Study on Settlement Characteristics of Mudstone Embankment

Ju xinghua (juxinghua0927@163.com)
Weifang University
Qiu zhijun
CCCC First Highway Northwest EngineeringCo Ltd
Yang xiaohua
Changan University: Chang'an University

Research Article

Keywords: Mudstone waste slag, Embankment settlement, Different moisture content, Centrifugal model test, Field test

Posted Date: May 4th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-488021/v1

Study on settlement characteristics of mudstone embankment

Xinghua Ju*

Associate professor, College of Architecture and Engineering, Weifang University, Weifang, PR China

Zhijun Qiu*

Senior engineer, CCCC First Highway Northwest Engineering CO.LTD, Xi'an, PR China

Xiaohua Yang

Professor, School of Highway,Chang'an University, Xi'an, PR China

Corresponding author:

Name: Xinghua Ju

Contact address: Weifang University, No. 5147, Dongfeng East Street, Weifang, Shandong Province, PR China

Telephone number: (+86)15269632638

Email address: juxinghua0927@163.com

Abstract: It is in line with the concept of sustainable development to fill embankment with mudstone waste slag. However, the property of mudstone softening and disintegrating in water may affect the operation quality of the road. Relying on the Hechang Highway project, the engineering properties of mudstone filler and the settlement characteristics of embankment are studied by centrifugal model test and field test. The results showed that: under Optimum moisture content, the settlement of mudstone embankment mainly occurred in the filling stage (accounting for 62.96% of the total), and it could reach stability after 24 months of operation. The embankment settlement in cross-section showed the trend of "upward concave", and the settlement difference is not significant. Under continuous rainfall condition, the settlement mainly occurred in the operation stage (accounting for 49.05% of the total), and it could reach stability after 44 months of operation, in cross-section showed the trend of "M", the largest settlement at the shoulder. The trend of the basement earth pressure and the settlement on top of embankment is basically the same. Under continuous rainfall condition, the basement earth pressure is more concentrated toward the road centerline. It can be seen that rainfall has a certain influence on the strength and stability of mudstone embankment. The above research results provided a reliable basis for the design of embankment filled with mudstone waste.

Key words: Mudstone waste slag; Embankment settlement; Different moisture content; Centrifugal model test; Field test

Introduction

Mudstone is a kind of rock mass with high clay mineral content and low compressive strength, including iron, siliceous, carbonaceous and silty. It is widely distributed in Sichuan, Chongqing, Guizhou, Yunnan and southwest Gansu. The main characteristics of mudstone are low strength ($5MPa < f_r \leq 15MPa$), easy weathering and easy disintegration when exposed to water, which are important factors that lead to geological disasters and affect engineering safety.

For a long time, researchers have never stopped studying the disintegration mechanism, weathering characteristics, mechanical properties and improvement effect of mudstone. In order to study the effects of dry-wet cycle, temperature, mineral composition and external load on mudstone disintegration, a large number of laboratory tests, field tests and theoretical analysis were carried out (Zeng and Kong 2019; Doostmohammadi et al.2009; Qi et al.2015; Zhang et al.2012; Lu and Wang 2017; Liu and Zhang 2020; Deng et al.2016). Moreover, the disintegration evaluation indexes such as durability index, decay rate and surface energy were studied, and the classification method and standard of mudstone disintegration were put forward (Zhu and Deng 2019; Shen et al.2020). The method of inhibiting the disintegration of mudstone was studied, and the scheme of mixing seawater or calcium salt into mudstone to alleviate its disintegration and improve the overall strength was put forward (Liu et al.2019). The lateral restraint was added to restrain the water-rock interaction and water migration in mudstone, so as to control the disintegration expansion and improve the engineering properties (Wang et al.2019). Weathering is another bad characteristic of mudstone. Ohishi and Terakawa studied the influence of montmorillonite content on the disintegration degree of mudstone by scanning electron microscope, and classified the weathering degree of mudstone (Ohishi and Terakawa 2019). Ceryan and Samui obtained porosity and disintegration resistance index by experiments, and predicted uniaxial compressive strength of mudstone without weathering degree by computer software, which provided important parameters for the application of mudstone in engineering (Ceryan and Samui 2020). Disintegration is an important reason that weakens the mechanical strength of mudstone and affects its engineering performance. Many researchers have studied the stress and strain of mudstone and its mixture by triaxial test, considering the factors of dry-wet cycle, temperature change, load application, confining pressure change etc., and has established calculation models and fitting curves to predict the influence of various factors on mudstone disintegration (Wang et al.2019; Zhang et al.2014; Shi et al.2014; Wang et al.2016; Taheri and Tani 2010). Liu studied the creep characteristics of mudstone and established a nonlinear viscoelastic-plastic creep model, and proposed using Burger model to simulate the primary creep and secondary creep behavior of mudstone under different water content and temperature (Liu et al.2016;Yu et al.2017; Lu and Wang 2017; Hu et al.2018). Zhang studied the cumulative strain of mudstone under dynamic load and established a prediction model of cumulative strain (Zhang et al.2018). Yao studied the applicability of mudstone as embankment filler, and proposed that the engineering performance of mudstone mixture can meet the construction requirements when the water content and compaction degree are well controlled (Yao et al.2016). In the aspect of improvement, Phan added cement to mudstone, and its shear strength was significantly improved. After comparative analysis, it was proposed that 4% of the admixture was the most cost-effective (Vu To-Anh Phan.2018). Zeng analyzed the improvement effect of fly ash, cement and red clay on mudstone through experiments. From the mechanical index, the order of influence of the three additives on mudstone adhesion is cement, red clay and fly ash (Zeng et al.2020). Wang studied the improvement effect of nano-additives on mudstone, which can effectively reduce the softening coefficient and improve the compressive and tensile strength (Wang et al.2020).

Engineering survey

In recent years, with the gradual improvement of China's transportation network, a large number of highway construction projects have been started in the western mountainous areas.There are two prominent problems in these projects: first, the embankment filler such as gravel and sand are scarce and the cost is high; second, because of slope excavation and tunnel excavation, a large amount of mudstone waste slag is produced. In order to shorten the construction period and reduce the construction cost, many projects directly used mudstone waste slag for embankment filling, road diseases caused by the bad properties of mudstone often occurred, as shown in Fig.1.

"The Code for Design of Highway Subgrade (JTG D30-2015)" clearly stipulates the particle size and structural design of soft rock as embankment filler. However, the properties of mudstone are quite different from those of ordinary soft rock, so these regulations are not completely applicable. How to reasonably judge the applicability of mudstone as embankment filler and ensure the long-term stability and safety of mudstone embankment needs to be studied through specific tests.

Hechang Highway is a part of Chongqing Third Ring Road Project. The altitude of the project ranges from 500 m to 1000 m, which is a typical landform of "one mountain, two troughs and three ridges". The total spoil is 5.895421 million cubic meters (including main line, tunnels and interchanges), and 41 spoil grounds are needed, covering an area of 150.2 acres. The total debit is 426700 cubic meters, and 3 gravel-soil-taken fields are needed, covering an area of 11.69 acres. This scheme requires a large amount of cultivated land, and it is difficult to transport and is costly. Moreover, a large amount of spoil can easily destroy the ecological environment and induce geological disasters. The design scheme was optimized by adjusting the route and structures several times.

The design scheme was optimized through many adjustments of routes and structures. The amount of filling and excavation was reduced, and the scheme of using excavation to fill embankment as much as possible was put forward, with the debit of 0, so as to save the construction cost. However, the project site is rich in rainfall, with an average annual rainfall of 1204.3mm, the maximum daily rainfall of 206.11mm, and heavy rain in summer. In view of the bad properties of mudstone disintegration softening and creep deformation when it meets water, can mudstone be used for embankment filling? Can the strength and stability of embankment meet the requirements during operation? In this paper, based on the existing research results, relying on the Hechang Highway project, the applicability of mudstone as embankment filler and the settlement characteristics of mudstone embankment were studied by using the method of combining model test and field test, which provides a basis for the design and construction of similar projects.

Centrifugal model test

Engineering properties of test materials

The test material were taken from the mudstone waste slag generated from slope excavation in HC05 section of Hechang Highway. The mineral composition, microstructure, disintegration characteristics and mechanical indexes of mudstone were studied by scanning electron microscope, X-ray diffraction, disintegration test and point load test. The road performance of mudstone spoil was studied by compaction test, CBR test, large-scale direct shear test and consolidation test.

The results showed that: the main mineral composition of mudstone is quartz, accounting for about 55%; Followed by clay minerals (including illite, illite / montmorillonite mixed layer, chlorite, kaolinite, etc.), accounting for about 25%; Thirdly, calcite 11.7%, hematite 4.6%; It also contains a small amount of anatase and feldspar. A large number of pores and micro-pores were developed in mudstone. The saturated uniaxial compressive strength is equal to 9.72 MPa. According to "The Standard for Classification of Engineering Rock Mass (GB / T 50218-2014) ", it can be defined as silty mudstone. After immersion in water, mudstone disintegrates strongly, and the anti-disintegration index is equal to 10.52%. Before and after disintegration, the mineral composition of mudstone hardly changed, but under the action of water, the internal flaky crystal structure was tilted and curled outside, and the internal pores became larger, as shown in Fig.2 and Fig.3.

According to the screening test results of samples before and after compaction, it can be seen that the initial gradation of mudstone filler can be greatly changed by watering and compacting. The gradation changes of the samples before and after compaction were as follows: before compaction, the particles with diameter D greater than 5mm were too concentrated, the coarse particle content (P_5) was 90%, the uneven coefficient (Cu) was 2.12, and the gradation was poor, which could not meet the requirements of subgrade filler gradation in "Code for Design of Highway Subgrade". After compaction, the coarse grain particle (P_5) is 53%, the uneven coefficient (Cu) increases to 21.21, and the gradation is good, reaching the maximum dry density. Therefore, it is of little significance to use the gradation before compaction to control mudstone filler according to the codes. Before filling, it is necessary to determine the best gradation of mudstone filler through compaction test. The optimum water content and maximum dry density of mudstone filler in this project are 8.63% and 2.166g/cm^3.

When the compaction degree of mudstone filler exceeds 93%, the CBR of the sample is greater than 12.0%, the swelling in water is less than 1.39%, and the wetting deformation rate under load is less than 2.89%. The laboratory test results showed that the indexes such as shear strength, CBR and compressibility of mudstone filler all met the requirements of "Highway Subgrade Design Code (JTG D30-2015)"and "Highway Subgrade Construction Technical

Code (JTG F10-2006)" for highway embankment filler. Embankment filling can be carried out directly when the gradation is reasonable.

Model test scheme

According to the design principles, slope ratio, compactness and other requirements of the soft rock embankment in the design codes, and in combination with the actual situation of the supporting project, the structural section of mudstone embankment field test is designed as shown in Fig.4.

The centrifugal model test method was used to analyze the stability of embankment under the conditions of optimum water content and continuous rainfall. The specific research contents include:

⑴ The Optimum moisture content (modelI, abbreviated as MI), the change trend of settlement and earth pressure of mudstone embankment model in different engineering stages (filling stage, stabilizing stage and operation stage);

⑵The continuous rainfall condition (modelII, abbreviated as MII), the change trend of settlement and earth pressure of mudstone embankment model in different engineering stages (filling stage, stabilizing stage and operation stage).

The similarity ratio (n) of model test was determined to be 100. The model is in the form of full-section embankment, with specific dimensions of 245mm wide and 80mm high at the top, 1:1.5 gradient, 485mm wide and 360mm long at the bottom.

The test simulated three stages: filling stage, stabilizing stage and operation stage, and converted the pavement structure layer and traffic load into an iron plate weighing 1.657kg. Under the condition of optimum water content, after the simulated stabilizing stage, the equivalent load was applied to the top surface of embankment, and the simulated operation stage was continued. Under the condition of continuous rainfall, combined with the meteorological data of Chongqing from 1961 to 2018, the simulated rainfall was determined as follows: continuous rainfall of 8.4d days, total rainfall of 53.8mm, and average daily rainfall of 6.4 mm. After a simulated filling stage and stabilizing stage, the equivalent load is applied. Then, sprinkle water on the top surface of embankment and slope to simulate the rainfall process, and carry out the next round of rainfall simulation after 24 hours. The cycle will be terminated after 8.4 times, and the operation stage simulation will continue.

Process of model test

The particle size range and dosage of mudstone filler required for model preparation are shown in Table 1.

In order to ensure the degree of compaction, the model was filled in four layers, with compaction first and slope cutting later. Three parallel models were prepared for each working condition, totaling six. Displacement sensors, micro earth pressure sensors and pore water pressure sensors were buried in the process of model making. The model making and installation are shown in Fig.5.

In order to avoid the error caused by the over-consolidation of the model due to repeated starting and braking of the centrifuge. Before the test, the embankment model was made at one time, and the layered filling was simulated by applying different accelerations to the centrifuge during the test. It is assumed that the filling stage of embankment is 48d, and the stabilizing stage (self-weight consolidation stage from completion of filling to construction of pavement structure layer) is 90d. The operation stage is initially five years after completion (1825d) (the specific time is determined according to the change of settlement data during the test). According to the similar proportion relationship: $\frac{model\ \ time}{prototype\ \ time} = \frac{1}{n^2}$, the loading state of each stage in the model test process is determined, as shown in Fig.6 .

According to the change of test data, under the optimal water content condition, the settlement of embankment model was stable after the centrifuge operated for 157min (24 months after construction); under continuous rainfall condition, the settlement was stable after 243min (44 months after construction).

Analysis of model test results

Settlement analysis of the center point of embankment top surface

Taking the settlement change of the center of embankment top surface (No. 3 monitoring point) as an example, the settlement change trend of mudstone embankment in different engineering stages under two conditions is compared and analyzed. The specific results are shown in Fig.7.

It can be seen from Fig.8 that under the Optimum moisture content, the total settlement of the mudstone embankment (M I) with a height of 8m is 8.18cm (5.15cm in the filling stage + 1.48cm in the stabilizing stage + 1.55cm in the operation stage). Settlement mainly occurred in the filling stage, accounting for 62.96% of the total. Gravity of pavement structure layers and traffic load in operation stage have little influence on mudstone embankment deformation, and the ratio of post-construction settlement to embankment height is only 0.194%, which meets the requirements of "Code for Design of Highway Subgrade" on post-construction settlement of highway embankment.

Under the continuous rainfall condition, the total settlement of the mudstone embankment (MⅡ) is 12.68cm (4.83cm in the filling stage + 1.63cm in the stabilizing stage + 6.22cm in the operation stage). Settlement mainly occurred in the operation stage, accounting for 49.05% of the total.

It can be seen from Fig.8b that under the effect of rainfall, the mudstone embankment expanded by 2.19cm. Under the effect of continuous rainfall, the expansion rate of embankment is only 0.27%, and the road diseases caused by swelling of mudstone filler will not occur. The ratio of post-construction settlement to height of embankment under rainfall is 0.778%, which still meets the requirements of design code.

In terms of settlement rate, the settlement rate is higher during the filling stage due to the increase of embankment height. In the stabilizing stage, the compression coefficient of mudstone filler decreases, the compression modulus increases and the degree of consolidation increases. It continues to settle under the action of its own gravity, but the rate decreases significantly; In the operation stage, the settlement rate of embankment under the optimum water content is very slow, and it reaches stable state after 24 months. Under the action of continuous rainfall, the filler on the top surface and both sides of embankment softens and disintegrates, and the strength decreases. After a short expansion, the settlement rate increases, but the duration is not long.

According to the settlement trend and rate of the center point of the top surface of mudstone embankment, the grading and compaction degree of mudstone filler can be controlled well, and the design scheme of mudstone embankment at the project site can meet the quality requirements of expressway. From the settlement trend and rate of the top center point of the mudstone embankment, the control of the gradation and compactness of the mudstone filler, relying on the mudstone embankment design scheme of the project location, can meet the quality requirements of the expressway.

Judging from the settlement trend and rate of embankment, it is feasible to fill embankment with mudstone in supporting engineering.

Settlement analysis of embankment with the same section

The final settlement trend of mudstone embankment in the same cross-section under two conditions is shown in Fig.8.

Under the condition of optimum water content, the cumulative settlement of mudstone embankment along the cross-sectional direction is "upward concave", which is large in the middle and small on both sides. The maximum settlement of model MⅠ in the same section is 8.18cm, which occurred at the center line of embankment. The minimum settlement is 5.53cm, which occurred on the right shoulder. The maximum settlement difference of the same section is 2.65cm, with little difference. Under the condition of continuous rainfall, the cumulative settlement of mudstone embankment along the cross-sectional direction is in the shape of "M". The maximum settlement of model MⅡ in the same section is 19.86cm, which occurred on the right shoulder. The minimum settlement is 10.12cm, which occurred in the right half of the road, 6m away from the center line of the road. The settlement at the center line of the road is 12.68cm.The maximum settlement difference of the same section is 9.74cm, which is quite different.

There are two main reasons for the settlement deformation of mudstone embankment: one is the compression deformation under the action of self-weight and upper load, and the other is the wetting deformation caused by the softening and disintegration of filler when it meets water. By comparing and analyzing the settlement changes of the two models, it can be seen that the strength of mudstone filler fully meets the requirements of load. Under the condition of continuous rainfall, the filler on both sides of embankment has high softening degree and large deformation, and the settlement is mainly wetting deformation. At the same time, due to the scouring action of rain, the fillers at the shoulders on both sides will peel off and collapse without external restraint, resulting in a sudden increase in deformation. After the experiment, the appearance of the embankment models is shown in Fig.9.

After the test, there was no obvious change in the appearance of embankment model MI, only a small number of tiny irregular cracks appeared on the surface. This is because the centrifuge rotates rapidly, which makes the filler on the surface of the model lose water and dry. However, obvious cracks appeared on both side slopes of model MⅡ, which were not deep but distributed widely, especially at both side slopes. This phenomenon is due to the swelling and disintegration of mudstone filler in slope after rainfall. Operation stage, the moisture on the embankment surface evaporates, and the mudstone filler shrinks due to water loss, which leads to a large number of cracks on the surface. It can be seen that under the condition of unprotected slope, continuous rainfall can easily lead to slope slip, surface disintegration and peeling of mudstone embankment. Although the settlement can meet the requirements of the code, the road diseases caused by slope damage can not be ignored. Therefore, in order to ensure the operation quality of highway, it is suggested that the mudstone embankment slope should be covered and waterproof.

Analysis of basement earth pressure

Mudstone embankment is composed of loose particles, and its settlement process is accompanied by pore compression, water discharge, stress change and so on. Now, the change of basement earth pressure in centrifugal model test is analyzed.The stress change during the test was a dynamic process. Now, the average value of earth pressure in stabilizing stage, operation stage and continuous rainfall operation period is selected for analysis, and the change trend of earth pressure of mudstone embankment is determined as shown in Fig.10.

It can be seen from the above figure that the basement earth pressure in different engineering stages is generally parabolic distribution along the cross-sectional direction, which is large in the middle and small on both sides. According to the layout of the micro earth pressure sensors, the load generated by the fillers at the slope is small, and the earth pressure borne by the basement is small. Within the width of pavement, the load generated by fillers is large, and the soil pressure on the basement is large. The distribution trend of earth pressure within the width of pavement is basically consistent with the settlement trend, and the load exerted by embankment on the foundation surface is not evenly distributed along the cross-sectional direction.

The ratio of basement earth pressure to the corresponding upper load is shown in Table 2.

It can be seen from the statistical data that during the stabilizing stage, the values in the pavement range are all greater than 1.0, and the values in the slope positions are all less than 1.0. In other words, the basal earth pressure is greater than the upper load within the range of pavement, while the basement earth pressure at the slope is less than the upper load, and part of the loads on both sides of the embankment are borne by the foundation at the pavement. Under the condition of optimum water content (M I), the compressive modulus of the filler increases with the increase of embankment settlement from the stabilizing stage to the operation stage. The stiffness of embankment increases, and the load sharing and transmission capacity increases. During the operation stage, the trend of basal earth pressure concentrating towards the center line of the road slows down. Under the condition of continuous rainfall (MⅡ), due to the infiltration of water, the mudstone filler softens and disintegrates, and the basal earth pressure of MⅡ concentrates more obviously towards the center line of the road, which requires higher bearing capacity of the foundation at the center line of the road.

Field test of settlement monitoring

It has good economic and social benefits to use mudstone waste slag as embankment filler. However, the engineering properties of mudstone are greatly affected by the environment. Whether the embankment filled with mudstone meets the requirements of stability needs to be determined by tests. Settlement monitoring is an effective method to study embankment engineering characteristics and optimize design. By analyzing the monitoring data of embankment settlement in different engineering stages, on the one hand, the construction speed of embankment can be reasonably controlled to ensure the construction quality; On the other hand, it can predict the settlement law of embankment and the final settlement after construction.

The field test was carried out in HC05 section of Hechang Highway. In this paper, the rationality of the design scheme of mudstone embankment is analyzed based on the field settlement monitoring and indoor model test data.

Field monitoring test scheme

Layout of monitoring instruments and monitoring points

Two monitoring sections are set in the test section, the specific locations are K50 + 740 and K50 + 780. The number of test instruments, test points and layout scheme of the two sections are shown in Fig.11.

Frequency of field monitoring

According to the construction schedule, the settlement monitoring frequency was determined as follows:

⑴Filling stage. The monitoring frequency is once every 2 days. When the settlement of embankment is not more than 10mm/d and the displacement change at the toe of slope is not more than 4mm/d, the next layer shall be filled.

⑵Stabilizing stage. In the first month, the monitoring frequency of horizontal inclinometers, top piles are once every 5 days. In the second month, is once every 10 days. The third month and beyond, is once every 15 days. Until the settlement rate is less than 5.0 mm / month in two consecutive months, the next stage of construction can be carried out.

⑶Construction stage of subbase course. The thickness of cushion layer, subbase layer and base layer is 20cm, the monitoring frequency is once for each layer.

⑷Operation stage. The monitoring frequency is once every 15 days in the first 3 months and once every 30 days in the third to sixth months. In case of rainfall, increase the monitoring frequency.

Analysis of field settlement monitoring test results

The monitoring of horizontal inclinometers and side piles includes three stages: filling stage, stabilizing stage and operation stage. The monitoring of embankment top surface includes two stages: stabilizing stage and operation stage. In order to ensure the test progress, rainproof measures were taken for the embankment during the filling stage, without considering the influence of rainfall. There were 7 rainfalls in the stabilizing stage. After the construction was completed, the test section was used as an access road, and the settlement can be regarded as the settlement at the operation stage, and five rainfalls occurred in the operation stage.

Analysis of settlement rate of embankment

The settlement changes monitored by three horizontal inclinometers with different buried depths in embankment are shown in Fig. 12 ~ Fig.14.

The No.1 horizontal inclinometer is buried at the bottom of embankment, and its monitoring results show the change of foundation settlement with upper load and time. It can be seen from Fig. 14 that the influence of embankment load on foundation settlement mainly occurred in the filling stage. When the filling height was 8.0m, the foundation settlement was 10.22mm, accounting for 92.3% of the total, and the settlement rate was 0.21mm/d. Two monitoring points at the toe of the slope appeared slight uplift with the increase of embankment load, but the uplift amount was very small, and the maximum value was only 1.5 mm. The settlement changed little during the stabilizing stage and operation stage, and the accumulated settlement was 11.07mm after the 328-day on-site settlement monitoring. According to the monitoring results, because of the high bearing capacity of the underlying bedrock, the foundation settlement of the supporting project is not affected by various factors such as filler weight, construction machinery, traffic load and external environment. The construction scheme of embankment filling directly can meet the settlement requirements after removing the surface soil and compacting the original ground.

The No.2 horizontal inclinometer was buried 3.0m above the basement, and the monitoring content was the settlement of mudstone embankment within 3.0m below and part of foundation. It can be seen from Fig. 15 that the upper filler load is the main cause of settlement. The settlement during the filling stage reached 38.63mm, accounting for 59.23% of the total, and the settlement rate was 1.29 mm/d. In the stabilizing stage, the increase of settlement at the road centerline was 9.54mm in the first month, 3.71mm in the second month and 1.75mm in the third month. The construction of embankment structure layers had little effect on the settlement of No.2 inclinometer, but the upper load gravity and the action of construction machinery prolonged the stability time of mudstone embankment. About 270 days later, the settlement of No.2 horizontal inclinometer gradually stabilized, and the accumulated settlement during the monitoring period was 65.22 mm.

Compare the meteorological data analysis during the field test. In the stabilizing stage, the settlement of $1^{\#}$ and $11^{\#}$ monitoring points located at the slopes on both sides suddenly changed during rainfall, which increased by 15.72mm in a short time. Settlement of $2^{\#}$ and $10^{\#}$ monitoring points also changed a little, increased by 5.63 mm. However, the settlement of internal points of embankment was not affected by rainfall. Operation stage, the settlement of embankment was not obviously affected by rainfall, including the slopes on both sides. It is because under the effect of early rainfall, the filler at the slope has disintegrated into fine particles, part of which is washed away by rain, and the remaining part forms a slope protection layer, which can prevent water from penetrating into the mudstone embankment.

The No.3 horizontal inclinometer was buried 6.0m above the basement, and the monitoring content was the settlement of mudstone embankment within 6.0m below and part of foundation. It can be seen from Fig. 16 that the maximum settlement during the filling stage occurred at the road centerline, with a value of 42.39mm, accounting for 52.94% of the total, and the settlement rate was 3.53 mm/d. Compared with the No.2 horizontal inclinometer, the No.3 horizontal inclinometer produces more settlement during the stabilizing stage and operation stage, and it takes longer for the settlement to reach a stable state. In the stabilizing stage, the increase of settlement was 12.56mm in the first month, 4.02mm in the second month and 2.30mm in the third month. As shown in Fig. 16, the settlement rate of No.3 horizontal inclinometer increased to a certain extent in the early stage of operation. It can be seen that the increase of pavement structural layers load and traffic load in operation stage have a greater impact on the upper part of embankment.

According to the settlement changes of horizontal inclinometers at different depths of mudstone embankment, the following conclusions are drawn: ⑴The upper embankment construction has different influences on the settlement at different depths. The settlement range of different points in embankment is 2.58～7.06mm after each layer of filling is completed. The greater the height, the greater the settlement. In order to ensure the construction quality, it is suggested that the filling rate of embankment within 0 ~ 4m height should not exceed 2 layers per day, and within 4 ~ 8 m height should not exceed 1 layer per day;⑵When the mudstone embankment with height of 8m enters the second and third months of the stabilizing stage, the settlement rate at different depths is less than 5mm/ month, which meets the construction standard of pavement structure layer. The construction time of pavement structure layer can be determined as 3 months after the completion of filling, and other embankments with different heights can take this as a reference.⑶ Traffic load and pavement structural layers load have great influence on the stability of the upper part of embankment. In order to ensure the overall stability of embankment, the compactness of this part should be ensured during construction.⑷After a rainy season, the overall strength and stability of mudstone embankment can meet the requirements. However, due to the scouring of rain and its own softening and disintegration, the filling materials at the slope has a large settlement. In order to ensure its long-term stability, measures such as clay wrapping and slope drainage can be adopted to reduce the impact of rainfall on mudstone embankment.

Settlement analysis of mudstone embankment in different engineering stages

The settlement trend of mudstone embankment along the cross-sectional direction in different engineering stages is shown in Fig.15 ~ Fig.17.

In the filling stage, the settlement of different monitoring points is "concave" along the cross-sectional direction, with the maximum settlement at the filling height of 6m, the second at 3m and the minimum at the basement. The settlement of No.1 horizontal inclinometer is mainly due to the compression deformation of the foundation caused by the upper load, and the settlement is only about 1.0cm. The settlement of No.2 and No.3 horizontal inclinometers is caused by the compression deformation of the lower filler and foundation.

In the stabilizing stage, the settlement of mudstone embankment is mainly the compression deformation caused by its own gravity. It can be seen from Fig. 18 that the distribution trend of settlement at different heights along the cross-sectional direction is different, and the settlement increases with the increase of embankment height. At this stage, the settlement of the basement was almost zero, and the settlement of the monitoring point with a height of 3m was 1.5cm, 1.89cm at 6m and 2.66cm at the top of the embankment. It is basically consistent with the earth pressure distribution trend monitored by the indoor model test, and the settlement at the road centerline is the largest, showing a "concave" curve as a whole. However, due to the influence of multiple rainfalls at this stage, the settlement of the slope increased suddenly.

In the operation stage, the settlement is mainly the compression deformation of filler under the gravity of pavement structure layer and traffic load. It can be seen from Fig. 19 that during the 190 day operation monitoring process, the settlement of mudstone embankment was relatively small, the settlement at the top of embankment and the height of 6m were about 1.9cm, and at 3m was 1.16cm. The settlement of mudstone embankment is little affected by pavement structure layers and traffic load, and the strength of mudstone filler completely meets the requirements of upper load.

According to the settlement distribution of mudstone embankment in three engineering stages, the following conclusions can be drawn: ⑴The settlement at different depths of embankment tends to be larger in the middle and smaller on both sides along the cross-sectional direction. In order to reduce the uneven settlement of the same cross-section, the compactness of filler at the road centerline can be appropriately increased; (2)In the stabilizing stage, the greater the filling height of embankment, the greater the settlement. At this stage, the settlement of the top surface of the embankment with a height of 8m is 2.66cm, so it is suggested to reserve a height of about 3cm when filling the embankment. Mudstone embankments of other heights can refer to this standard to design the reserved height of embankments. (3)According to the settlement trend of the whole section, the strength of mudstone embankment can meet the requirements of structural dead weight and traffic load. However, due to the particularity of mudstone, rainfall has certain influence on slope stability. In order to ensure the stability of embankment, anti-seepage design of pavement structure layer and the waterproof and drainage design of side slopes should be done well.

Conclusions

In this paper, the settlement characteristics of mudstone embankment in different engineering stages were studied by combining indoor model test with field test, and got the following conclusions:

(1)According to the research results of engineering properties of mudstone filler, it is shown that the control of filler gradation and compactness during construction is an important prerequisite to avoid softening deformation and ensure the overall stability of embankment.

(2)Under the condition of optimum water content, the settlement of mudstone embankment mainly occurred in the filling stage (accounting for 62.96% of the total). After 24 months of operation, the settlement reached a stable state, and the ratio of post-construction settlement to embankment height is only 0.194%. Under the condition of continuous rainfall, the settlement mainly occurred in the operational stage (accounting for 49.05% of the total). After 44 months of operation, the embankment reached a stable state, and the ratio of post-construction settlement to embankment height was 0.778%. It can be seen that rainfall has certain influence on the settlement deformation of mudstone embankment. However, the post-construction settlement under both conditions can meet the requirements of "Code for Design of Highway Subgrade".

(3)Along the cross-sectional direction: Under the condition of optimum water content, the settlement of embankment is "concave" shape, with the maximum settlement occurred at the road centerline, and the minimum settlement occurred at the right shoulder. The ratio of differential settlement and filling height in the same section is 0.33%, and the settlement is relatively uniform. Under the condition of continuous rainfall, the settlement of embankment is "M" shape. The maximum settlement was 19.86cm, which occurred at the right shoulder. The minimum settlement was 10.12cm, which occurred at 6m on the right side of the road centerline. The settlement at the road centerline was 12.68cm. The ratio of differential settlement and filling height in the same section is 1.22%. It can be seen that rainfall has the greatest influence on the mudstone filler at the slopes on both sides, so it is necessary to take anti-seepage and drainage measures for the mudstone embankment slope.

⑷The distribution trend of basement earth pressure and settlement at the top of embankment is basically consistent. Under the condition of continuous rainfall, the basement earth pressure is more concentrated towards the road centerline, which requires higher bearing capacity at the road centerline. In order to avoid uneven settlement of mudstone embankment, the foundation reinforcement design should be carried out according to the distribution trend of foundation stress.

⑸During construction, it is suggested that the filling rate within 0 ~ 4m height should be 2 floors per day and 1 floor per day within 4 ~ 8m. The higher the height of embankment, the lower the filling rate. When filling, it is necessary to properly improve the compactness of the filler at the road centerline. The settlement of mudstone embankment increases with the increase of filling height. When the filling height is 8m, it is necessary to design a reserved height of 3cm and ensure a stabilizing stage of 3 months, which can be used as a reference for other filled embankments.

Funding This work is financial supported by the National Natural Science Foundation of China (no.51908051), the Doctoral Research Fund Project of Weifang University (no.2020BS31).

References

Zeng ZX, Kong LW (2019) Effect of wetting–drying–freezing–thawing cycles on the swelling behaviour of the Yanji mudstone . Environ Earth Sci 78: 435 https://doi.org/10.1007/s12665-019-8447-1

Doostmohammadi.R, Moosavi.M, Mutschler.Th, Osan.C (2009) Influence of cyclic wetting and drying on swelling behavior of mudstone in south west of Iran. Environ Geol 58:999–1009 DOI 10.1007/s00254-008-1579-3

Qi JF, Sui WH, Liu Y, Zhang DY (2015) Slaking process and mechancisms under static wetting and drying cycles slaking tests in a red strata mudstone. Geotech Geol Eng 33:959–972 DOI 10.1007/s10706-015-9878-4

Zhang D, Chen AQ, Liu GC (2012) Laboratory investigation of disintegration characteristics of purple mudstone under different hydrothermal conditions. J. Mt. Sci 9: 127–136 DOI: 10.1007/s11629-012-2204-1

Lu YL, Wang LG (2017) Effect of water and temperature on short-term and creep mechanical behaviors of coal measures mudstone. Environ Earth Sci 76:597 DOI 10.1007/s12665-017-6941-x

Liu W, Zhang ZH (2020) Experimental characterization and quantitative evaluation of slaking for strongly weathered mudstone under cyclic wetting-drying condition. Arabian J. Geosci 13: 65 https://doi.org/10.1007/s12517-019-5044-2

Deng HF, Zhou ML, Li JL, Sun XS, Huang YL (2016) Creep degradation mechanism by water-rock interaction in the red-layer soft rock. Arabian J. Geosci 9: 601 DOI 10.1007/s12517-016-2604-6

Zhu JJ, Deng H (2019) Durability classification of red beds rocks in central Yunnan based on particle size distribution and slaking procedure. J. Mt. Sci 16(3): 714-724 https://doi.org/10.1007/s11629-018-5234-5

Shen PW, Tang HM, Wang DJ, Su XX, Huang L (2020) Weakening of mudstone fragments due to disintegration: an experimental inverstigation. Bull Eng Geol Environ 79:5477–5497 https://doi.org/10.1007/s11629-018-5234-5

Liu Z, He XF, Fan J, Zhou CY (2019) Study on the softening mechanism and control of red-bed soft rock under seawater conditions. J. Mar. Sci. Eng 7: 235 doi:10.3390/jmse7070235

Wang S, Han LJ, Meng QB, Jin YH ,Zhao WS (2019) Investigation of pore structure and water imbibition behavior of weakly cemented silty mudstone. Advances in Civil Engineering https://doi.org/10.1155/2019/8360924

Ohishi.T, Terakawa.M (2019) Characteristics of weathered mudstone with X-ray computed tomography scanning and X-ray diffraction analysis. Bull Eng Geol Environ 78:5327–5343 https://doi.org/10.1007/s10064-018-1429-9

Ceryan.N, Samui.P (2020) Application of soft computing methods in predicting uniaxial compressive strength of the volcanic rocks with different weathering degree. Arabian J. Geosci 13: 288 https://doi.org/10.1007/s12517-020-5273-4

Wang JJ, Liu MN, Jian FX, Chai HJ (2019) Mechanical behaviors of a sandstone and mudstone under loading and unloading conditions. Environ Earth Sci 78:30 https://doi.org/10.1007/s12665-018-8020-3

Zhang LY, Mao XB, Liu RX, Guo XQ, Ma D (2014) The mechanical properties of mudstone at high temperatures: an experimental study. Rock Mech Rock Eng 47:1479–1484 DOI 10.1007/s00603-013-0435-2

Shi CH, Ding ZD, Lei MF, Peng LM (2014) Accumulated deformation behavior and computational model of water-rich mudstone under cyclic loading. Rock Mech Rock Eng 47:1485–1491 DOI 10.1007/s00603-013-0427-2

Wang JB, Liu XR, Zhao BY, Song ZP, Lai JX (2016) Experimental investigation and constitutive model for lime mudstone. SpringerPlus 5:1634 DOI 10.1186/s40064-016-3297-8

Taheri A, Tani K (2010) Characterization of a sedimentary soft rock by a small in-situ triaxial test. Geotech Geol Eng 28:241–249 DOI 10.1007/s10706-008-9245-9

Liu JX, Liu W, Liu P, Yang CH, Xie Q, Liu YT (2016) Preliminary research on the theory and application of unsaturated Red-layers embankment settlement based on rheology and consolidation theory. Environ Earth Sci 75:503 DOI 10.1007/s12665-016-5313-2

Yu HC, Liu HD, Huang ZQ, Shi GC (2017) Experimental study on time-dependent behavior of silty mudstone from the three gorges reservoir Area, China. Journal of Civil Engineering 21(3):715-724 DOI 10.1007/s12205-016-3645-9

Lu YL, Wang LG (2017) Effect of water and temperature on short-term and creep mechanical behaviors of coal measures mudstone. Environ Earth Sci 76:597 DOI 10.1007/s12665-017-6941-x

Hu M, Liu YX, Song LB, Zhang Y (2018) Constitutive model and damage evolution of mudstone under the action of dry-wet cycles. Advances in Civil Engineering https://doi.org/10.1155/2018/9787429

Zhang CL, Jiang GL, Su LJ, Liu WM (2018) Dynamic behavior of weathered red mudstone in Sichuan(China) under triaxial cyclic loading. J. Mt. Sci. 15(8): 1789-1806 https://doi.org/10.1007/s11629-017-4756-6

Yao HY, Jia SP, Gan WN, Zhang ZH, Lu KL (2016) Properties of crushed red-bed soft rock mixtures used in subgrade. Advances in Materials Science and Engineering http://dx.doi.org/10.1155/2016/9624974

Phan V.T.-A (2018) Improvement in engineering properties of mudstone in southwestern Taiwan through compaction and a cement additive. Geotech Geol Eng 36:1833–1843 https://doi.org/10.1007/s10706-017-0435-1

Zeng L, Yu HC, Gao QF, Bian HB (2020) Mechanical behavior and microstructural mechanism of improved disintegrated carbonaceous mudstone. J. Cent. South Univ. 27: 1992−2002 https://doi.org/10.1007/s11771-020-4425-8

Wang JJ, Shi ZN, Zeng L, Qi SX (2020) The effects of different nanoadditives on the physical and mechanical properties of similar silty mudstone materials. Advances in Civil Engineering https://doi.org/10.1155/2020/8850436

Figures

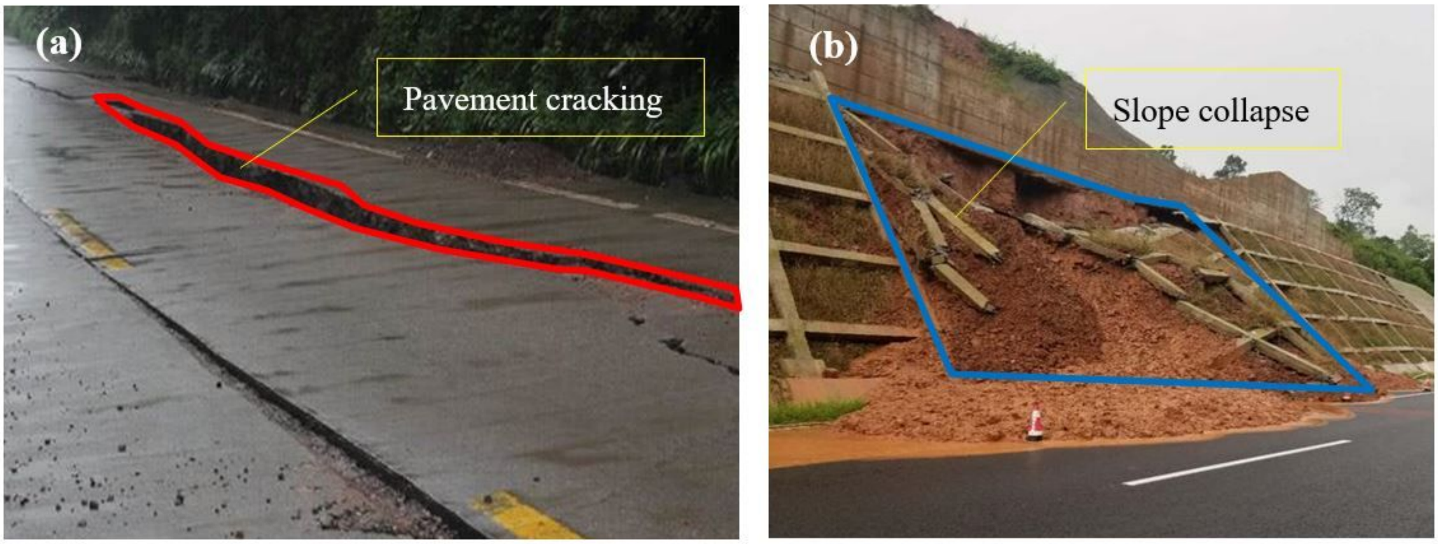

Figure 1

Road diseases. (a) Pavement cracking (b) Slope collapse

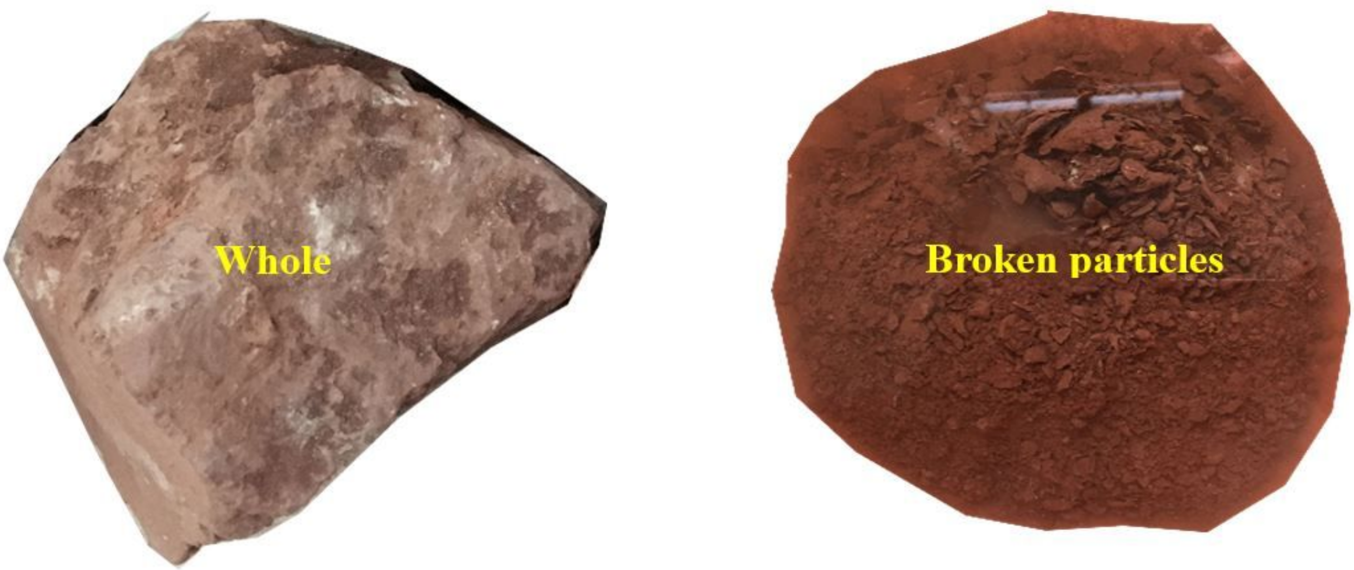

Figure 2

Comparison of mudstone appearance before and after disintegration. (a) Before disintegration (b) After disintegration

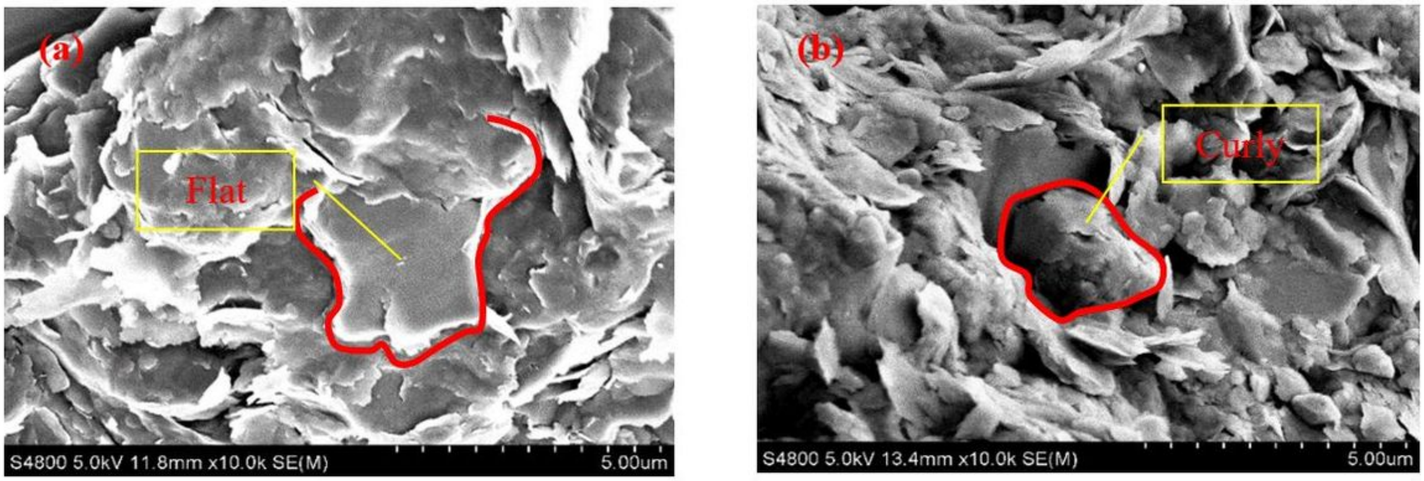

Figure 3

Comparison of mudstone microstructure before and after disintegration. (a) Before disintegration (b) After disintegration

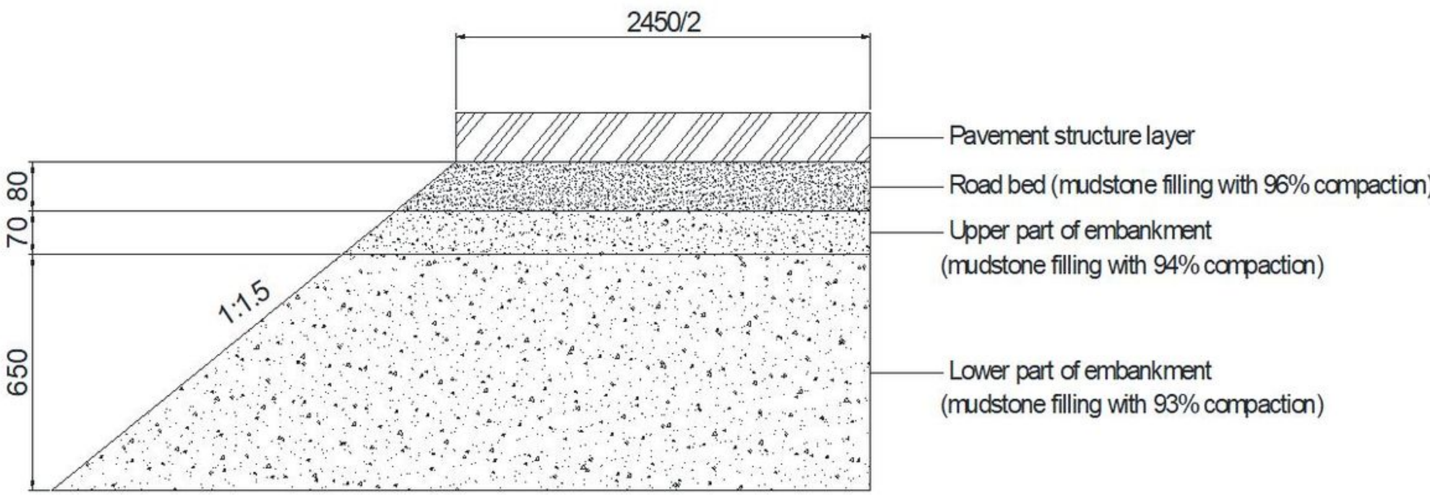

Figure 4

Structure section of mudstone embankment (half range)

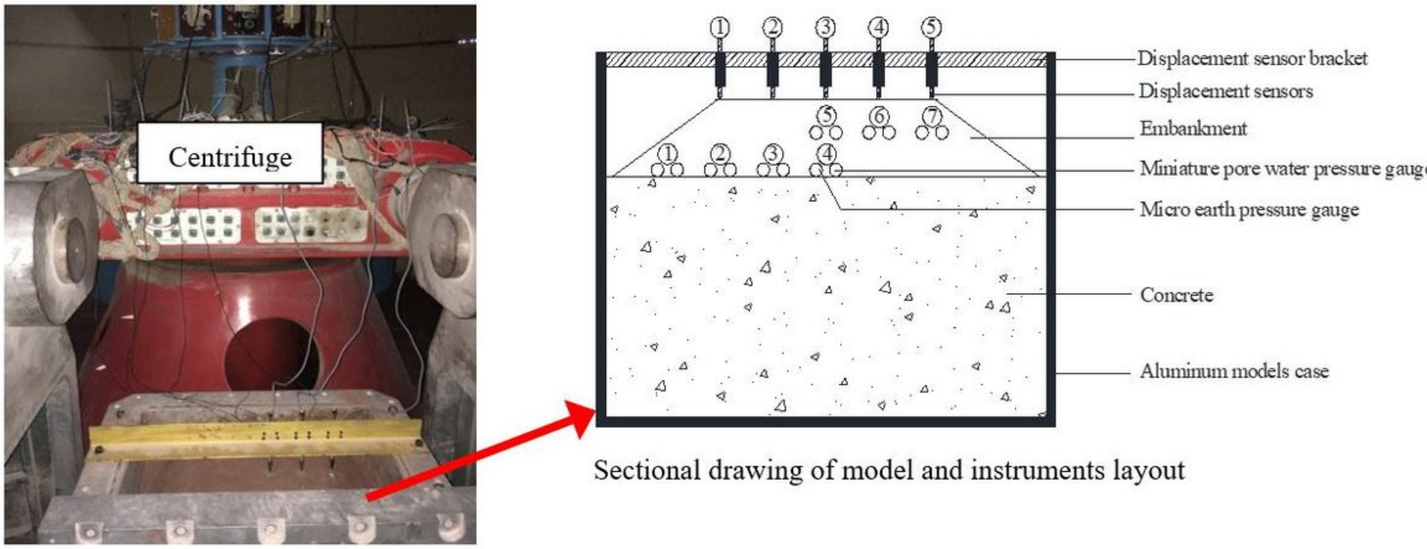

Figure 5

Model making and installation

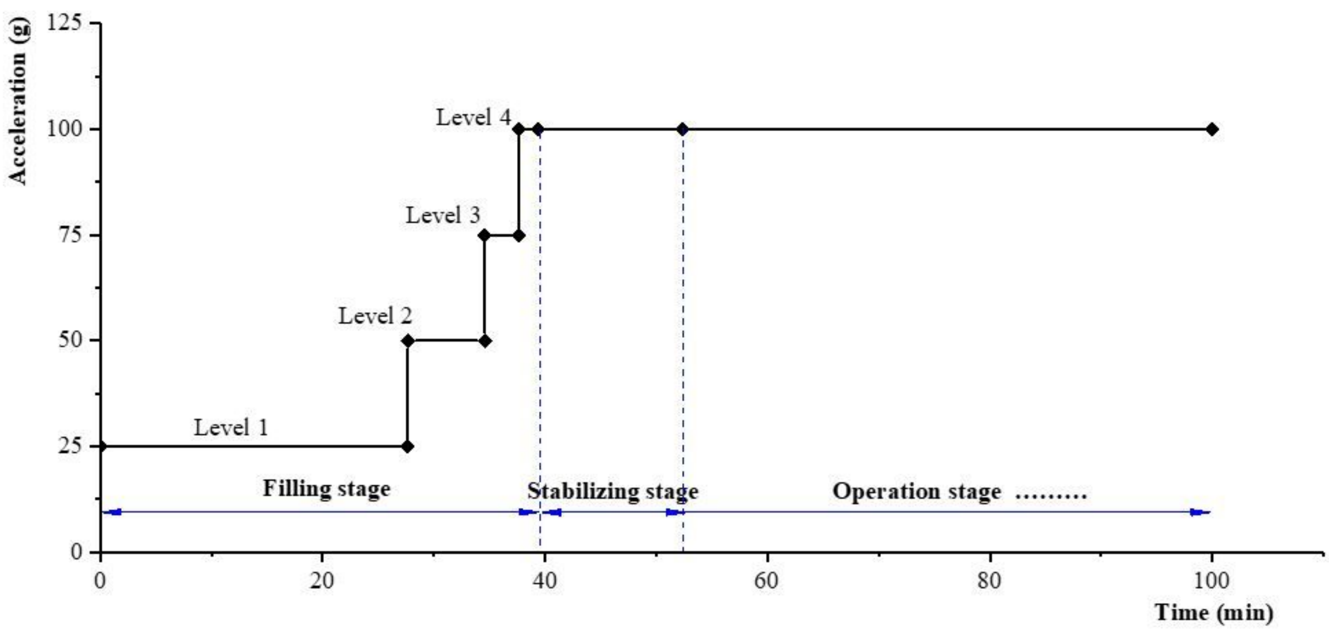

Figure 6

Loading state at different stages of centrifugal model test

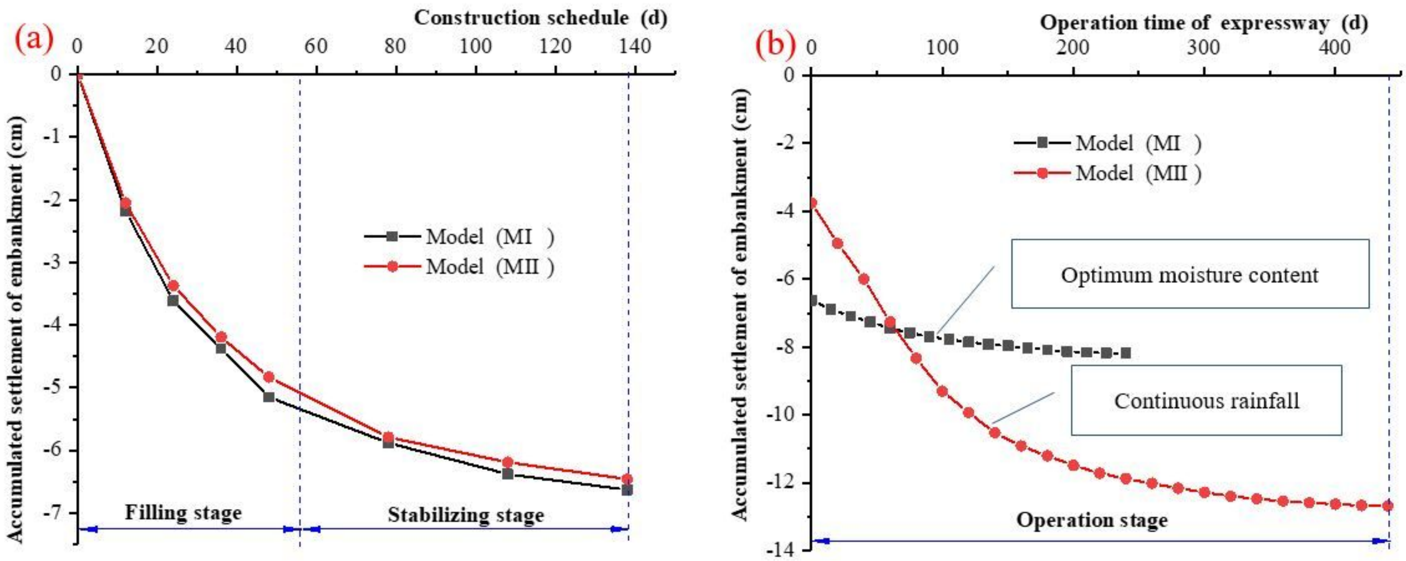

Figure 7

Comparison of mudstone cumulative settlement of embankment under two working conditions. (a) Filling stabilizing stage (b) Operation stage

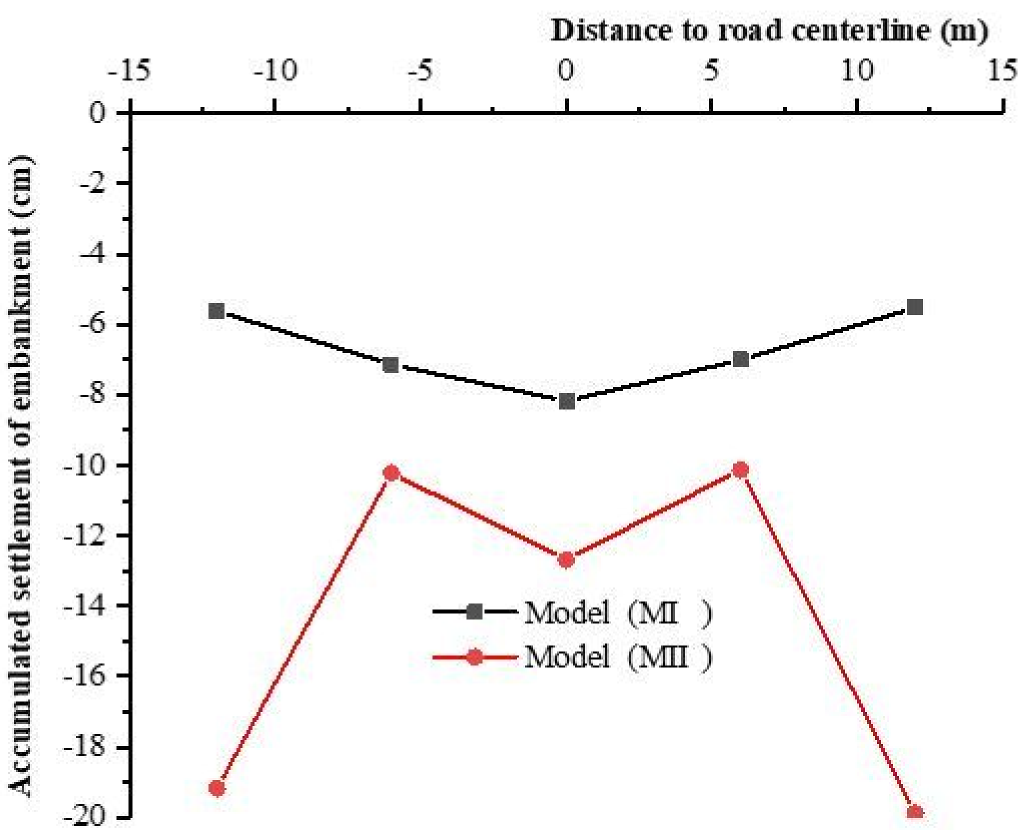

Figure 8

Comparison of settlement trend of mudstone embankment in cross-section direction.

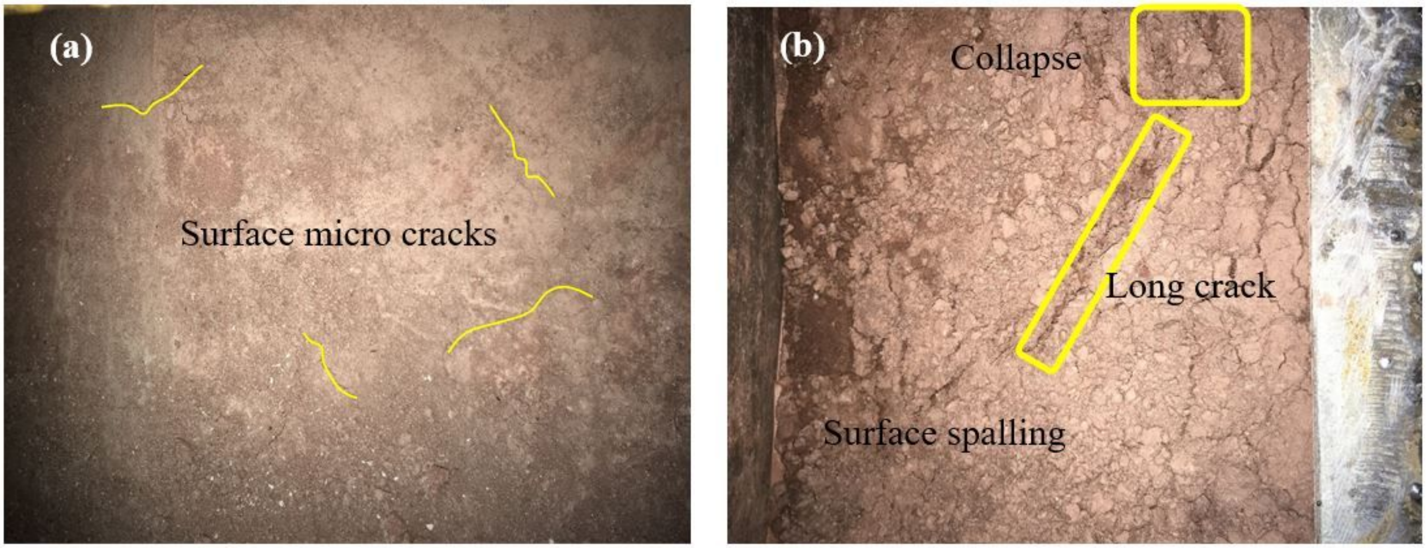

Figure 9

Appearance of embankment model after test. (a) Model M (b) Model M

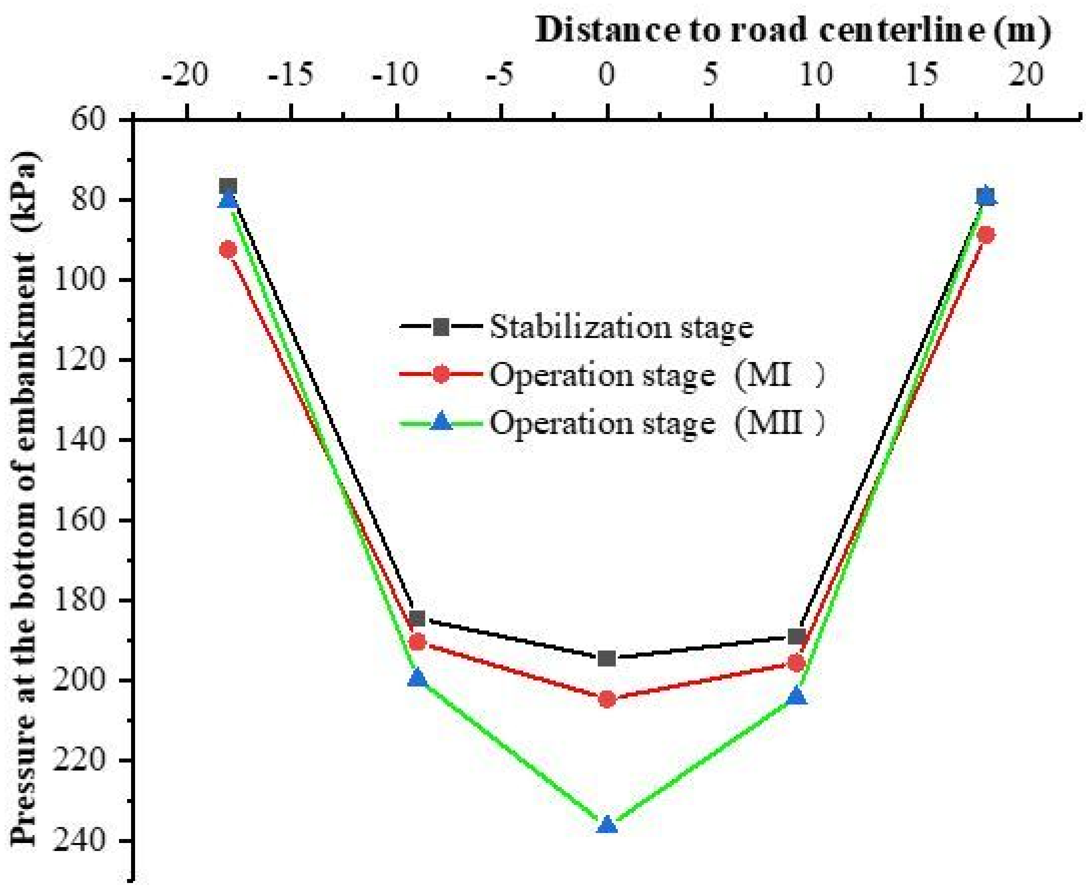

Figure 10

Distribution of basement earth pressure.

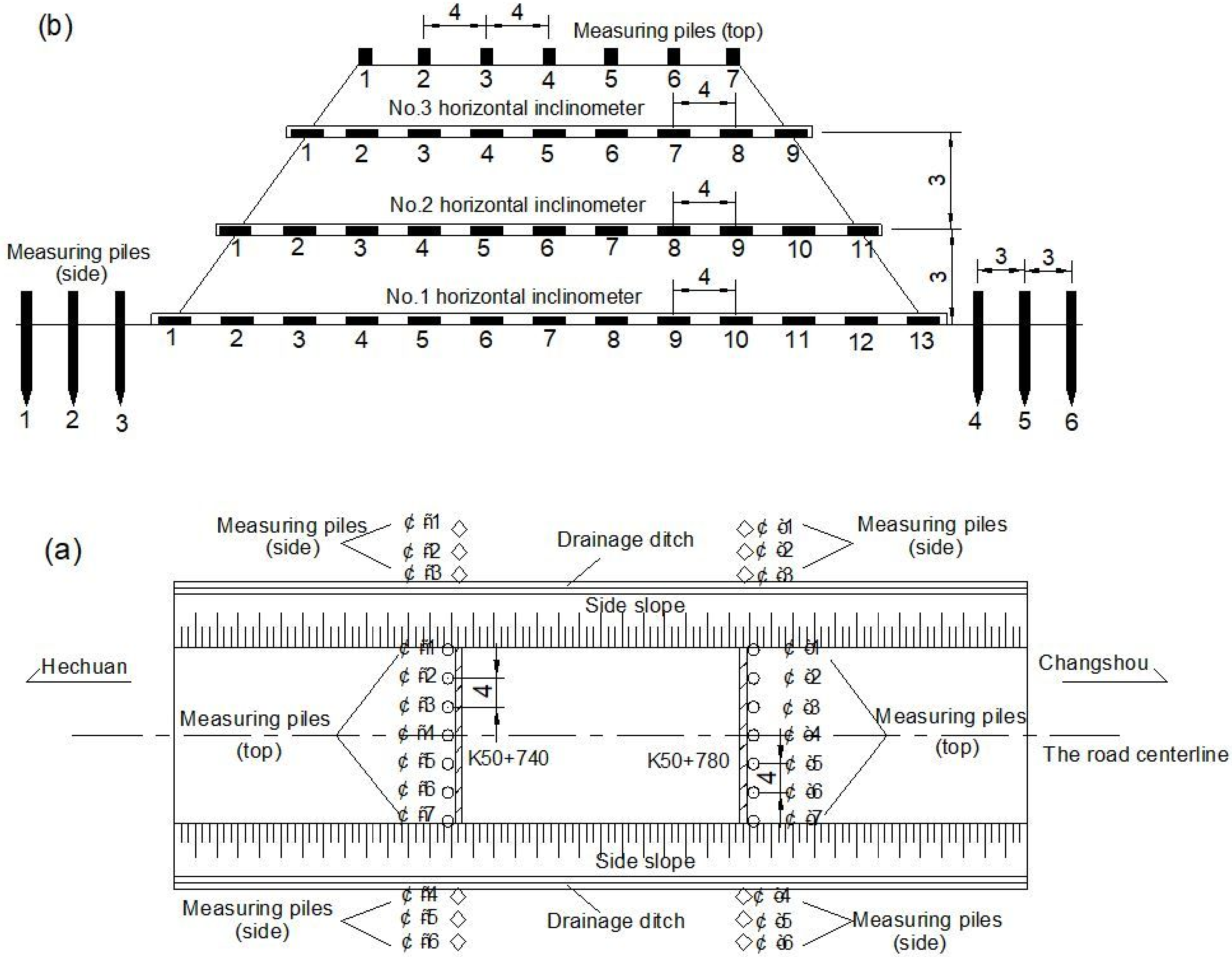

Figure 11

Layout of test instruments and monitoring points. (a) Plan (b) Elevation

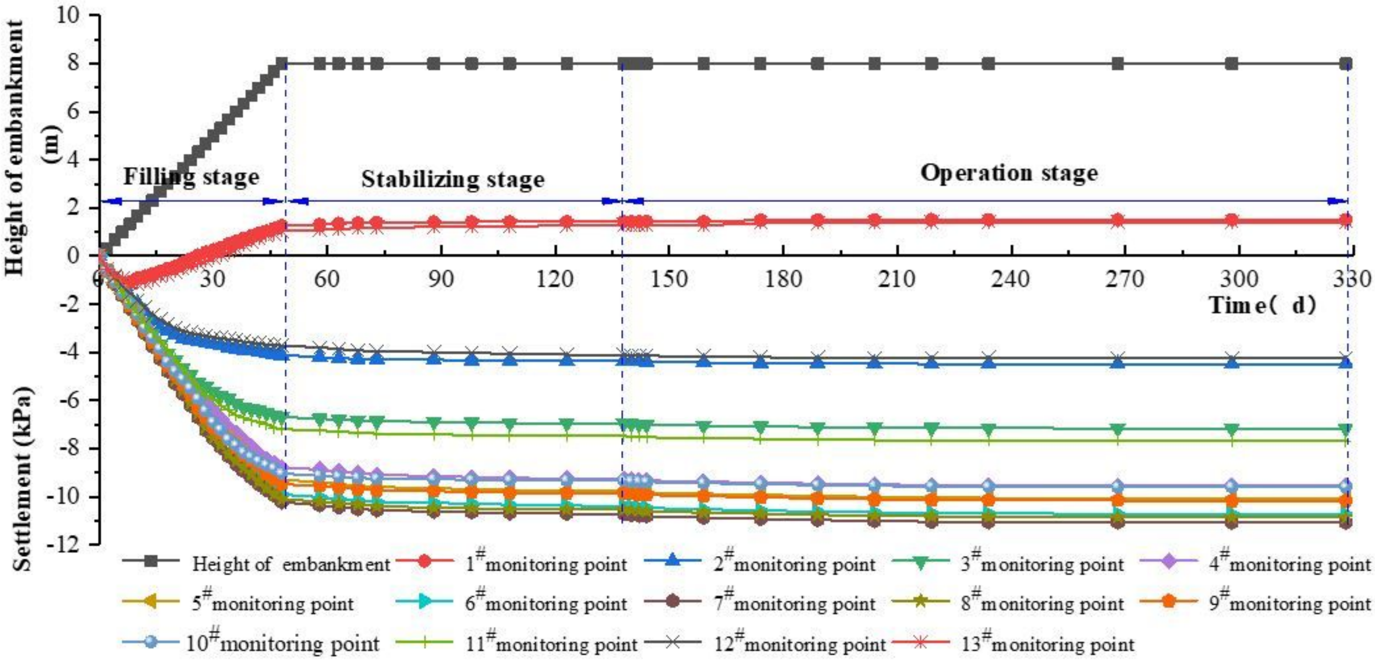

Figure 12

Load-time-settlement curve of No.1 horizontal inclinometer.

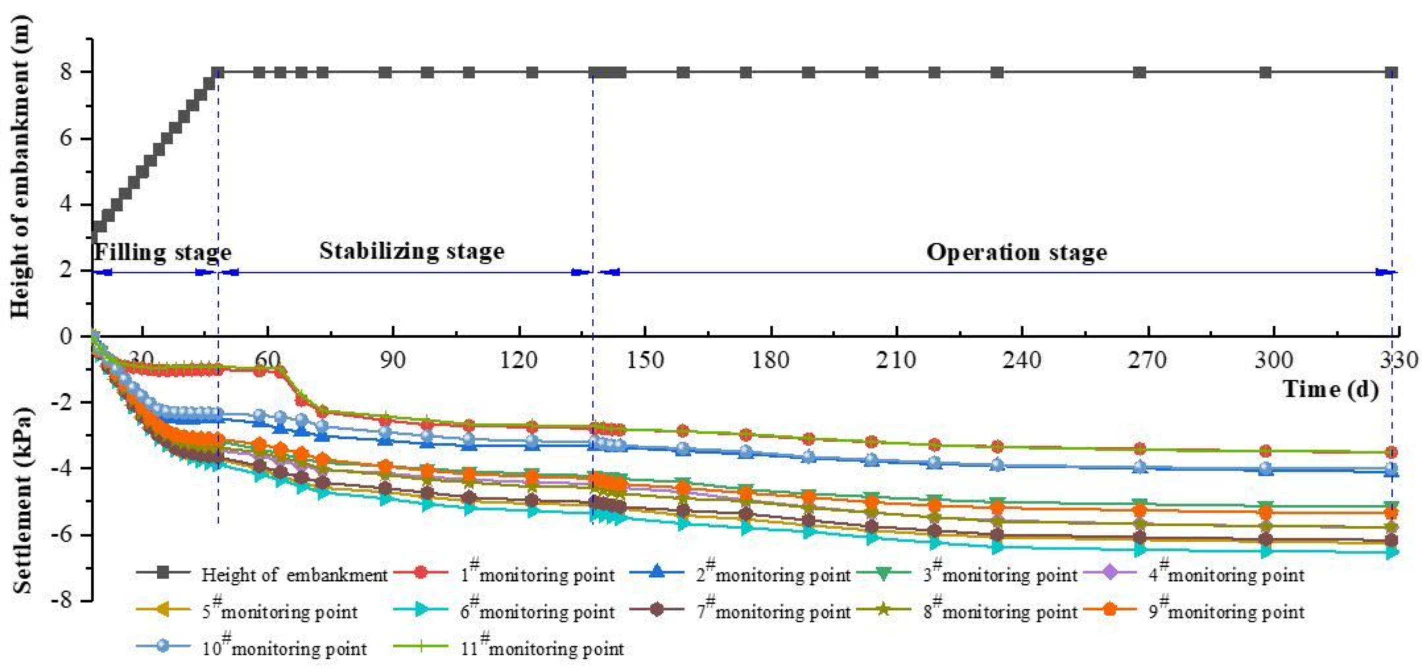

Figure 13

Load-time-settlement curve of No.2 horizontal inclinometer.

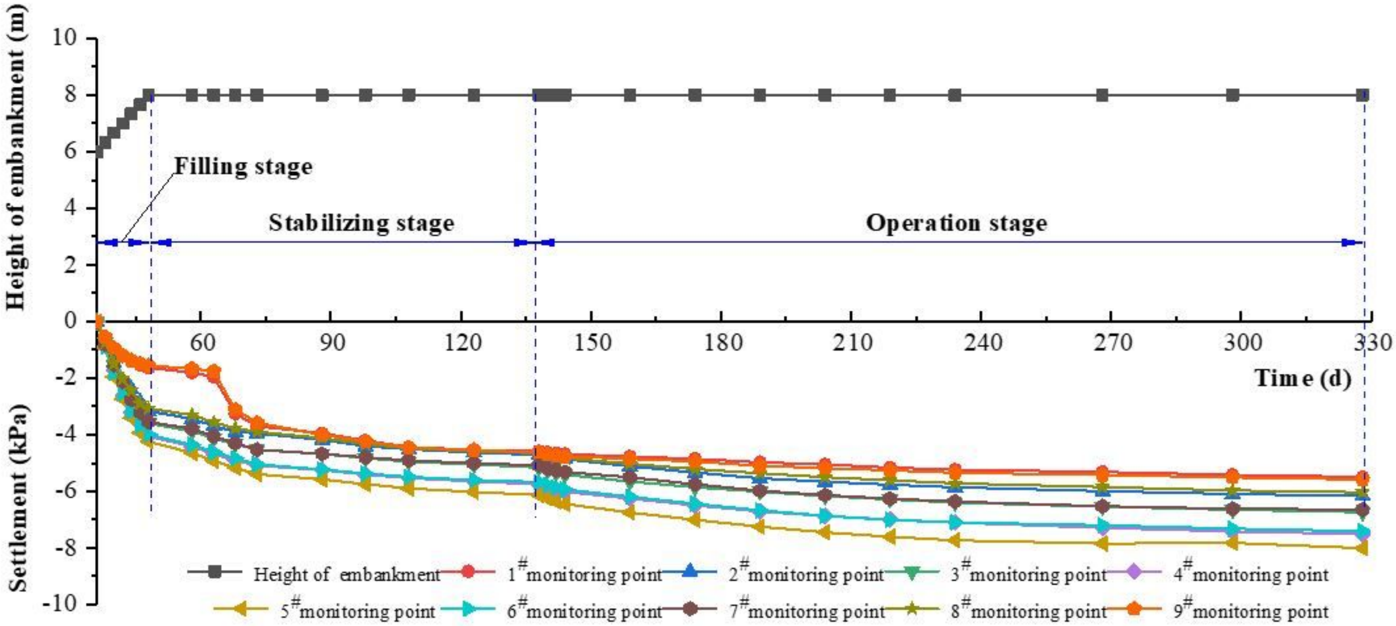

Figure 14

Load-time-settlement curve of No.3 horizontal inclinometer.

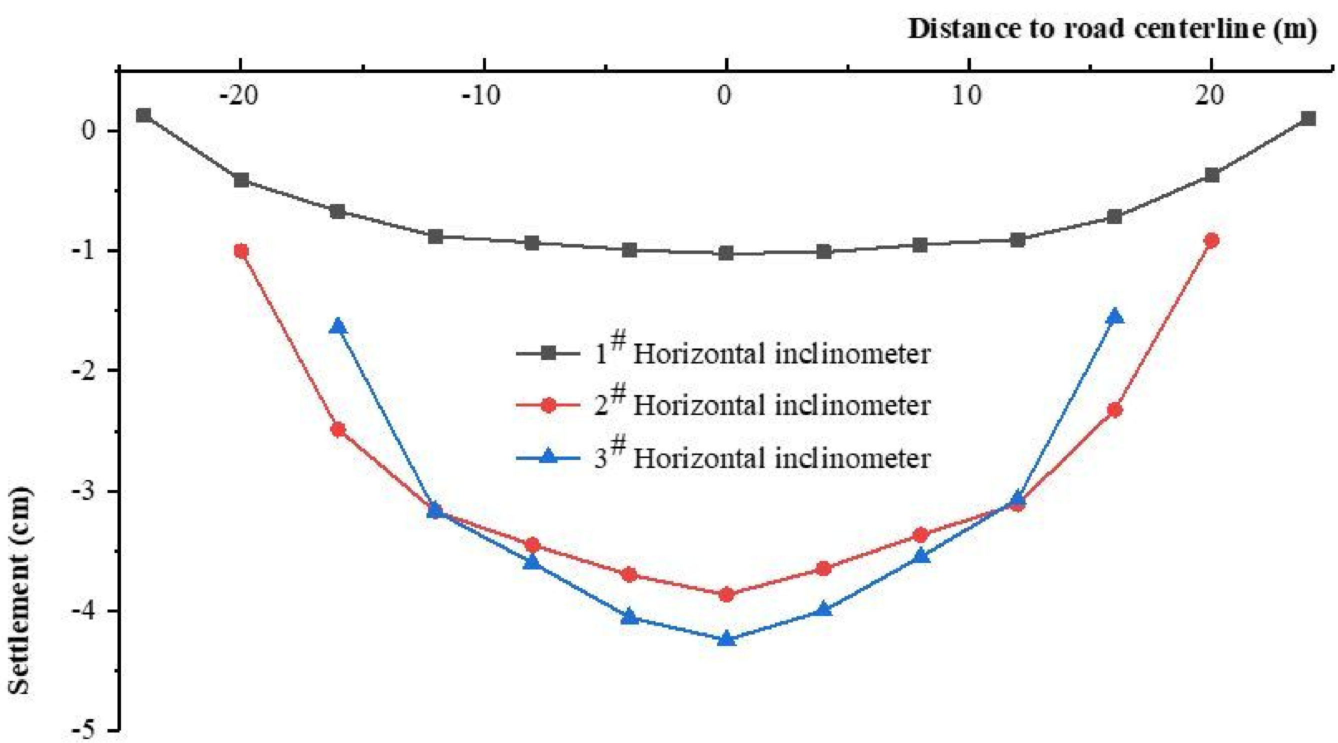

Figure 15

Settlement curve of mudstone embankment in cross-sectional direction during filling stage.

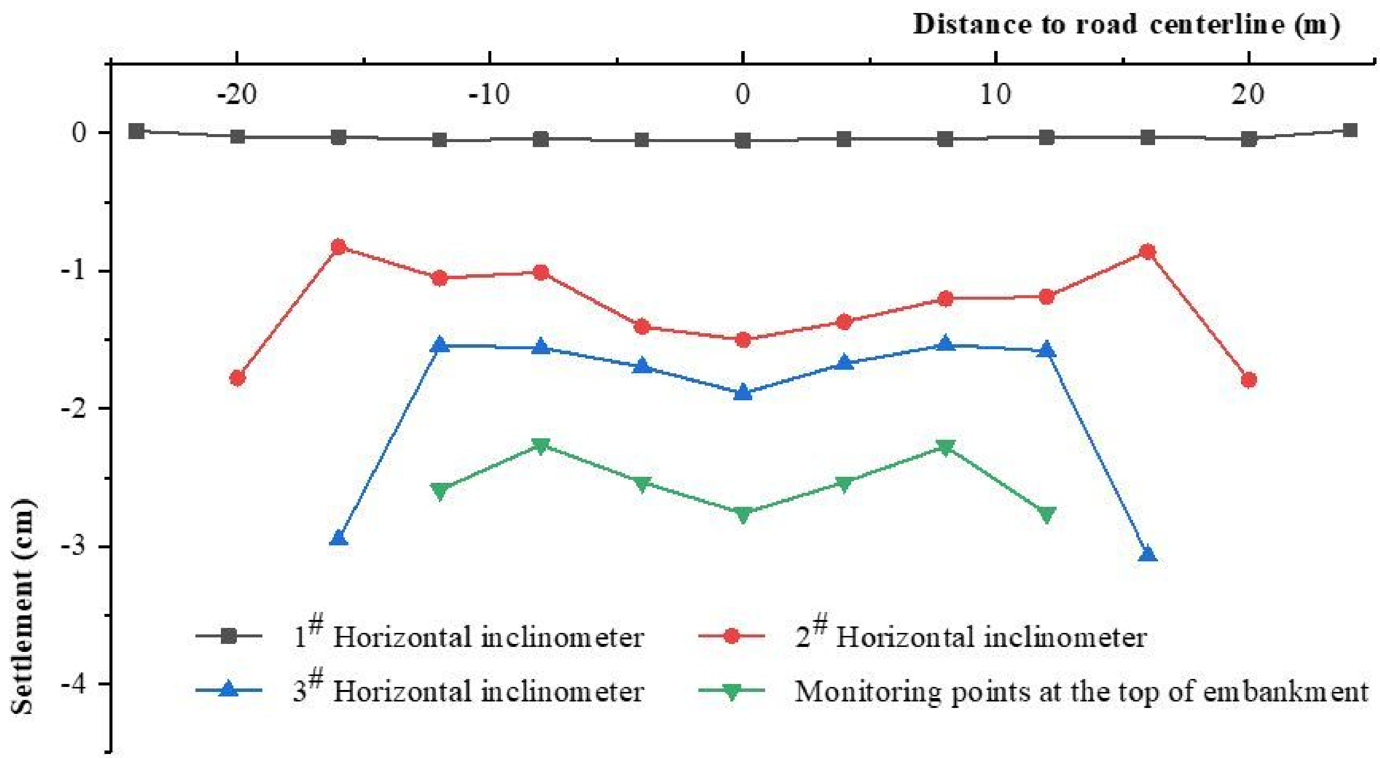

Figure 16

Settlement curve of mudstone embankment in cross-sectional direction during stabilizing stage.

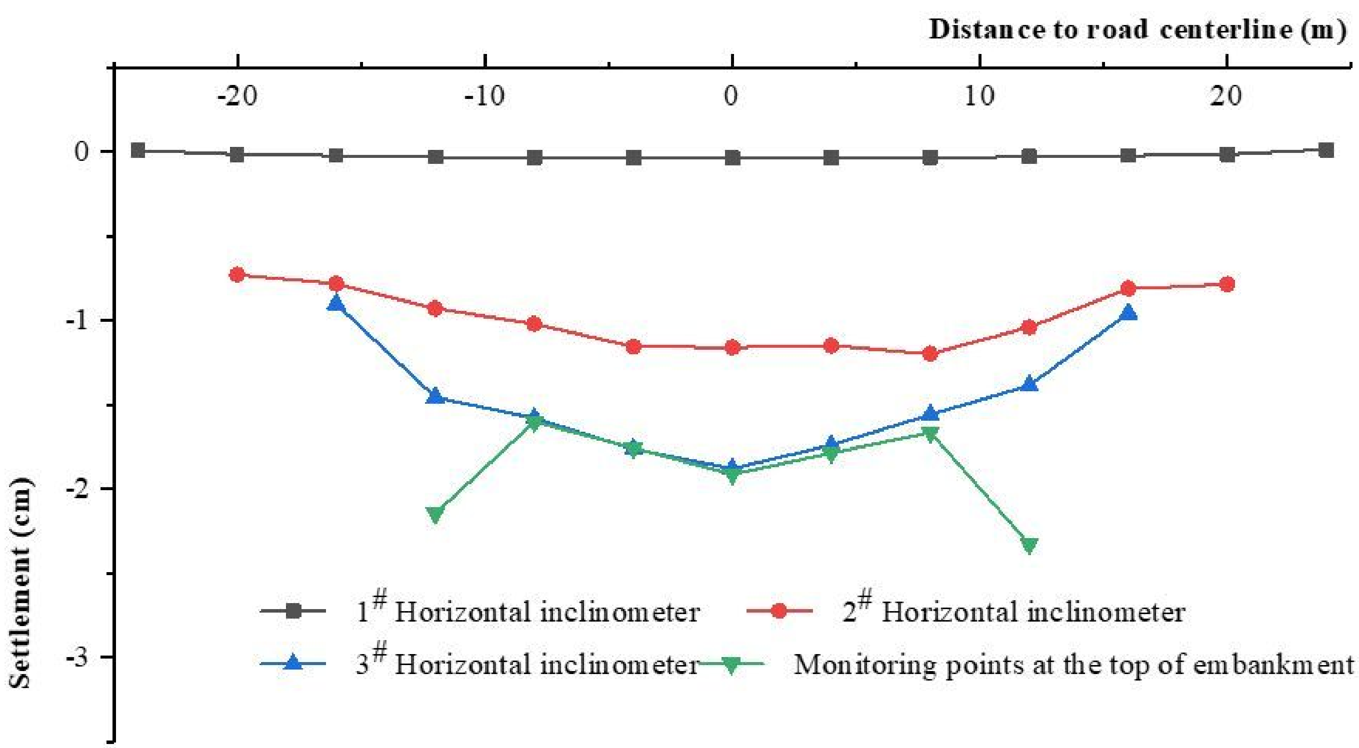

Figure 17

Settlement curve of mudstone embankment in cross-sectional direction during operation stage.