manifested as road damage (U1), roadbed and pavement damage (U2), roadside environmental damage to the road surface (U3), road tunnel damage (U4). Therefore, the factor sets of four main elements can be established in the comprehensive evaluation model of highway pavement damage:

$$U = \{U_1, U_2, U_3, U_4\} \tag{1}$$

The corresponding weight index set:

$$A = \{a_1, a_2, a_3, a_4\} \tag{2}$$

Factor U also contains sub-factors, namely:

$$U_i = \{u_1, u_2, u_3, u_4\} \tag{3}$$

The corresponding secondary weight index set should be established:

$$A_i = \{a_1^i, a_2^i, a_3^i, a_4^i\} \tag{4}$$

Dividing the evaluation set and evaluation matrix

For example, the damage degree of the earthquake to the highway surface is generally divided into: destruction (recorded as V_1), that is, the traffic line is completely blocked, which cannot be repaired and used in a short time; serious damage (recorded as V_2), the main structure is seriously damaged, which cannot be repaired and used in a short time; moderate damage (recorded as V_3), the structure is only partially damaged or damaged, and can be completely repaired in a short period of time; mild damage (recorded as V_4), the structure is not damaged, but part of the road is damaged, the carrying capacity has been reduced; basically intact (recorded as V_5), which has little impact on the carrying capacity of 5 states (Ward 2002). In the comprehensive evaluation model of road damage, the post-earthquake evaluation set of road function can be set as:

$$V = \{V_1, V_2, V_3, V_4, V_5\} \tag{5}$$

The average earthquake damage index in the Chinese earthquake intensity table is divided into the above five states. The number of evaluation sets can be expressed by taking its average value:

$$V_n = \{0.85, 0.6, 0.4, 0.2, 0.05\} \tag{6}$$

If r_{ij} is set, it means factor U_i, and the state is about the degree of membership of V_i, then $r_i = r_1$, r_2,···, r_5) is the first factor U_i the single factor evaluation matrix of the first factor, and it is a fuzzy subset of V weighed matrix:

$$R = (r_{ij})_{4\times5} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{15} \\ r_{21} & r_{22} & \cdots & r_{25} \\ \vdots & \vdots & \ddots & \vdots \\ r_{41} & r_{42} & \cdots & r_{45} \end{bmatrix} \tag{7}$$

Evaluating the damage degree of highway pavement

In the time history analysis of horizontal seismic force response, for the structure that the stiffness center of highway pavement does not coincide with the mass center, the torsion of highway pavement structure caused by horizontal ground motion input should be considered. For some special highway pavement structures, especially those with uneven mass distribution and located near the epicenter area, the vertical ground movement should be considered (Zhang and Ali 2021). For longer road pavement structures, the ground effects along the different lengths of the road surface structure shall also be taken into account:

$$B = \{b_1, b_2, b_3, b_4, b_5\} = A \times R \tag{8}$$

Among them, if $b = a_i \times b_i$, the degree of damage to the road surface is in the state described in V_m, and $m \leq 2$, then it means that the road surface is seriously damaged and cannot be used for a short time (Schultz et al. 2018). Otherwise, the transportation function of the road surface shall be evaluated, for this reason, the elements of type (8) b shall be normalized, that is:

$$w_j = b_j \Big/ \sum_{i=1}^{5} b_i \left(j = 1, 2, \ldots 5 \right) \tag{9}$$

The weight matrix w = {w_1, w_2, w_3, w_4, w_5}, then

$$Q = w \times V \tag{10}$$

The fuzzy number Q, which denotes the highway pavement damage index, is used to evaluate the impact of earthquakes on its transportation function.

METHOD OF HIGHWAY PAVEMENT EARTHQUAKE DAMAGE PREDICTION

As stated by its application principle, foundation settlement prediction method can be roughly divided into two categories: One class is a pure theoretical calculation method based on soil consolidation compression principle; the other class is the settlement prediction method based on the measured settlement data. The pure theoretical calculation method can be divided into theoretical formula method and numerical analysis method. The prediction methods based on settlement data can be divided into dynamic and static prediction methods. **Figure 1** illustrates the specific classification. These two kinds of methods have their effectiveness and operability. These methods are of great significance to the solution of practical problems to different degrees.

Settlement prediction method based on measured data

A large quantity of uncertain factors exist in the subgrade settlement analysis, which often have a big influence on the calculation results of roadbed settlement. Due to the defects of settlement theory and the limitation of parameter selection, the results obtained by the settlement method based on the soil compression consolidation theory are often far from the measured settlement. Thus, based on the shape regularity of the measured settlement time curve in the project, a new settlement calculation based on settlement measured data is put forward (Lokke and Chopra, 2018). Its main idea is to use the settlement time curve to find the necessary parameters. To calculate the settlement, the advancement of later settlement by using the early settlement observation data of the project is predicted. Soil engineering is very complex. Due to the variety of soil, any kind of engineering property will change greatly in the state and external conditions (Allstadt et al. 2018). The consolidation and compression law of soil is quite complex, and its parameters are not easy to be accurately determined. Therefore, there are often some differences between the calculation results and the measured results of the project. How to use the measured settlement data to calculate the settlement is important and meaningful.

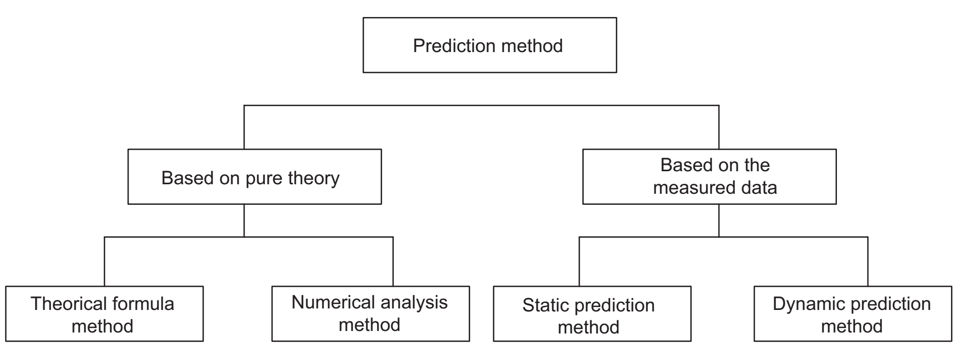

Fig. 1. Classification diagram of settlement prediction method.

Power polynomial based time prediction method

The original data processing system can continuously adjust according to the change trend of settlement observation data, and can also timely incorporate the data into the final settlement prediction (Mahootchi and Golmohammadi 2018). Although the dynamic method is more accurate, the static method is simple and easy to operate, so it is widely used. The power polynomial prediction method can analyze massive data. When there are many measured data, the higher the order of the polynomial is, the higher the prediction accuracy will be. The settlement observation data is extremely complex and rich. Applying this method to this field can improve the accuracy of settlement prediction. Therefore, this section introduces a new prediction model - power polynomial prediction method. The relationship curve of typical settlement time change is shown in **figure 2**.

From **figure 2**, the relationship curve between settlement s and time t is highly nonlinear. It is characterized by gradual increase of settlement in the later period. The settlement is slow, and gradually increases to a certain value of s^{-1}. The measured data shows that the settlement countdown a and time countdown t^{-1}. It is also a non-linear relationship. Therefore, simple linear fitting cannot be performed.

The relationship function of settlement s and time t should satisfy the following conditions: settlement and increase with time, and the growth rate gradually decreases and tends to a certain value.

Accordingly, the functional relationship between the reciprocal s^{-1} of settlement and the reciprocal of time t^{-1} should meet the following conditions: When t gradually increases, t^{-1} gradually decreases, s^{-1} decreases, deceleration gradually slows down and tends to a certain value. Then s increases, and the growth rate gradually slows down as well as tends to a certain value.

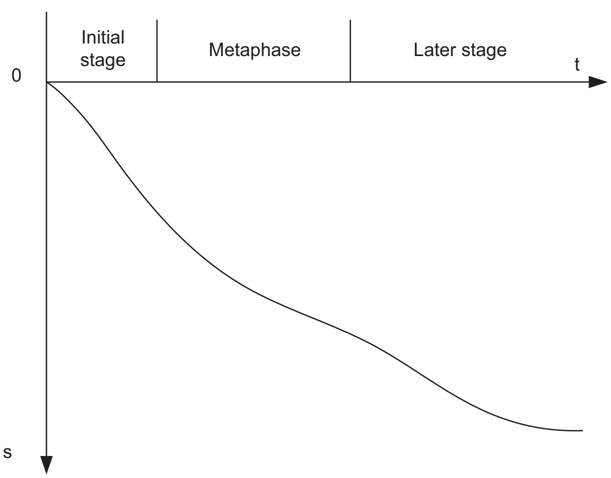

Fig. 2. Settlement - time curve.

The prediction period of power polynomial should be limited by a prediction time. Currently, the prediction of the next 1-2 years indicates that the model is very accurate. While for the prediction of final settlement, the model can be further fitted according to the newly measured engineering data, so as to determine the final settlement. The prediction accuracy of 2-3 order is higher than that of the conventional method, and the prediction results meet the requirements of engineering and specifications. The measured data of typical sections with stable load are selected for specific classification. The fitting parameters are calculated and the settlement of soft foundation is reasonably predicted.

PREDICTION OF HIGHWAY PAVEMENT STABILITY UNDER EARTHQUAKE DAMAGE

Classification of urban road slopes in mountainous areas

According to the geographical location of slope collapse and slide, it can be divided into three categories:

The first category: The landslide body is located above the road surface, which will produce a certain amount of earth and stone, resulting in traffic jams.

The second category: The landslide body is located below the road surface, which will reduce the width of the road surface and seriously affect the traffic of vehicles.

The third category: The road and slope collapse together, and the traffic is basically impassable.

The stability discrimination method of highway slope under earthquake can objectively and accurately predict the disaster area.

According to the prediction results, appropriate emergency plans can reduce casualties and economic losses. Quasi-static force can be used to predict seismic collapse and sliding of geotechnical slope (Kang et al. 2018). If each slope adopts quasi-static strip method for calculation, the required parameters are particularly much. For large area of slope earthquake damage prediction, the calculation amount is particularly large. However, earthquake-induced slope collapse often occurs in groups, with a large number and a wide distribution area. Therefore, the analysis method involves multiple parameters. The test calculation workload is large and the investment cost is high. Therefore, it cannot meet the needs of large-scale and multi-point prediction. Slope seismic collapse is restricted by many factors, including site geological unit structure, site topography and geomorphology, geotechnical material characteristics, atmospheric rainfall, etc. Many parameters are involved, and the workload of field investigation, indoor and outdoor experiments and calculation and analysis is large, which is tough to meet the needs of large-scale and multi-point prediction, and the cost of investment is also very high. Therefore, it is quite important to propose a classification and prediction method suitable for China's earthquake collapse from thick to thin according to the characteristics of earthquake collapse. The proposed method needs to meet the requirements of step by step identification of the large range and many seismic collapse problems of seismic collapse, so as to determine the slope that does not need further prediction and analysis. Next, a step-by-step forecast and analysis can be carried out (Li et al. 2015, Zhang et al. 2016, Azzam et al. 2018, Schultz et al. 2018, Ochoa Gutiérrez et al. 2019, Leventeli et al. 2020). This can not only meet the requirements of rapid prediction, but also save time and the cost of investigation, experiment and calculation, with greater economic and social benefits. Based on the statistical data of slope earthquake damage, the empirical formula of prediction is obtained. By comparing the calculation results of comprehensive indexes with the seismic damage performance of natural slopes in historical earthquakes, two enhanced comprehensive index methods for predicting seismic collapse and sliding of geotechnical slopes are put forward.

Selection of influence factors

The selection of influence factors should not only fully consider the main factors affecting earthquake collapse and slide, so as to ensure its scientific nature. Aside from that, it is also required to consider the commonly used quantity of the selected factors to ensure its practicality. According to the analysis of the existing results, the factors affecting earthquake collapse and sliding should be divided into internal factors and external factors.

The comprehensive index method considers geology as a factor. It is divided into two factors: 1) Geotechnical properties and structures, and 2) Neotectonics and geological structures. The former reflects the characteristics of the slope itself, while the latter reflects the regional structural conditions of the slope. They are both related and different, and can be classified in the same or different grades. The study considers the height and angle of slope as influencing factors.

Internal factors belong to the internal conditions of slope itself, which are easy to collapse and slide, and they are the necessary conditions for collapse and sliding. Thus, the geological and geomorphic conditions become the preferred factors. As for geological factors, they are divided into three contents, namely, 1) Geotechnical properties and structures, 2) New tectonic movements, 3) Geological structure.

External factors are all kinds of factors acting on the slope body, which promote the change of internal conditions, and are the sufficient conditions for the occurrence of collapse and sliding. Landslides do not have to meet all external conditions. Earthquake and rainfall are the two main external factors.

Selection of single factor index value

Before selecting the single factor index value, the factor should be graded. To ensure the rationality of grading and selected index values, the grading and assignment principles proposed on the basis of analyzing a large number of existing collapse data are classified and assigned to internal and external factors, as shown in **table I**.

From **table I**, it follows: (1) The geological conditions in **Table I** all contain two factor assignments. Single factor assignments are not meaningful. (2) The slippery strata in **table I** refer to broken, settled sand, sheet, mudstone, plate, schist, coal measure strata, Sigeda Formation, Gonghe Formation, loess, etc. In addition, the study shows that in the inclined rock slope body, the up-slope accumulation layer or loose gravel soil also belongs to the slippery texture layer. (3) The macro survey shows that there is a significant difference in slope Angle generated by landslide and collapse. So there are two criteria, each divided into five levels, as shown in **table II**. (4) According to the intensity in the region, the classification and evaluation of earthquakes are divided into two different classification criteria. Namely (1, 2, 3, 4, 5), and (6, 7, 8, 9, 10), so as to obtain the impact of the difference between the two kinds of evaluation on the calculation results.

EXPERIMENTAL RESULTS

To improve the prediction accuracy of expressway pavement earthquake damage, the classification results of sandy interlayer are obtained based on the relationship coefficient between settlement after construction and filling height. The relationship curve between settlement and time and the filling

TABLE I. CLASSIFICATION AND ASSIGNMENT OF MAIN INFLUENCE FACTORS OF EARTHQUAKE LANDSLIDES.

Geological conditions	Classification of influence degree	Single factor assignment	Two factor assignment	
		S_1	S_{21}	S_{22}
The rock is hard and the structure is complete.	Low	1	1	-
The neotectonic movement is weak, there is no earthquake with m ≥ 6, only a few small faults.			-	2
The rock is hard and the structure is complete.	Lower	2	2	-
The neotectonic movement is not strong, there have been earthquakes with m ≥ 6 and only small faults.			-	2
The rock is broken and the structure is incomplete.	Middle	3	3	-
The neotectonic movement is relatively strong, there have been earthquakes with m ≥ 6 and main faults.			-	3
Broken rock and incomplete soil mass	High	4	4	-
The fault zone is more intense than M 7, and large faults occurred			-	4
The rock is especially broken, the weak structural plane is developed, the rock and soil are particularly incomplete, and there are slippery strata.	Very high	5	5	-
The neotectonic movement is especially strong, and there have been many earthquakes with m ≥ 7, huge fault zone, fault concentrated zone and fault composite zone.			-	5

TABLE II. CRITERIA FOR SLOPE ANGLE IMPACT CLASSIFICATION.

Slope angle (°)		Classification of influence degree	Assignment
Landslide	Collapse		
≤10	≤30	Low	1
11-20	31-40	Lower	2
21-30	41-50	Middle	3
31-40	51-60	High	4
>40	>60	Very high	5

height and time is applied to the expressway slope to predict the seismic failure of the slope. The control precision of the control system is analyzed, and the test results demonstrates that the method presented in this paper has some advantages in predicting earthquake damage of expressway pavement. Experiment date: September 1, 2021. Laboratory address: School of Traffic & Transportation Engineering, Changsha University of Science & Technology Laboratory.

Taking an expressway as an example, the total length of the highway is 48 km. The design adopts closed four lanes. The driving speed is 120 km/h. The regional landform is mainly alluvial plain and plain micro-mound, along which there is a large number of discontinuous distributions of soft soil. The soft soil section is about 22 km, accounting for about 46% of the whole line. Its characteristic is that it not only has the characteristics of typical soft soil with high water content, high compressibility and low intensity, but also owns the characteristics of high organic matter content. In terms of spatial distribution, soft soil owns the characteristics of discontinuity and large thickness difference. These characteristics of soft soil layer determine that the sub-consolidation settlement of the soft foundation section of the expressway is relatively large, and the settlement difference of some sections is obvious, which is directly reflected in the large post-construction settlement of some sections. Further understanding the development law of earthquake damage prediction of highway pavement under the action of horizontal seismic force is beneficial to judge whether the deformation of highway pavement is stable. To provide a basis for the pavement and maintenance of the permanent pavement, the earthquake damage of the soft foundation section of the expressway is predicted by the experiment.

In the construction process of the expressway, the higher the height of filling soft soil, the higher the thickness of subgrade compression layer, and the greater the settlement of soft soil during compression. **Table III** clearly points out the various coefficient relations between post-construction settlement and soft soil thickness and filling height.

From **table III**, in each layer filling section, the coefficient relationship between settlement and soil layer thickness is higher than that between settlement and fill height. At the initial stage of loading, due to the increase of load rate, the filling rate of soil layer is too large, and the water in the pores of soil layer cannot be squeezed out in time, so the settlement of soil layer is small. However, in this case, lateral deformation is easy to occur, and the settlement of the soil layer increases rapidly after being loaded. On the contrary, if the filling speed of the soil layer is relatively slow, the pore water in the soft soil subgrade will be discharged slowly, and the water pressure in the pore will be converted into the force inside the soil layer. Under the action of this effect force, the lateral deformation in the settlement process is gradually reduced. Therefore, the settlement amount and settlement rate of soft soil roadbed are also reduced. If the settlement of the soil layer increases instantaneously during the increase of load, it is likely that the roadbed has serious plastic deformation.

TABLE III. LIST OF COEFFICIENTS OF RELATION BETWEEN POST-CONSTRUCTION SETTLEMENT AND FILLING HEIGHT.

Correlation coefficient	Filling height		
	3m section	4m section	5m section
Post construction settlement and soft soil thickness	0.9137	0.75580	0.8500
Post construction settlement and fill thickness	0.4182	0.0932	0.3706

To analyze the influence of the sand layer in the roadbed on the consolidation degree of soft soil, the static cone penetration test distribution curve of pore pressure was studied and analyzed in detail. Different sand layers are classified. There are five different sand layers according to the different amount of sand. The experiment is divided according to the cone tip resistance, cantilever pressure and sand layer thickness of each sand layer. The weight of different factors is 100. See **table IV** and **table V** for details

TABLE IV. GRADING TABLE OF SAND INTERLAYER.

Weight	<20	20-40	40-60	60-80	80-100
Grade	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5

According to **Table V**, the sand layer in the high-speed subgrade has a direct impact on the consolidation of soft soil. For the left section and middle section of K28 + 860 section, both are new sections within the same time, and the thickness of soft soil silt is the same. However, the sand gradation in the left end face of K28 + 860 is lower than that of the middle section. Thus, the settlement of this section is relatively large after construction, which is mainly because the seepage performance of the sand layer is greater than that of the soft soil layer. The sand layer in the soil layer is combined with the sand well drainage system, which effectively improves the consolidation degree and efficiency of the soft soil layer. Meanwhile, due to the large preloading load of the roadbed at the initial stage, the settlement of the sand layer after construction is less.

When the silt thickness in the local lower soil layer is higher than 20 m, the sandy layer has little impact on the settlement after construction. Due to the excessive silt thickness in the soft soil layer, even if the grade of the sandy layer is higher, it will not have a great impact on the settlement phenomenon in the later period. For example, in the left section of K32 + 290 and the right section of K36 + 650, the distribution of soft soil silt in these two sections is large, about 36.5 m and 40 m respectively, and the post-construction settlement of these two places has reached more than 100 mm. However, in this kind of soil layer with large silt thickness, there is a positive impact on the settlement of the later period. Among the above two sections, the sand gradation grade of the former is relatively high, so the settlement after construction is relatively small.

There is a positive correlation between the surface settlement of soft soil subgrade and pavement load. There is also a positive correlation between the settlement rate of soft soil layer subgrade and pavement load. During road construction, no matter the settlement rate or settlement amount of the roadbed, the response to the load is very strong. When the

TABLE V. RESULTS OF GRADE DIVISION OF SAND INTERLAYER IN EACH SECTION.

Name	K28+410 Right	K28+860 Left	K28+860 Middle	K29+075 Left
Silt thickness (m)	13	16.5	16.5	7.8
Sand interlayer grade	Grade 1	Grade 2	Grade 3	Grade 4
Filling height (m)	5.110	3.345	3.728	6.159
Post construction settlement	26.5	43.85	26.89	12.52
Name	K32+290 Left	K36+650 Right	K36+724 Left	K36+970 Right
Silt thickness (m)	36.5	40	25	20
Sand interlayer grade	Grade 5	Grade 3	Grade 3	Grade 3
Filling height (m)	5.586	4.607	5.113	5.974
Post construction settlement	104.33	146.97	166.9	141.53

pavement load increases, the settlement of soft soil subgrade will increase, the curve in the figure will gradually steepen as well. When the subgrade load increases to a certain extent, the settlement curve of the roadbed will gradually become stable. Correspondingly, the settlement rate changes, and the settlement rate increases first and then decreases, during embankment filling.

There is a critical paving height value, the total settlement of the roadbed has a turning point. When the filling height of the soft soil layer of the subgrade is less than this value, the settlement rate of the subgrade will be further reduced. When the paving height exceeds this value, the settlement rate of embankment will continue to increase. In serious cases, the subgrade will lose its due stability.

Figure 3 shows the relationship between filling and settlement of K36+030 section of expressway within one year. There is a positive correlation between subgrade settlement and pavement load, which can be analyzed and elaborated by Terzaghi (Ding C. et al, 2020). The saturated clay layer gradually drains the water in the pores under the pressure of load, so that the strength of the layer is enhanced and consolidation deformation occurs. During consolidation under load, not only the pore ratio in the soil layer is effectively reduced, but also the shear strength of the soil layer is effectively enhanced.

From **figure 4**, the larger the load on the highway subgrade, the greater the settlement rate of the soil layer. This is consistent with the relationship between settlement and load. Meanwhile, **figure 4** demonstrates that the settlement rate of the soft soil bed responds positively to the load. During the loading period, the settlement rate of the surface soil layer continues to increase. However, when the load on the pavement stops increasing, the settlement rate of the roadbed gradually decreases. This is mainly caused by the consolidation and lateral deformation of the roadbed during the loading period. However, when the load is applied to the subgrade, the lateral deformation of the subgrade will occur. At the initial stage of subgrade loading, the water and pore water in the soil layer cannot be discharged in time. Under the action of compressive stress, the soil layer undergoes lateral shear deformation.

In this stage, the settlement of the soil layer increases in linear form. With the continuous increase of load time, the water between the pores in the

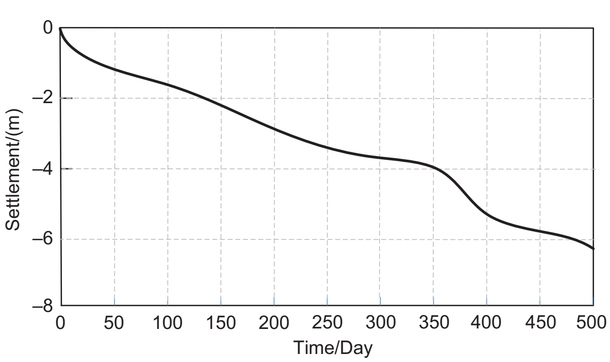

Fig. 3. Relation curve between settlement and time.

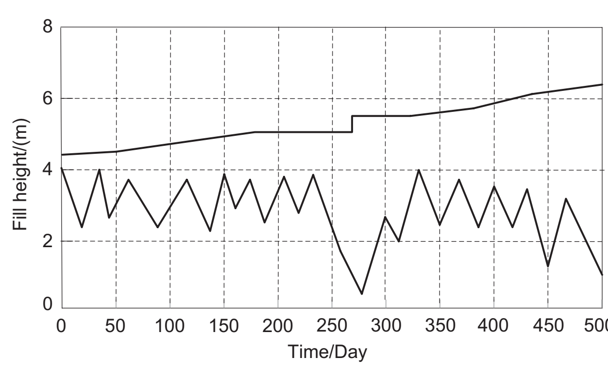

Fig. 4. Relation curve between filling height and time.

TABLE VI. SEISMIC DAMAGE PREDICTION RESULTS OF SLOPE.

Section slope	6 degrees	7 degrees	8 degrees	Remarks
Left side slope of Xiatuwan road	Stable	Possible instability	Instability	Section 50
Right side slope of xiatuwan road	Stable	Stable	Stable	Section 49
Left side slope of Shixin road	Stable	Stable	Stable	Section 48
Right side slope of Shixin road	It may be stable	Instability	Instability	Section 35

soil layer is continuously squeezed out. Moreover, under the continuous load, the soil layer gradually becomes dense in the deformation, and then the consolidation phenomenon occurs. When the load stops increasing, the pore pressure in the consolidation state tends to close to zero. At this time, the consolidation of the soil is not mature. The settlement of the subgrade is still gradually increased under the action of time, but the relative settlement rate has tended to be stable.

To verify the effectiveness of highway pavement earthquake damage prediction method considering horizontal earthquake force, Shixin road slope and Xiatuwan slope were selected as experimental objects to predict the earthquake damage results of slope. The actual situation diagram of highway slope is shown in **Figure 5**. The basic conditions of several slopes are:

Shixin road slope, the slope is located in the section from Shiqiao to Xinqiao. It is a rock slope with relatively hard rock and the structure is relatively complete. The slope height is 30 m and the slope angle is $\beta = 82^{o}$.

Xiatuwan roadside slope, which is located on Xiatuwan section. The top of the slope is rock, the slope body is shale. The rock is locally prominent. The soil is seriously weathered, layered and incomplete in structure. There are many vegetation on the mountain, with a slope height of 80 m and a slope angle of nearly $\beta = 90^{o}$.

The annual rainfall in this area is 1000-1400 mm, without earthquakes of magnitude 6 or above. According to the analogy of seismic structure, the region is in a state of seismic activity. Thus, it can be considered that the near field area in this area has the tectonic background of moderate and strong earthquakes. In the experiment, the comprehensive index method is used to predict the seismic damage of each slope. Four index schemes are used to predict each slope. In terms of safety, the lower limit of four prediction results is taken. The forecast results are shown in **Table VI**.

From **table VI**, one side of such road section is a slope and the other side is a building; The building was pre-damaged in the seismic survey of highway slope. Once the instability is determined, the traffic probability of this section is 0. The number of debris blocked by houses can be used to determine the possibility of road passage. According to the seismic damage prediction results of the section slope in this area, it can be concluded that the slope is steep under different seismic intensities, and rock fragmentation is highly possible under the action of moderate and strong earthquake instability or possible instability.

To better prove the prediction effect of the design method in this paper, contrast it with comparison

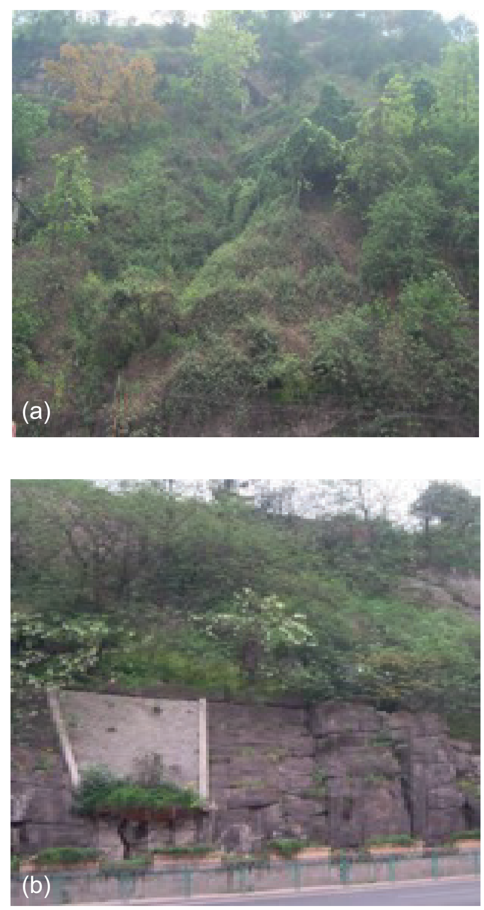

Fig. 5. The actual situation diagram of highway slope. (a) Hatu Wan roadside slope, (b) Shek sin road slope.

method 1 (Allstadt et al. 2018), comparison method 2 (Azzam et al. 2018) and comparison method 3 (Lokke and Chopra 2018), and get the settlement prediction accuracy of different methods, as shown in **figure 6**.

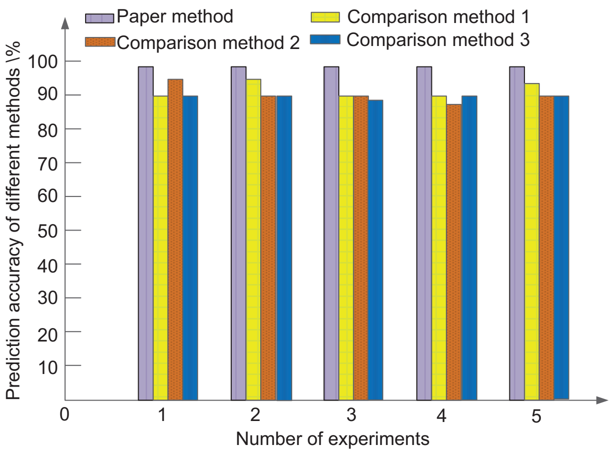

Fig. 6. Accuracy of comparison methods.

According to the analysis of **figure 6**, the settlement prediction accuracy of the design method is more than 90%. This is because this method proposes a power polynomial prediction model. The feasibility and parameters of power polynomial are determined, and the stability prediction of earthquake damage of expressway pavement under earthquake action is realized, with high prediction accuracy.

CONCLUSION AND PROSPECT

Conclusion

Highway pavement seismic damage is an extremely prominent problem. To improve the accuracy of highway pavement seismic damage prediction, this paper introduces the power polynomial into this field and proposes a highway pavement seismic damage prediction method considering horizontal seismic force. The specific contents are as follows:

1) The multi-level fuzzy comprehensive evaluation model of road damage is established, which gives a fuzzy evaluation of the damaged state of the traffic line after the earthquake. As the basic evaluation of the damage degree of the traffic lines after the earthquake, it provides an important reference for the selection of the transportation routes (or the calculation of the transportation volume) of the relief materials after the earthquake.
2) The earthquake damage prediction methods of highway pavement are mainly divided into pure theoretical settlement calculation methods based on the principle of soil consolidation and compression and settlement prediction methods based on measured data. Engineering practice shows that the latter method can more accurately determine the post-work. In addition, a new prediction method-power polynomial prediction method is proposed. This method can accurately predict the seismic damage of highway pavement, with an accuracy rate of more than 90%.
3) The long-term settlement is also the reason for the continuous settlement after the completion of the road. Road sinking after completion-downward pressure continues to occur. However, in the long period of use, the subsidence gradually tends to be stable. Different earthquakes have different effects on the stability of different slope strength.

Prospect

Complex geological conditions, vehicle load, soil disturbance and human factors will affect the observation results. Thus, the authenticity and representativeness of geological data and measured settlement data of highway surface earthquake will be also affected, and the accuracy of the prediction of road surface seismic damage will fluctuate with this. Meanwhile, the selection of prediction model also plays a key role in the prediction of highway pavement earthquake damage. According to the current research situation, the main problems to be solved are:

1) The prediction effect of power polynomials in practical engineering has been proved to some extent, however, its theory needs further argumentation and analysis. In this prediction, the settlement is simulated and predicted due to the small amount of simulation data.
2) There are many factors that are difficult to quantify in the earthquake damage prediction of expressway pavement and various influencing factors. When analyzing the influence factors, more attention should be PAID to the qualitative analysis, that is, the focus is the subgrade surface settlement and layered settlement. The influence of horizontal displacement and pore water pressure is not considered in this study, so it needs to be studied in the later stage effect of these factors on settlement.

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