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Vibrational diagnostics and physical modeling of subgrade at the railway line nearby White Sea for deregulation of train speed limit

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Abstract: The complex researches were carried out at the Russian North Railways on the routes of freight traffic, in direction of the embankments on weak (peaty and clayed) foundation. These complex researches included vibration diagnostics for prototypes, physical modeling, calculation of the deforming embankments and the variants of its reinforcing. Evaluation of efficiency of reinforcing of the peat foundation by wooden piles was provided by the centrifuge modeling. The results were compared with modeling embankments without reinforcing. Embankments on Obozerskaya-Malenga Line (northern part of Russia, Arhangelsk and Murmansk region) were taken as a prototype of the embankments. In MIIT (Moscow State Railway University), the numerical calculation methods of foundation stability, elastic settlement and final settlement are applied, and the influencing factors and coefficients of stability were determined by using special software. The results show that failure of embankments modeling without reinforcement in view of the bearing capacity which realized in the reduction of the embankment top, and displacements of the surcharge which fixed to the right side of the models. According to the base uplift of the foundation peat (for each side of the embankment model), the deformation tends to approach the slope of the embankment model, in which case the maximum settlement exceeds 15 mm. The further activities on the embankment: for the embankments where the unstable state is recorded on the basis of the main criterion, it is recommended to conduct a detailed survey and to make a project of reinforcing of the subgrade. 6 figs, 7 refs.

Key words: subgrade engineering; weak foundation; peat; physical modeling; vibrational diagnostic; stabilization

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白海附近解除火车限速的铁路路基振动诊断和物理建模

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摘 要:在俄罗斯北方铁路货运线路沿线路堤上开展了一系列针对软弱地基(泥炭土和黏土)的研究,包括原型振动诊断、物理建模以及计算路堤变形和加固类型变化等。利用离心模型试验对木桩

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加固泥炭土地基的性能进行了评价，并将其结果与未进行加固处理的路堤模型进行了对比。以 Obozerskaya-Malenga 线(俄罗斯北部阿尔汉格尔斯克和摩尔曼斯克地区)上的路堤作为路堤原型开展研究；在 MIIT 中，采用数值计算方法开展地基稳定性、弹性沉降、最终沉降分析，并采用专用软件确定路基稳定性的影响因素和系数。研究结果表明：未进行加固处理的路基建模失效是由路堤顶部承载能力的减小和固定在模型右侧超载的位移所导致的。根据泥炭土地基基础的隆起(路堤模型的每一侧)，其变形有接近路堤模型坡脚的变化趋势，在此情况下最大沉降量超过 15 mm。原型振动监测的结果决定了对路堤采取的进一步措施为：根据主要标准，对于其中被记录的非稳定状态路堤，建议进行详细的调查和路基加固工程。

关键词：路基工程；软弱地基；泥炭土；物理模型；振动诊断；稳定性

0 Introduction

At present time, the introduction of high speed train traffic is taking a part on Russian railways, especially in part of European countries (trunk line between Sankt Petersburg and Moscow, realized projects of the high speed moving between capital and Kazan). In this connection, the routes of freight traffic are changed, especially on Northern West of Russia and in connection of the development of the perspective project with state and non-state capital (BELCOMUR)—railway transport system between Ports Murmansk, Ust'-Luga, Arhangelsk and North-Ural part of Russia.

On the Line from Moscow to Obozerskaya and then to the Port Murmansk, freight moving was established with freight train weight more than 6 400 t (Fig. 1). The load from freight trains on lines with embankments on weak foundation (peat foundations) increased[1]. The main problems were caused on the Oboserskaya-Malenga Line near by White Sea and were indicated in Fig. 1. The main objective of this research was analysed on efficiency of the decisions applied to stabilization of the embankments. Now in this field, technology engineers have two main methods. The first method is the stabilization of the embankment foundation by using wooden piles—Sevstroyinvest technology[2]. The second method is the stabilization by using concrete piles—Rittransstroy technology. First technology provided the aim for the physical modeling. The physical centrifuge modeling was used to save materials, which is one of the main prototype characteristics and was divided into two stages.

Fig. 1　Obozerskaya-Malenga Railway section

图 1　阿尔汉格尔斯克-摩尔曼斯克铁路段

The modeling on the first stage was provided for prototype embankment without reinforcing. The modeling on the second stage was provided for the embankments with the construction of reinforcing by wooden piles[3]. In prototype dimensions, wooden piles are 6.5 m in length and 0.3 m in diameter. In the upper part, piles were connected with frame construction. Surface of the pile construction was covered by sand filler at the berm form.

1 Physical modeling of embankments

The preparing of the model was divided into several phases: preparing and laying of the sandy clay and placing of the peat monoliths box; compression of peat foundation in g (g is gravitational acceleration) in zone of embankment model; placing of the embankment model for lower and upper parts of embankment model (Fig. 2). For preparing of the model foundation, special monolith of the peat was taken with dimensions 0.5 m×0.5 m×0.5 m.

It is typical that the prototype embankment was placed on the sandy clay with plasticity 6% and moisture content 15%. Requirements for preparing of this artificially created soil were in proportion: sand is 56% and loam is 44% (for this

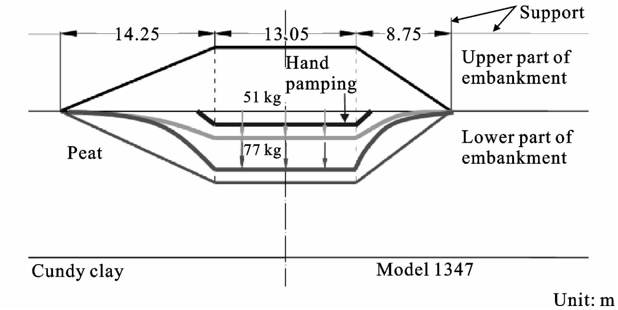

Fig. 2 Creation of pumping peat foundation and embankment model (from sandy clay)

图 2 抽水泥炭土地基的建立及路堤模型(砂黏土)

soil, $w_L=16.8\%$, $w_P=10.8\%$, $w=14\%$ and $I_L=0.53$. Where w_L is liquid limit; w_P is plastic limit; w is natural moisture content; I_L is liquidity index).

The second phase for creation of the model: compaction of the peat. The peat foundation of the model was preliminarily compacted for the creation of adequate state to prototype state (Fig. 2).

The hand pumping was provided before foundation settlements 12 mm. Then on the upper part of foundation, metal duralumin sheet was placed, under this sheet placed geotextile for organizing filtration way at compaction process. The metal sheet was applied of the static load at 51 kg (the compaction at first 4 h up to 35 mm). As a result, the maximum static load increased to 77 kg, and the settlements of the foundation were up to 54 mm after 96 h of compaction. The average value of the moisture content of the peat foundation at the top was reduced to 700%[4].

The final stage for model preparing was creation of the lower and upper parts of embankment. Failures and settlements of the embankment model were found in the result of centrifuge modeling under static load, presented in Fig. 3. Before modeling, the square of embankments was about 322.0 cm^2 and after modeling, this square was increased to 366.3 cm^2. The perimeter of embankment model was increased from 827 to 998 mm. This facts ware defined that the process of the soil failing (anti-compaction) in embankment model was happened.

Failure is caused by the reduction of the bearing capacity at the top of the embankment and the

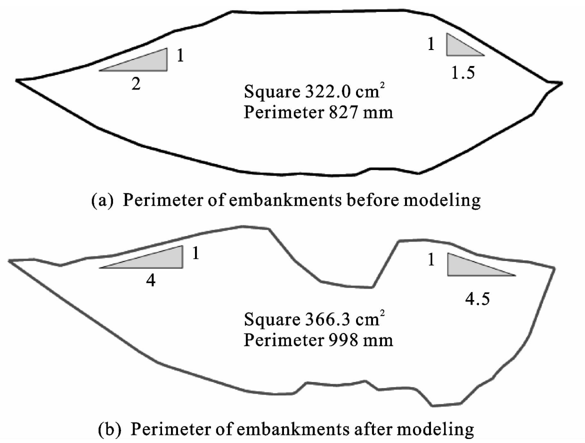

Fig. 3 Perimeters of embankments before and after modeling

图 3 路基建模前的周长和建模后的周长

displacement of the surcharge fixed on the right side of the models. The slopes of embankment model was given to ore gently form: left slope before modeling 1 : 2 and after modeling 1 : 4; right slope before modeling 1 : 1.5 and after modelling 1 : 4.5. The measurements of the deformations of the top surface of the model are shown that the maximum settlement under loading is 60 mm with displacement to the right side. Deformation has tendency to change of the sign close to the toe of embankment model in view of the foundation uplift of foundation peat (for each side of embankment model), the maximum settlement in this case is up to 17 mm.

Providing modeling shows that the prototype was needed as the model at the reinforcing of the foundation. Modeling of the embankments without reinforcing presented the results that failure is caused by reduction of bearing capacity at the top of the embankment, and the displacement of the surcharge fixed on the right side of the models. The slopes of embankment model were given to ore gently forms. The measurements of the deformations of top surface of the model show that the maximum settlement under loading is 60 mm with displacement to the right side. Deformation has a tendency to change of the sign close to toe of embankment model, in view of foundation uplift of foundation peat (for each side of embankment model), the maximum settlement in this case is more than 15 mm. Providing modeling shows that the prototype was needed as the model at the reinforcing of the foundation.

The physical modeling was providing with construction from wooden piles for prototype scale: diameter of the piles was 6.5 m (joined in the top) with small berms from the sand[5], which was performed in two series of experiments, for two rows of the piles and for four rows of the piles. This paper will present the data of this centrifuge tests and some results of field tests of the constructions for better analyzing efficiency of this technical decisions.

2 Vibrational diagnostics of railway embankments on weak foundation

The volume of railway embankments which were constricted and now at the exploitation are the potentially unstable embankments. The settlements occur on many of these embankments and this situation lead to train speed limitation. For some cases, large deformations of the embankments demand to closure of the train traffic, and the restoration in short time of the embankment workability. In accordance to this, monitoring of such embankments remains the crucial task.

At present time, the main practical methods of monitoring (survey) used for the embankments on weak foundations are geotechnical (drilling and grinding) and other geophysical ones (seismic exploration, electrical tomography, georadar, elecrodynamic sounding) allow to find out weak spots. Additionally, methods of loading tests are applied to monitor potential dangerous sections on the above mentioned embankments.

The application of such methods to the Russian railways were carried out according to the standard designed for monitoring investigations of the permanent way facilities under regular service and approved by the Department of Track and Facilities JSC "RZD" in 2006 (Technological Regulations 2006).

Analysis on the methods of monitoring shows that all of them undergoing monitoring is not under the load from really passing trains, and the application of the vibration method is considered to be promising, when the monitoring of embankment is carried out directly under the load from passing trains[6]. This method allows to fix soil vibrations of the embankment and of the subgrade with the help of seismic station when a train passes and the parameters, which should differ significantly if there are weak spots in soil mass.

The application of vibration method for monitoring the permanent way was proposed by Konshin[7].

The application of the vibration method for monitoring is currently constrained by the lack of distinctive characteristics obtained on specific sites. It shows the difference in parameters of vibration of passing rolling stock for stable embankments, which become weak under influence of the potentially dangerous objects. MIIT together with LLC "LogiS" conducted the research for the methodology of the usage of vibration method for embankments on weak subgrade. To test this method, full-scale vibration measurement of embankments on weak subgrades was carried out on the facilities of Obozerskaya-Malenga Section of the North Railway (Fig. 4).

They selected only 25 embankments on weak foundations (peat marshes) possessing various design parameters. Some of these facilities were deforming embankments, and others were reinforced. Besides, the measurements of deforming facilities were done in the sections with deformations and in the control section on stable lines. The scheme of installation of transducers is shown in Fig. 5.

For vibration monitoring, the computer appliance includes a seismic station, velocity-meters (special geophones), a power supply, a set of cables, a computer, software to operate the seismic station to transform and store transducer information. The equipment on the basis of RSS "Delta-03" was used as a seismic station. Specialgeophones SPV-3K and ordinary geophones were used.

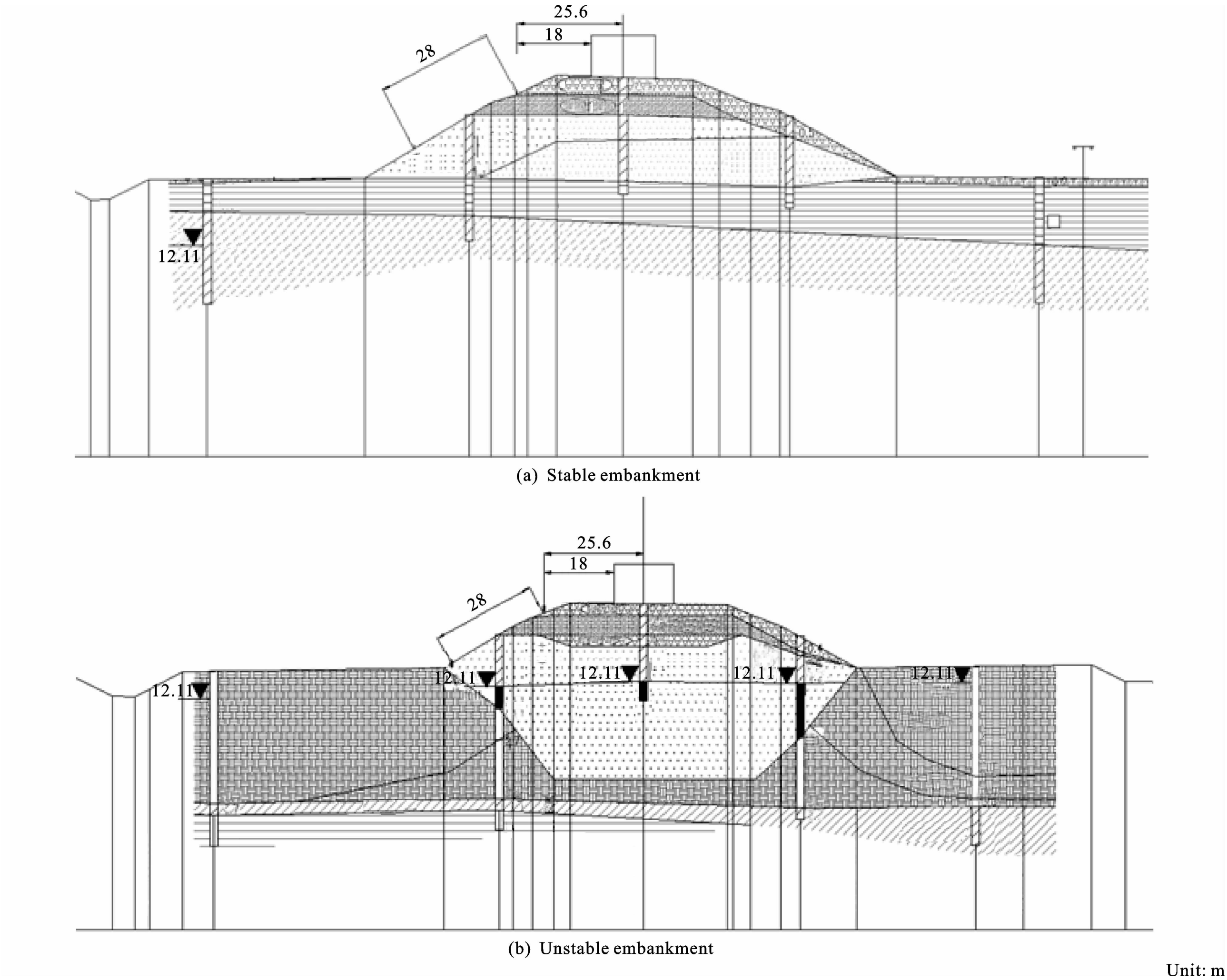

Fig. 4 Examples of stable and unstable embankments

图 4 稳定和不稳定路堤实例

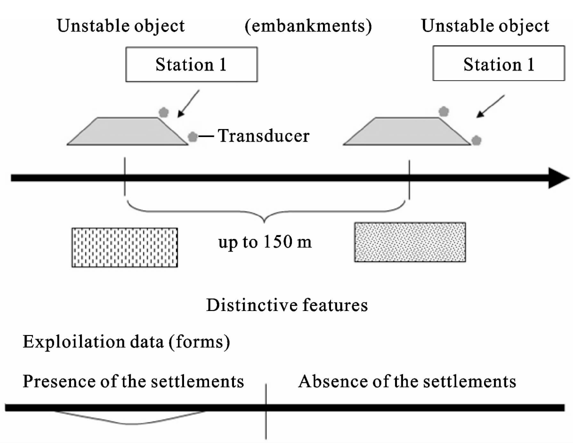

Fig. 5 Transducers installation scheme

图 5 传感器安装方案

The procedure of carrying out the vibration monitoring of embankments on weak foundation was as follows: preparatory work and field work of soil vibrations; office processing of measurement results; the statement on line condition and recommendations on its service and reinforcement. Field work on the site comprised: installation of seismoreceivers in the soil of slope at the marked observation points; connection of cables to the transducers, the equipment, the power supply and the computer; the activation and checkout of the measurement equipment and the computer; recording of soil vibrations in the embankment while the selected trains were passing and initial inspection of conditionality of measurements; dismantling of the transducers, the equipment and the transition to other section in accordance with the program.

On processing the data, obtained at the first stage of the research for the embankments on weak foundations, the frequency range of train recording was determined from 0.5 to 100 Hz. The characteristic feature of the vibrating field of embankments on weak subgrades is the presence of high values of spectral amplitudes in the range from 0.5 to 100 Hz (Fig. 6). The maximum values of vibration velocity recorded by the transducer on the edge of the embankment, may reach values of 70 to 80 mm/s. The use of a three-component recording allows to determine the value of the full vector of vibration velocity and the ratio between horizontal and vertical components of vibrations.

The characteristic feature of vibration field is also the presence of vertical and horizontal components of the sound particle velocity comparable to amplitude and the presence of long-wavelength component in vibrations. The latter circumstance makes it advisable to use periodogram methods, for the spectral evaluation of the recorded signals and the evaluation of random processes. In particular, the usage of non-parametric Welch method and parametric MUSIC (multiple signal classification) method were used. The stable embankment is characterized by the following characteristics of the vibration process: low amplitudes of the vibrations on the edge of the embankment as well as in other parts of the slope; smooth damping of vibration amplitudes from the edge down along the embankment slope according to the law close to the exponent; increase of the coefficient of attenuation; flat spectrum of the vibration process with the predominance of the maximum amplitudes of higher frequencies (Fig. 6). Vertical component of the vibrations and its estimation by Welch spectrum method load the same train. Hemming wind is 4 096.

According to the results of the research, the following criteria are accepted as the criteria for vibration monitoring of the embankments on weak subgrades: the amplitude of vibration velocity 0 to 20 mm/s with the frequency range of 0.1 to 20 Hz; the amplitude of vibration velocity 20 to 60 mm/s comply with the frequency range of 20 to 60 Hz (Fig. 6).

The coefficient of vibration attenuation alongside the embankment slope is determined by every direction of the vibration recording. Due to the vibration monitoring results, all the monitoring em-

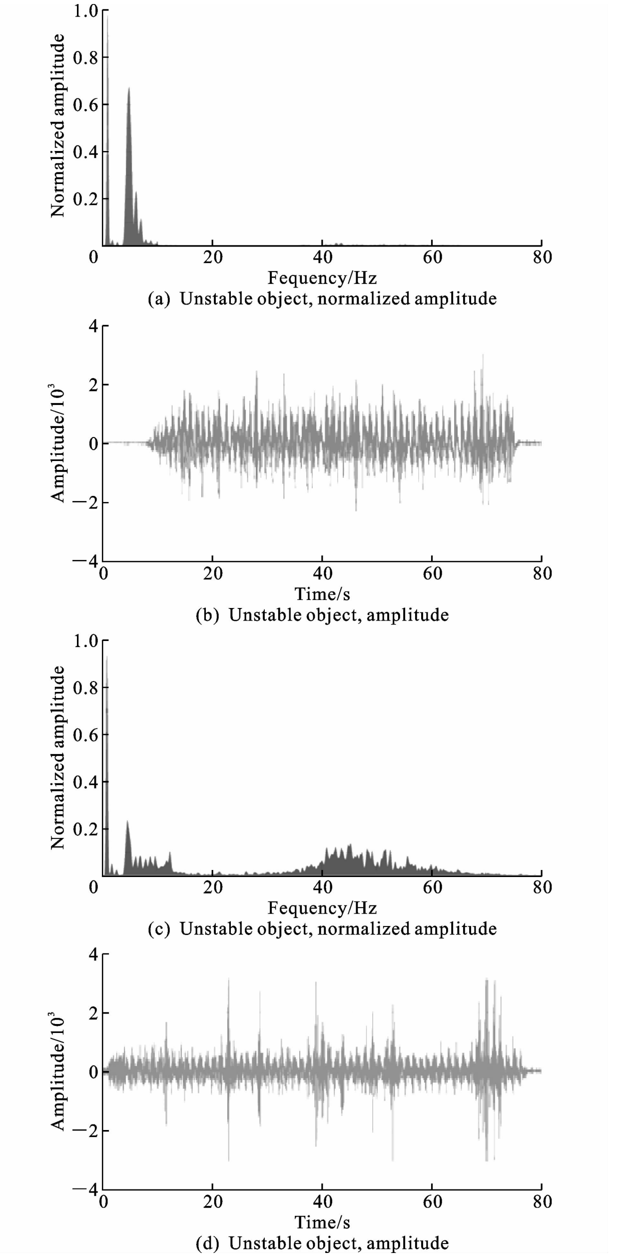

Fig. 6　Amplitude Fourier spectrum for vibration realization on the top of embankment

图 6　实现的路堤顶部振动傅立叶频谱振幅

bankments on weak subgrades are classified into three categories: stable; relatively stable; unstable. The evaluation is made separately for every slope (single-track or multi-track lines), for every measuring section and for every group of similar trains. At the same time, the evaluation is referred to the whole embankment if the evaluating state of two slopes coincides. If the evaluation of slopes does not coincide, each side of the slope and each track of the multi-track embankment should be evaluated.

The evaluation is based on the main criterion (the amplitude of the vibration velocity on the edge of the embankment). If the evaluation differs due to various criteria, then the state is also mentioned with additional criteria.

According to the results of vibration monitoring, the decision is made up about the further activities on the embankment: for the embankments where the unstable state is recorded on the basis of the main criterion, it is recommended to conduct a detailed survey and to make a project on reinforcing the subgrade; however, the embankments of the top priority are those, where an unstable state is detected with all criteria; where a relatively stable state is fixed with the main criterion or an unstable state is fixed with additional criteria, it is recommended to begin monitoring the facility state and to plan the reinforcement of the subgrade; monitoring is carried out according to the requirements of the process procedure for the potential dangerous facilities; embankments in a stable state or in a relatively stable state on the basis of additional criteria can be used under conventional operation conditions.

3 Conclusions

(1) The complex researches were provided at the Russian North Railways on the routes of freight traffic in the direction of embankments on weak (peaty and clayed) foundation for the deregulation of train speed limit. The physical centrifuge modeling of the embankments without reinforcing presented the results that failure was caused by the reduction of bearing capacity at the top of embankment and the displacement of surcharge fixed on the right side of the models. Deformation has tendency to change of the sign close to the toe of embankment model in view of the foundation uplift of foundation peat (for each side of embankment model), the maximum settlement in this case is more than 15 mm. In MIIT, the analysis on the methods of numerical calculation of foundation stability, elastic settlements, final settlements were used, and the factor and coefficient of stability are determined by using of the special software.

(2) According to the results of vibration monitoring of the prototypes, the decision is made up about the further activities on the embankment. For the embankments where the unstable state is recorded on the basis of the main criterion, it is recommended to conduct a detailed survey and to make a project on reinforcing the subgrade.

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