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Optimum Study on Composite Soft Foundation of Highway Cement Mixing Pile Based on Microscope Technology

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Abstract
Cement mixing pile is a common way to treat soft soil roadbed of expressway. The consolidation settlement of soft soil roadbed of expressway can be accelerated by using surcharge preloading method. The consolidation of cement mixing pile foundation of highway can be simplified as plane strain and space seepage. In order to study and predict the application of cement mixing piles in soft soil foundation treatment, PDSS method (Plane Deformation, Spatial Seepage) is used to simulate and predict the application of cement mixing piles in soft soil foundation treatment. In this paper, we mainly focus on the research of micro-image mosaic technology in automatic microscopy system, aiming at mosaic the collected micro-images from local vision into a complete image of the global reaction target. The core of image mosaic in automatic microscope system is matching and fusion technology. Aiming at the matching problem in micro image mosaic, the 0, 1 template and gray scale template are studied and analyzed. A matching algorithm based on the ratio template of analogous field character is proposed. This method is an improved gray scale template matching algorithm. It takes the ratio of four rectangular edges and two diagonal lines as the characteristics of the template, and realizes image matching by combining the pyramid idea. The results show that PDSS is suitable for the consolidation settlement of cement mixing pile foundation. The PDSS settlement curve has a high consistency with the measured settlement curve. The overall fit of the curve is high. The error is only 0.05mm when loading for 201 days. The measured values in less than 29 days and more than 200 days are basically the same as the PDSS solution, showing excellent predictive effects. Predictions indicate that the subgrade will not substantially settle after 60 days. This research has a certain guiding role for the foundation of cement mixing piles.

Key words: PDSS; Cement Mixing Pile; Soft Soil Roadbed; Prediction; Microscopic Techniques.

1. Introduction

In recent years, with the economic prosperity of China's cities, the demand for expressways is increasing, and the construction of highways is mostly soft ground. Soft soil foundation has the characteristics of large settlement, long settlement time, and easy to produce uneven settlement. Therefore, it is necessary to treat the soft soil foundation before it can be put into use [1, 2]. There are many treatment schemes for soft soil foundation, in which cement mixing pile combined with preloading method is often used to treat soft soil foundation [3]. The cement-soil mixing pile is a method for reinforcing the saturated soft clay foundation. It uses cement as a curing agent, and the soft soil and the curing agent are forcibly stirred in the depth of the foundation through a special mixing machine. The cement-soil mixing pile utilizes a series of physical and chemical reactions between the curing agent and the soft soil to harden the soft soil into a high-quality foundation with integrity, water stability and certain strength.

At present, scholars usually use field data to analyze and predict settlement or simulate it through relevant software [4]. However, empirical formulas such as curve fitting method only perform settlement analysis fitting from geometric angle, and it is difficult to accurately express the settlement law of soft soil roadbed. At present, there are few accurate reasoning, calculation prediction analysis and error research based on three-dimensional consolidation theory [5]. With the maturity of image processing technology, image mosaic is called possible. That is to say, many local images can be mosaic into a panorama with a large field of vision through image processing technology. Thus, an automatic digital microscope system has emerged. With the development of image processing technology, the automatic microscope system with image processing technology has become a new research hotspot. The automatic microscope not only contains the functions of ordinary optical microscope, but also extends many intelligent functions beyond the reach of ordinary microscope. The automatic microscope platform can precisely control each axis of the microscope, and collect all kinds of slices and objects automatically and efficiently. Ultimately, it can provide high quality panoramic view to the client to browse, which can solve many problems, such as uneven image, local information and so on.

In addition, scholars have also studied more on cement-soil mixing piles. Diamond et al believe that in the cement-soil mixing pile material, the soil sample and the cement are fully mixed to adsorb CaO in the cement to form a cement-soil composite material, which greatly improves the bearing capacity of the foundation [6]. Horpibulsuk studied the compressive strength test of a kind of cement-clay composite material, and made a comparative study of the strength and field application [7]. However, none of the above literature has analyzed the characteristics of soft soil in Guangxi, and no precise consolidation settlement analysis of cement-soil mixing pile composite roadbed has been carried out based on consolidation theory.

Based on the roadbed engineering of soft soil foundation of Guihe highway in Guangxi, this paper studies the applicability of cement-soil mixing pile in soft soil foundation in Guangxi, and analyses the consolidation settlement of the treated soft soil foundation. The submarine engineering of Guangxi Guihe highway of soft soil uses PDSS program to analyze the settlement of soft soil roadbed of cement mixing pile [8]. The PDSS theory is based on the simplified Boit three-dimensional consolidation theory. Considering the soil layer parameters, the settlement problem of soft soil roadbed can be well analyzed, and the PDSS program has fast calculation speed, low requirements on computer configuration and wide applicability [9].

2. PDSS Theory

2.1 Characteristics of PDSS Method

PDSS method is mainly used to calculate and analyze the static consolidation of saturated soft clay foundation. Composite foundations, such as sand pile composite foundation, gravel pile composite foundation and mixing pile composite foundation, can be regarded as plane deformation and spatial seepage consolidation problems. In the past, the PDSS problem was often equivalent to the analysis of general planar problems, and there were obvious limitations. PDSS is based on finite element theory and calculation formulas [5]. The finite element program compiled by Fortran can consider plane deformation, spatial seepage and two-dimensional and one-dimensional consolidation problems. The main functions and features of the program:

(1)It can perform effective stress analysis on composite foundations such as natural foundations, sand well foundations and sand piles subjected to uniform or long strip loads.

(2) It can perform linear or non-linear elastic analysis.

(3) Can consider the load stiffness.

(4) Can carry out total stress analysis.

(5)By using Front Solution to solve the finite element equations, the consolidation problem of PDSS with tens of thousands of degrees of freedom can be analyzed on a general computer.

2.2 Derivation of PDSS Method Based on Biot's Three-dimensional Consolidation Theory

In three-dimensional space coordinates, the direction of load length is taken as x direction. For PDSS problem, the x-direction displacement u=0.Therefore, in the PDSS finite element analysis, each node has only three unknowns, namely the displacements v and w along the y and x directions and the pore pressure p. Therefore, the PDSS consolidation problem can be considered as a special case when u=0 in the Biot three-dimensional consolidation problem.

Biot's three-dimensional consolidation finite element equation is derived from the spatial and temporal discretization of its three-dimensional consolidation square. Biot's three-dimensional consolidation equation consists of equilibrium equation and continuous equation. Therefore, spatial discretization can be divided into the spatial discretization of equilibrium equation and the spatial discretization of continuous equation [5].

$$
\begin{aligned}
& d_1 \frac{\partial^2 u}{\partial x^2} + d_3\left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) + (d_2 + d_3)\left(\frac{\partial^2 v}{\partial x \partial y} + \frac{\partial^2 w}{\partial x \partial z}\right) - \frac{\partial p}{\partial x} = 0 \\
& d_1 \frac{\partial^2 v}{\partial y^2} + d_3\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial z^2}\right) + (d_2 + d_3)\left(\frac{\partial^2 v}{\partial y \partial x} + \frac{\partial^2 w}{\partial y \partial z}\right) - \frac{\partial p}{\partial y} = 0 \\
& d_1 \frac{\partial^2 w}{\partial z^2} + d_3\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right) + (d_2 + d_3)\left(\frac{\partial^2 v}{\partial z \partial x} + \frac{\partial^2 w}{\partial z \partial y}\right) - \frac{\partial p}{\partial z} = 0
\end{aligned}
\qquad (1)
$$

$$\frac{1}{\gamma_{\omega}}\left[k_A\left(\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}\right)+k_v\frac{\partial^2 p}{\partial z^2}\right]=\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right) \tag{2}$$

Equilibrium equation expressed by total stress after spatial discretization:

$$\iint_{D^e}[B]^T\{\sigma\}dxdydz=-\iint_{D^e}[N]^T\{F\}ds \tag{3}$$

The relationship between $\{\sigma\}$ and element nodal displacement and nodal pore pressure is as follows:

$$\{\sigma\}=-[D]([\partial][N])\{\delta\}^e+\{M\}[\overline{N}]\{p\}^e=[D][B]\{\delta\}^e+\{M\}[\overline{N}]\{p\}^e \tag{4}$$

By substituting the formulas above into the equilibrium equation, we can get that:

$$[K_e]\{\delta\}^e+[K_c]\{P\}^l=[R_F]^e \tag{5}$$

Using the same method as the spatial dispersion of the equilibrium equation, the equation for eliminating the internal residuals of the continuous equation unit can be obtained:

$$\iiint_{V^l}N_I\left(\{M\}^T[\partial]\frac{\partial\{f\}}{\partial t}-\{M\}^T[\partial][k][\partial]^T\{M\}p\right)dxdydz=0 \quad i=1,2,\cdots,8 \tag{6}$$

From the flow velocity boundary condition and the weighted residual method, the equation for eliminating the residue of the flow velocity boundary is obtained as follows:

$$\iint_{D^l}N_I\left[\frac{k_h}{\gamma_{\omega}}\left(l\frac{\partial p}{\partial x}+m\frac{\partial p}{\partial y}\right)+\frac{k_{\upsilon}}{\gamma_{\omega}}n\frac{\partial p}{\partial z}\right]^T ds=0 \quad i=1,2,\cdots,8 \tag{7}$$

$$\begin{aligned}&-\iiint_{V^{\ell}}N_I\{M\}^T[\partial][N][\delta]^{\ell}\{M\}dxdydz\\&+\iiint_{V^{\ell}}\{\nabla\}^T N_I[k]\{\nabla\}[\overline{N}]\{p\}^{\ell}dxdydz=-\iint_{D^{\ell}}N_I\upsilon_n ds\end{aligned} \tag{8}$$

After each node is expanded, there are eight equations, which are expressed as matrices.

$$[K_{\ell}]^T\{\delta\}^{\ell}-[K_s]\{P\}^{\ell}=\{R_F\}^{\ell} \tag{9}$$

The equilibrium equation and the continuum equation after spatial discretization are called the Biot three-dimensional consolidation equation after spatial discretization [1-3].

The $\{\delta\}^e$ with the first differential term of nodal displacement with respect to time needs to be further discretized in time domain to obtain the linear equations for solving nodal displacement and pore pressure.

For this reason, t_n and t_{n+1} are considered as two points in time domain, and the displacement and pore pressure of t_n are $\{\delta\}_n^{\ell}$ and $\{p\}_n^{\ell}$ respectively. The nodal displacement and pore pressure increment of element in period $\Delta t=t_{n+1}-t_n$ are $\{\Delta\delta\}^{\ell}$ and $\{\Delta p\}^{\ell}$, respectively. The nodal displacement and pore pressure of period t_{n+1} can be expressed as follows:

$$\{\delta\}_{n+1}^{\ell}=\{\delta\}_n^{\ell}+\{\Delta\delta\}^{\ell} \tag{10}$$

$$\{p\}_{n+1}^{\ell}=\{p\}_n^{\ell}+\{\Delta p\}^{\ell} \tag{11}$$

This allows the equilibrium equation to be written in incremental form:

$$\left[K_\ell\right]\{\Delta\delta\}^\ell+\left[K_C\right]\{\Delta p\}^\ell=\{\Delta R_F\}^\ell \tag{12}$$

Where $\{\Delta R_F\}^\ell$ is the incremental array of equivalent node load in the Δt period, 24×1 order, and the calculation formula is:

$$\{\Delta R_F\}^l=\iint_{D^C}[N]^T\{\Delta F\}^l ds \tag{13}$$

$$\{\Delta R_F\}^l=\begin{Bmatrix}\Delta R_X\\ \Delta R_Y\\ \Delta R_Z\end{Bmatrix} \tag{14}$$

Then, the integrals of t from t_n to t_{n+1} on both sides of the continuous equation are obtained.

$$\int_{t_n}^{I_{n+1}}\left[K_c\right]^T\{\delta\}^e dt-\int_{t_n}^{I_{n+1}}\left[K_s\right]\{p\}^e dt=\int_{t_n}^{I_{n+1}}\left[R_q\right]^e dt \tag{15}$$

The approximation formula is used:

$$\int_{t_n}^{I_{n+1}}\{p\}^\ell dt\approx\left(t_{n+1}-t_n\right)\left[\theta\{p\}_{n+1}^\ell+(1-\theta)\{p\}_n^\ell\right]=\Delta t\left(\{p\}_n^\ell+\theta\{\Delta p\}^\ell\right) \tag{16}$$

Available:

$$\left[K_c\right]^T\{\delta\}^e-\theta\Delta t\left[K_s\right]\{\Delta p\}^e=\left[\Delta R_q\right]^e \tag{17}$$

The three-dimensional consolidation equations after spatial and temporal dispersion are combined to obtain the Biot three-dimensional consolidation finite element equation:

$$[K]\{\Delta U\}^\ell=\{\Delta R_q\}^\ell \tag{18}$$

When the displacement u=0, the rows and columns corresponding to the x-direction displacement u in the unit consolidation matrix [K] are deleted, and the order is reduced from 3232 to 2424. The simplified matrix [K] consists of eight 3×3 sub-matrices, namely [1]:

$$\left[K_{ij}\right]=\begin{bmatrix}K_{ij}^6 & K_{ij}^7 & K_{ij}^8\\ K_{ij}^{10} & K_{ij}^{11} & K_{ij}^{12}\\ K_{ij}^{14} & K_{ij}^{15} & K_{ij}^{16}\end{bmatrix}(i,\ j\ =\ 1,2,\ldots,8) \tag{19}$$

The unknown incremental matrix $\{\Delta U\}^e$ of element nodes and the reduced order of element node load and flow incremental matrix $\{\Delta R\}^e$ to 24×1 are composed of eight 3×1 sub-matrices, namely:

$$\{\Delta U_i\}^e=\left[\Delta\upsilon_i\quad \Delta\omega_i\quad \Delta p_i\right]^T\ (i=1,2,\ldots,8) \tag{20}$$

$$\{\Delta R_i\}^e=\left[\Delta R_{yr}\quad \Delta R_{xr}\quad \Delta R_{pr}\right]^T\ (i=1,2,\ldots,8) \tag{21}$$

The above formulas (18), (19), (20), (21) are simplified three-dimensional consolidation finite element equations of Biot and are the basic formulas of PDSS method [1, 5].

3. Engineering Measurement Based on Microscope Technology

This experiment takes the right section of K71+625 of Guihe Highway as the simulation section, as shown in Figure 1. The section has a width of 28m, and the thickness of soft soil is 4-6m. There is a sandy clay layer with a thickness of 3.85M in the lower layer of soft soil. Under the sandy clay layer, granite is considered as impervious layer. The road section was preloaded by cement mixing pile foundation. The weight of the piled soil was 19.1kN/m3 and the filling height was 9.13m, which lasted for 378 days. The specific loading situation is shown in Figure 2. A 0.6m sand cushion is placed above the road section to facilitate drainage. The soil layer parameters are shown in Table 1.

(a)Soft soil roadbed (b)Cement mixing pile (c)Monitoring equipment embedment

Figure 1. Scene photos

Table 1. Parameter table

Parameter	H(m)	μ	E_s(MPa)	k_v(cm/s)
Sand cushion	0.6	0.34	20	6E-3
Soft soil	5	0.385	2.5	3.59E-7
Sandy clay	3.85	0.34	15	5E-5
Mixing pile	8.85	0.3	450	1E-9

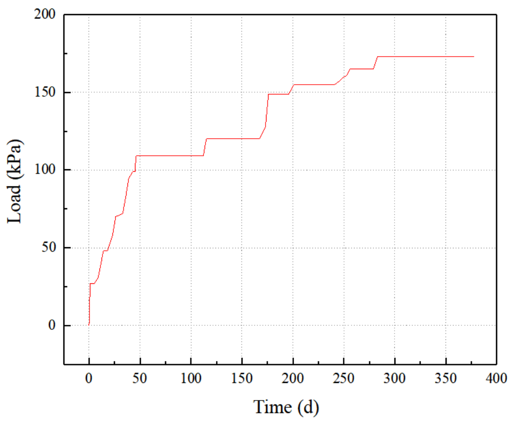

Figure 2. Time-dependent loading

The two blocks of mosaic of microscopic images are also the matching of image sequences and the fusion of matched images. At present, there are many mature methods in image registration. The feature-based method can deal with multi-scale deformation image matching. But for those images which are difficult to extract feature points, there is nothing to do, such as urine cell slices extracted by microscopy. The Open Scene Graph three-dimensional rendering engine is used to render and render the microscope scene. In the three-dimensional scene, users can magnify, roam and observe the microscope from multiple perspectives, and select, move and rotate the components of the microscope. The automatic microscope mainly consists of three parts: the platform of the microscope, the computer and the control part. The microscope is equipped with image acquisition equipment and image acquisition card. The control box controls the stepper motor. The three stepper motors control the precise movement of the XYZ axis in three axes. Mainly responsible for two-dimensional experimental data display and text description. When virtual experiments are carried out, users can observe the experimental phenomena displayed by microorganisms on slide through a microscope. When users operate the functional platform, they can also display the description of functional components.

4. Computation and Analysis Based on PDSS Method

4.1. Computational Model

PDSS method is used to calculate and analyze the project, and cement mixing pile is selected for construction [2]. The soft soil foundation is drilled in square arrangement. The average thickness of soft soil is 5m, the diameter of cement mixing pile is 500mm, and the spacing is 1300mm, which runs through the soft soil layer. The layout scheme is shown in Figure 3.

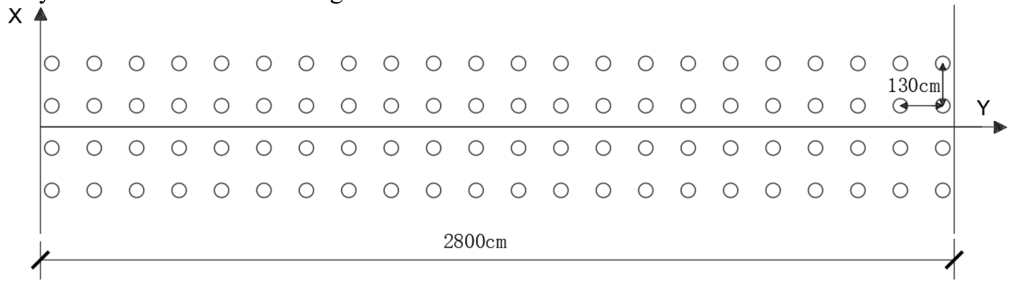

Figure 3. Plane layout scheme of cement mixing pile

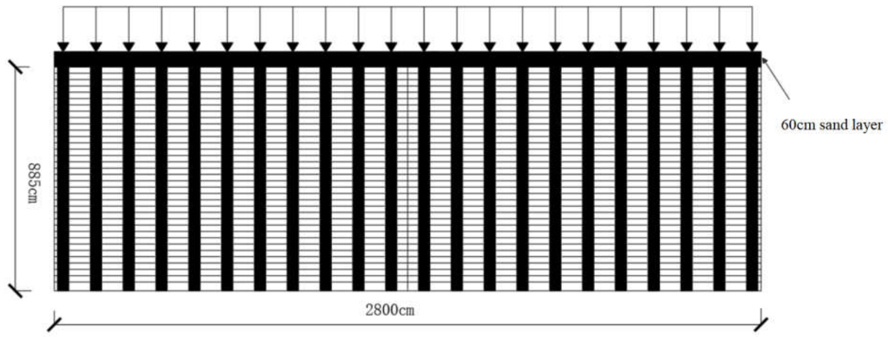

Figure 4. Unit partition diagram

(1)Determination of computational domain

For PDSS problem, when the pile body is square distributed, the height of calculation domain (the distance between upper and lower) is taken as the thickness H of soft soil or compression layer of foundation. The thickness of calculation domain (the distance between front and back) is taken as half of the distance between piles, i.e. S/2.It can be seen from the symmetry that any plane that is normal to the load length direction (i.e., X direction) and passes through the center of the pile or the center of the pitch is a plane of symmetry. On these symmetry planes, the X-direction displacement is zero and no seepage occurs. Therefore, the calculation domain only needs to take the separator between any adjacent symmetry planes, and the thickness is S/2.

According to the calculation domain determination principle, the entire soft soil base calculation domain is determined to be 0.65m×28 m×8.85m. 22 cement mixing piles were arranged along the Y direction. According to the principle of area equivalence, the circular mixing pile with diameter of 500mm is equivalent to a square, and the square side length is $\sqrt{\pi}d/2 \approx 0.8862d$. The calculated side length is 440mm.

(2)Unit partition

According to the above conditions, the general principle of element meshing is that the areas with large pore pressure and stress (or stress) variation (gradient), such as sand well area, load area and near the water permeability surface, should be dense and the other parts can be sparse. Along the X-axis direction, it is divided into two units, 220 mm mixing pile unit and 430 mm long soil unit. There are 46 units in the Y direction, 22 440 mm mixing pile units, and one 860 mm soil unit between each two sand wells. There are two 430mm soil units at the center, and the left and right sides of the Y axis are soil units with a width of 130mm. 36 units are divided along the z direction, with a width of 0.6 m sand layer unit from top to bottom, 34 width 0.25 m units, and 1 width 0.35 m unit. The vertical unit division diagram is shown in Figure 4.

(3) Boundary conditions

Both the front and the back are set to a watertight boundary, and the x direction is fixed, and the y and z directions are free. The left and right sides generally pass through the center of the load, which is a plane of symmetry, fixed in the y direction, free in x and z directions, and impervious to water. The upper permeable boundary is fixed in x direction and free in y and z direction. The following is impervious surface and fixed in x, y and z directions.

(4)Calculating Series, Time Period and Load Division

During the filling period, the calculation series, time period and load division are consistent with the actual project. The thickness of filling soil is converted into filling load, i.e. total load p0= 173KPa. After 283 days, the filling load will be full and the total loading time will be 378 days. As shown in Figure 1.

4.2. Result Analysis

The PDSS solution and the measured settlement time history curve are plotted as shown in Figure 5. As shown in Figure 5, the PDSS solution time history curve is in good agreement with the measured settlement time history curve, showing an exponential growth curve. From the overall trend of PDSS solution time history curve, it can be seen that the settlement of foundation consolidation in the early stage is larger, and with the increase of time, the settlement increment gradually decreases and slowly tends to be stable. In the early and middle stages of loading, the PDSS solution coincides with the measured settlement, and the curves of < 36 days and > 90 days coincide basically, which indicates that the time history curve of PDSS solution has better prediction effect on foundation settlement. In 36 to 90 days (pre-filling and mid-filling), the difference between measured settlement and PDSS solution is large. According to the time-error curve shown in Figure 5, the maximum deviation is 32.01 mm. Further, combined with the time-error curve of Figure 3, it can be seen that the PDSS solution is smaller than the measured settlement, and the minimum error is only 0.05 mm as the loading time error decreases. It can be seen from the analysis that the initial soft soil foundation has high water content, large compression coefficient and dispersed soil particles, and is prone to large settlement, i.e. instantaneous settlement, at the initial stage of filling load. With the continuous application of load and the passage of time, the excess pore water pressure in the foundation soil dissipates rapidly, the pore water gradually discharges, and the excess pore water pressure gradually decreases. With the continuous application of load and the passage of time, the soil gradually compacts to produce compressive deformation and enters the elastoplastic state. The settlement rate of the foundation is large at this stage. At this stage, the settlement of the foundation accounts for a large proportion of the total settlement. The total settlement of soft soil roadbed is 215mm, and within 43 days, the settlement amount reaches 107mm, reaching 50% of the total settlement. As the settlement increases, the soil gradually becomes denser, the compressive modulus increases, and the sedimentation increment gradually decreases and tends to be stable. The settlement stopped after 283 days, and it was found that the settlement of the foundation was only 14 mm in 283 days to 378 days, so the time-history curve of the foundation settlement was approximately exponential. The settlement of the soft foundation has experienced a period from occurrence to development to stability.

Comparing the ground settlement time history curve and the loading time history curve (Figure 2), it can be found that the two curves have similar trends. This is due to the change of the stress state in the foundation soil under the load of the foundation, which causes the foundation to deform and the settlement of the roadbed. Settlement values show a stepped shape with the change of filling load, which reflects the characteristics of subsidence development of foundation soil under the action of step loading.

The consolidation settlement development of the cement mixing pile soft soil foundation is predicted by PDSS method. The prediction time is 60 days. See the "PDSS prediction section" in Figure 5. The prediction shows that the consolidation of soft soil foundation with cement mixing piles is basically completed, and the slope on the 60th day is predicted to be 0, indicating that the increase of settlement is almost no longer increased. The predicted settlement on the 60th day is 214.31mm, which is less than the measured value. It is further concluded that the consolidation settlement of cement mixing pile is analyzed by PDSS method, and the later calculation value is less than the measured value.

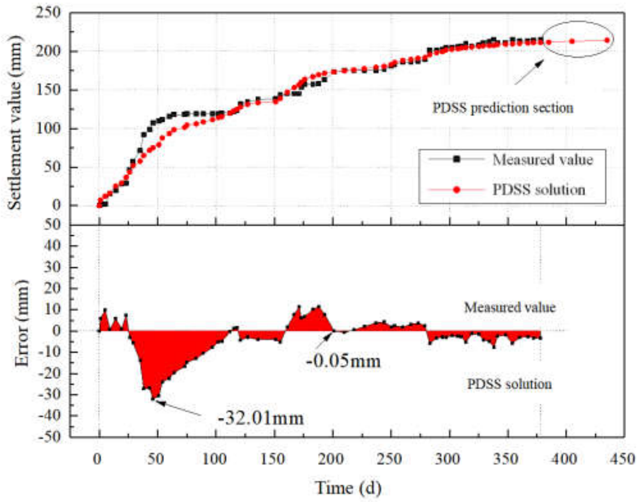

Figure 5. Loading Time-Subgrade Settlement Diagram

5. Conclusions

In this paper, the consolidation settlement of cement mixing pile foundation under surcharge preloading is simulated and predicted by PDSS program based on simplified Boit three-dimensional consolidation theory relying on the actual soft soil roadbed project, and verified by the measured settlement in situ. Some useful conclusions are drawn. In this paper, several matching methods in image matching are analyzed and studied. Through the analysis of 0 and 1 template matching and the best gray scale template matching. An image matching method based on analogous field character ratio template is proposed. The results show that the accuracy and speed of the algorithm are improved by stitching microscopic images in different situations.

(1)Based on Biot's three-dimensional consolidation theory, considering pore water pressure, combined with equilibrium equation and continuity equation, PDSS method in matrix form can be derived.

(2)The settlement curve obtained by PDSS simulation has a high consistency with the measured curve. The curves less than 36 days and more than 90 days are basically coincident, indicating that the PDSS program has a good predictive effect on the settlement of cement mixing pile foundation.

(3)The measured values of less than 36 days and more than 90 days are basically the same as those of PDSS solution. Therefore, in the case of long loading time, using PDSS program simulation has a high accuracy. It is further found that the PDSS solution is generally smaller than the measured settlement value.

(4)Based on the theory of PDSS, the curve slope of PDSS solution is 0 after 438 days of loading, which indicates that settlement no longer occurs. The PDSS solution of 438 days is 214.31mm, which is less than the measured settlement value of 378 days. It further shows that the overall settlement value calculated by PDSS program is small, but the error is very small.

(5)Among the various methods of image fusion, this paper focuses on the analysis and research of weighted fusion and wavelet fusion. Considering the fusion effect and time efficiency, a method combining brightness equalization with gradual evolution is proposed to achieve fusion. The method is simple, effective and efficient.

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