

Research Article

Mechanics Model for Inclinator Deformation in Soft Soil and Improvement of the Measurement Method

Dengheng Zheng ^{1,2,3} Liansheng Tang ^{1,2,3} Yuxi Wang ^{1,2,3} and Yang Chen ^{1,2}

¹School of Earth Sciences and Engineering, Sun Yat-sen University, Zhuhai 519082, China

²Guangdong Provincial Key Lab of Geodynamics and Geohazards, Zhuhai 519082, China

³Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai 519082, China

Correspondence should be addressed to Liansheng Tang; eestls@mail.sysu.edu.cn

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In practical engineering, data of lateral deformation in field soft soil are measured by inclinometers. Error is always present in soft soil deformation surveys due to rigidity differences and other objective factors, which means that the measured data do not reflect the actual amount of soft soil deformation. Therefore, the forces acting on an inclinometer when soft soil deforms and the difference between the soft soil deformation and the inclinometer deformation were analyzed during this study. A mechanics model for inclinometer deformation in soft soil under different geological conditions was developed, and inclinometer deflection equations were obtained, which can be used to calculate quite accurately the maximal deformation of an inclinometer. Combined with monitoring data of an inclinometer tube in the field, this model can be used to determine whether the soft soil completely bypasses the inclinometer pipe, resulting in a complete distortion of the data measured by the inclinometer tube. On this basis, an improved method for performing inclinometer pipe measurements was proposed, recommending that a new inclinometer be inserted to continue the observations when the original inclinometer reaches its ultimate strain.

1. Introduction

In practical engineering, the lateral deformation of soft soil is measured by inclinometers and side piling [1–3]. Since the top of the soft soil generally has a hardpan, the difference in stiffness between the hard shell layer and the underlying soft soil layer causes the deformation of the crust layer to be much smaller than that of the soft soil layer in the subgrade [4–6]. Therefore, it is difficult to accurately detect the actual lateral displacement of the soft soil by embedding side piling in the hard surface crust [7, 8]. After recognizing the limitations of side piling, scholars have generally used inclinometers to observe the lateral deformation of soft soil in recent years [9, 10].

A traditional geotechnical inclinometer system primarily consists of an inclinometer probe, an inclinometer pipe with a guide slot, a cable with a scale, and a data acquisition and storage device [11–13]. There are errors associated with this

method when obtaining data on the lateral deformation of the soft soil subgrade. Lateral deformation of soft soil is caused by shear deformation, while deformation of an inclinometer is elastic deformation, which is caused by the direct thrust of the soft soil and the thrust produced by the flow [14–16]. There are essential differences between soft soil lateral deformation and inclinometer pipe deformation [17, 18]. The stiffness of the inclinometer pipe is much larger than that of the saturated soft soil, which means that the soft soil and the inclinometer cannot coordinate their deformations; so, the horizontal displacement of the soft soil is greater than the deformation of the inclinometer pipe [19, 20].

At present, using an inclinometer is still the best way to measure the lateral deformation of soft soil. Therefore, it is very important for real-time analysis data to predict inclinometer failure to avoid subsequent invalid monitoring. Research regarding inclinometer system applications has

primarily focused on analyzing measurement error [21–23] and accuracy as well as the processing methods of measured data [24–26]. Dowding and Connor concluded that slope inclinometers are especially sensitive to gradual changes in inclination by comparing TDR (Time Domain Reflectometry) technology and slope inclinometer measurements [27]. Li and Chen used the elastic theory to integrate the horizontal stress caused by an embankment load. They obtained the horizontal force and displacement of the inclinometer pipe and believed that the interaction mechanism between the inclinometer pipe and the soft soil could be further discussed theoretically [28]. Liu et al. derived the limiting curvature or the limiting angle of an inclinometer pipe by using the geometric relationship between the inclinometer probe and the pipe. They compared the results with actual monitoring data to determine the invalidation of the inclinometer pipe [29]. Fosalaui et al. presented a new type of inclinometer for detecting and measuring very small ground displacements in incipient landslides [30].

Since inclinometer pipe deformation is not the same as that of soft soil, a mechanics model for soft soil under different geological conditions was developed. The model was based on an analysis of the relationship between the lateral deformation of soft soil and the deformation of an inclinometer pipe. The model was validated by field measurement data and a determination criterion of whether the soft soil completely bypasses the inclinometer was established. On this basis, an improved method was proposed for performing inclinometer measurements.

2. Mechanics Model for Inclinometer Deformation

Typically, the bottom of an inclinometer is extended to a hardpan that experiences little or no displacement. However, there is no specific requirement for the top of an inclinometer. Due to complex geological conditions, the forces acting on an inclinometer pipe are different under different geological conditions, so a uniform stress model to describe the deformation of the inclinometer pipe is difficult to establish. Therefore, two types of mechanics models are proposed in this paper.

2.1. One End of the Inclinometer Constrained. It was assumed that the inclinometer pipe is elastic, that the soft soil layer is single, homogeneous, and isotropic, and that the lower soil layer of the soft soil layer is hard or bedrock. The inclinometer pipe penetrates through the soft soil and enters the hard soil layer at the bottom. The soft soil extruded by the roadbed load deforms, and the inclinometer pipe is pushed to generate elastic deformation during the flow process of the soft soil. The deformation of the inclinometer is related to the pressure of the soft soil.

2.1.1. Mechanics Model When the Soft Soil Does Not Completely Bypass the Inclinometer Pipe. When the soft soil does not completely bypass the inclinometer pipe, there is an intersection “A” between the deformation curve of the pipe

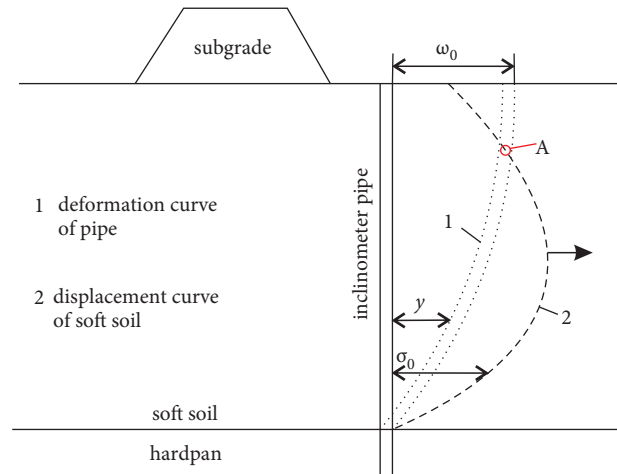


FIGURE 1: Schematic of the inclinometer pipe and soft soil deformations.

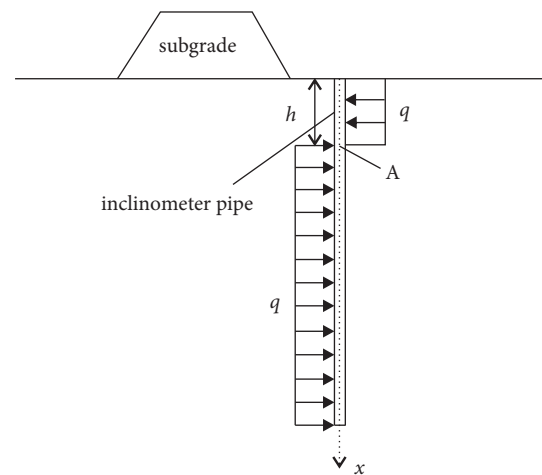


FIGURE 2: Stress analysis of the inclinometer.

and the lateral deformation curve of the soft soil. As shown in Figure 1, σ_0 represents the actual lateral deformation of the soft soil, y is the measured deflection of the inclinometer tube, and ω_0 is the deflection of the top of the inclinometer.

Point A indicates that the lateral displacement of the soft soil is the same as the deformation of the inclinometer pipe. Because of the stiffness of the inclinometer pipe and its other characteristics, the deformation of the upper portion is greater than that of the lower portion, especially at the upper and lower boundaries of the soft soil layer. Therefore, below point A, the displacement of soft soil is greater than the amount of deformation of the pipe. Shear failure of the soft soil is due to shear stress on the shear surface, which is equal to the shear strength. According to the interaction between the forces, the force on the inclinometer pipe is also equal to the shear strength. Above point A, the displacement of the soft soil is smaller than the deformation of the pipe, and the soft soil bypasses the pipe in the opposite direction. The pipe is subjected to a resistance equal to the shear strength of the soft soil. If the force between the inclinometer and the soil is less than the shear strength of the soft soil, shear failure will

not occur, indicating that soil did not flow past the pipe. According to Figure 2, when soil flows past the pipe, the stress on the pipe should be equal to the sum of the maximum shear stress that the soft soil can bear and the friction between the soft soil and the pipe.

The shear strength of the soft soil, τ , can be conveniently expressed using the Mohr-Coulomb strength criterion as follows:

$$\tau = c + \tan \varphi, \quad (1)$$

where c represents the cohesion and φ is the inner friction angle.

The friction force, f , on the pipe when the soft soil flows around it can be calculated as follows:

$$f = \mu N, \quad (2)$$

where N represents the normal stress that the soft soil exerts on the pipe, and μ is the friction coefficient for the pipe surface. In practical engineering, most inclinometer pipes are made of the polyvinyl chloride plastic, which has a friction coefficient of 0.04.

The thrust, q , of the inclinometer pipe for a unit length is given by

$$q = \tau d + \mu \tau = (d + \mu)\tau, \quad (3)$$

where d represents the outside diameter of the inclinometer pipe and μ is the friction coefficient for the pipe surface.

It was assumed that the junction of the pipe and the soft soil is at the origin and the vertical downward direction is the positive X -direction. According to the force deformation formula of material mechanics, the equation of the deformation curve can be expressed as follows:

$$\omega = \frac{1}{EI} \begin{bmatrix} -\frac{q}{24}x^4 + \frac{q}{24}(x-h)^4 \\ +\frac{q}{6}L^3x - \frac{q}{3}(L-h)^3x \\ +\frac{q}{3}L(L-h)^3 - \frac{qL^4}{8} - \frac{q(L-h)^4}{12} \end{bmatrix}. \quad (4)$$

The deflection of the pipe at the top of the soft soil can be expressed as follows:

$$\omega_0 = \frac{[qL(L-h)^3/3 - qL^4/8 - q(L-h)^4/12]}{EI}, \quad (5)$$

where ω represents the deformation deflection of the pipe at any depth X , ω_0 is the deformation deflection at the top of the pipe, h is the depth of point A, L is the length of the inclinometer pipe, E is the elastic modulus of the inclinometer pipe, and I is the moment inertia of the pipe.

2.1.2. Mechanical Model for an Inclinometer Pipe in the Critical State. When the soft soil is in the critical state of completely bypassing the inclinometer pipe, point A is located at the top of the soft soil layer. The deformation curve

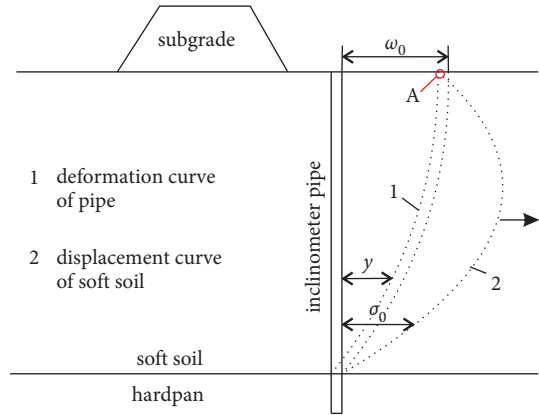


FIGURE 3: Schematic of the deformations of the inclinometer pipe and soft soil.

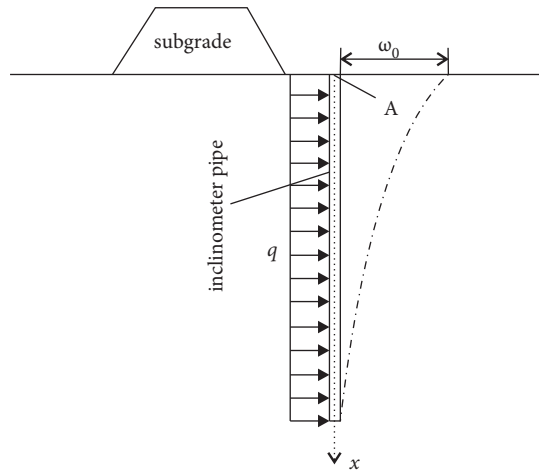


FIGURE 4: Stress analysis for the inclinometer in the critical state.

for the inclinometer pipe and the actual lateral deformation curve for the soft soil are shown in Figure 3.

In the critical state, the inclinometer pipe is pushed by the soft soil, and the stress between the measured point on the pipe and the soft soil is equal to the shear strength of the soil. The intersection of the deformation curve and the lateral deformation curve of the soft soil is located at the top of the soft soil layer. The force on the inclinometer pipe is shown in Figure 4.

According to the bending deformation principle, it was assumed that the junction of the pipe and soft soil is at the origin and the vertical downward direction is the positive X -direction. An expression for calculating the deflection of the pipe can be obtained for these conditions:

$$\omega = \frac{q}{24EI} (-3L^2 - 2Lx - x^2)(L-x)^2. \quad (6)$$

The deflection at the junction of the inclinometer pipe and the soft soil layer (point A) can be expressed as follows:

$$\omega'_0 = \frac{qL^4}{8EI}, \quad (7)$$

where ω represents the deformation deflection of the pipe at any depth X , and ω'_0 is the deformation deflection at the top of the pipe in the critical state.

If the lateral deformation of the soft soil is relatively large and the pipe is completely bypassed, the force is composed of three parts: the shear force of the soil, the thrust produced by the flow, and the friction at the inclinometer pipe surface when the soft soil flows around the pipe. According to fluid mechanics, the thrust of the inclinometer can be expressed as follows:

$$F_D = \frac{C_D \rho v^2 A}{2}. \quad (8)$$

The thrust produced by the flow is proportional to the square of the soft soil velocity. In fact, the lateral velocity of the soft soil is very small, generally only a few millimeters or centimeters per day, so the thrust generated by the flow around the inclinometer can be ignored. When the deformation of the inclinometer reaches its critical deformation deflection, even if lateral deformation of the soft soil continues to occur, the reaction force generated by the deformation of the inclinometer pipe is sufficient to resist the thrust exerted by the soft soil, and the deformation does not continue to increase. Therefore, the calculations for the deformation of the inclinometer are the same as those in the critical state and can be expressed as shown in (5).

This model can be used as a criterion to determine whether the soft soil completely bypasses the inclinometer. When the soft soil does not completely bypass the inclinometer pipe, the actual deflection, ω_0 is smaller than ω'_0 , which means that the measured data can essentially reflect the lateral deformation of the soft soil. In practical engineering, there is a small amount of deformation in the inclinometer pipe even at the end of the observation. This deformation occurs because during the process of embankment filling, as the loading time increases, the soft soil consolidates, the shear strength of the soft soil increases, the deformation of the inclinometer pipe increases accordingly, and the deflection of the inclinometer pipe increases according to the equations (6)–(8). Compared with the lateral displacement of the soft soil, the deflection of the inclinometer pipe is relatively small. When the actual measured deflection of the inclinometer pipe is larger ($\omega \geq \omega'_0$), the soft soil completely bypasses the inclinometer pipe, and the measured data show less deformation than the actual lateral of the soft soil.

2.2. Both Ends of the Inclinometer Constrained. In general, the top of the soft soil layer is covered with a hard soil layer. Sometimes, the soft soil distribution is not continuous, and there are hard interlayers. The pipe is bound at the top and bottom when buried in the hard interlayers; therefore, only the parts buried in the soft soil are free to deform. According to the soil layer characteristics, four primary simplifying assumptions were made:

- (1) There is no lateral deformation when the hard soil layer is subjected to an embankment load
- (2) The inclinometer is constrained in the hard soil layer and cannot deform freely
- (3) The soft soil layer is homogeneous and isotropic, and there is no change in the physical parameters during loading consolidation

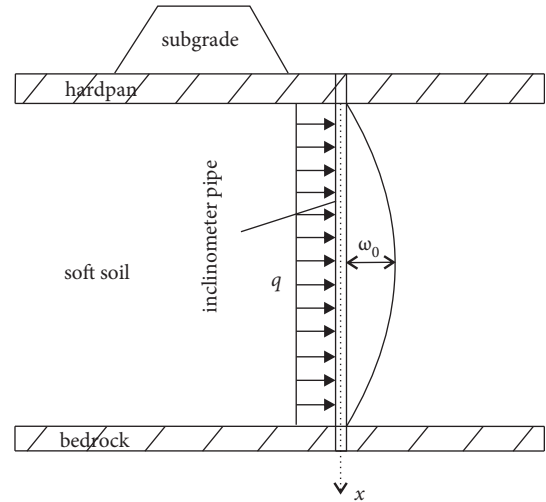


FIGURE 5: Stress analysis for the inclinometer when both ends are constrained.

- (4) The deformation of the pipe is an elastic deformation

2.2.1. Mechanical Model for a Hard Soil Layer at the Top.

The pipe penetrates through the hard shell and the soft soil and enters the hard soil layer at the bottom. Both the top and bottom ends of the inclinometer are constrained by the hard soil layers, so they cannot deform freely. Only the middle part of the pipe that is in the soft soil can deform freely. In the case of a uniformly distributed load, the maximum deformation of both ends of the rod is approximately equal to 1/10 of that at one end, and the deformation reaches a maximum in the middle. Therefore, the soft soil soon bypasses the inclinometer pipe. When the soft soil is about to completely bypass the inclinometer pipe, the force acting on the soft soil is measured as shown in Figure 5.

It was assumed that the junction of the pipe and soft soil is at the origin and the vertical downward direction is the positive X-direction. According to the force deformation equation from material mechanics, the deformation curve can be expressed as follows:

$$\omega = \frac{qx}{24EI} (2Lx^2 - L^3 - x^3), \quad (9)$$

$$\omega_0 = \frac{5q_i L_i^4}{384EI_i}, \quad (10)$$

where ω represents the deformation deflection of the pipe at any depth X and ω_0 is the maximum deflection of the pipe.

2.2.2. Mechanical Model for Hard Soil Layers at the Top and in the Middle.

In practical engineering, the distribution of the soft soil layer is not a continuous single stratum; rather, there are certain interlayers. In the case of a hard soil interlayer in the soft soil, the top, middle, and bottom of the inclinometer pipe are constrained by the hard soil layers. The deformation of the pipe is therefore greatly restricted. The soil was divided into several segments according to the

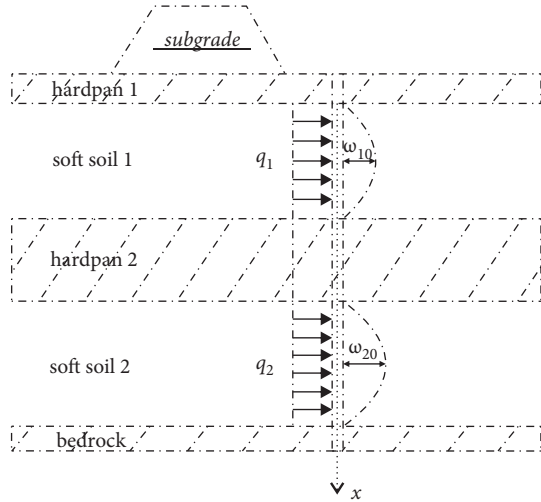


FIGURE 6: Stress analysis of the inclinometer with hard interlayer in middle.

distribution of the soft soil and hard soil layers for research purposes. The stress conditions of the inclinometer pipe under the critical state could then be analyzed, as shown in Figure 6.

The deflection of the inclinometer pipe can be expressed as follows:

$$\omega_i = \frac{q_i x_i}{24EI_i} (2L_i x_i^2 - L_i^3 - x_i^3), \quad (11)$$

$$\omega_{i0} = \frac{5q_i L_i^4}{384EI_i}, \quad (12)$$

where ω_{i0} represents the maximum deflection of the inclinometer pipe in the soft soil layer i , x_i is the depth of the soft soil in layer i (assuming that the junction of the pipe and the top of layer i is at the origin and the vertical downward direction is the positive X -direction), q_i is the thrust of the soft soil on the inclinometer pipe in layer i , L_i is the thickness of soft soil layer i , and EI_i is the bending rigidity of the inclinometer pipe in layer i .

(12) can also be used as a criterion to determine whether the soft soil completely bypasses the inclinometer. ω_{i0} is the maximum deflection of the inclinometer pipe in critical state. If the measured deflection of the inclinometer is less than ω_{i0} , the soft soil does not completely bypass the inclinometer pipe, and the measured deflection essentially reflects the lateral deformation of soft soil. If the measured deformation is greater than ω_{i0} , the soft soil completely bypasses the inclinometer pipe, and the measured deformation is less than the actual lateral displacement of soft soil.

3. Inclinometer Measurement Method Improvement

There are some disadvantages associated with the method of measuring actual lateral deformation of soft soil in situ using

an inclinometer pipe. If the actual lateral displacement of the soft soil is relatively large, the soft soil will bypass the inclinometer pipe, and this part of the lateral deformation cannot be directly reflected by the deformation of the inclinometer pipe. The observation data of the inclinometer pipe only reflect the displacement of the inclinometer pipe when it is pushed by the soft soil.

3.1. Method for Determining Whether the Soft Soil Bypasses the Inclinometer Pipe. A quantitative method for determining whether the soft soil completely bypasses the pipe can be obtained from the mechanical model for an inclinometer pipe discussed above.

There is a critical deformation deflection, ω_0 , when the soft soil is about to bypass the pipe completely. When the measured deflection is less than the critical deflection, the counterforce of the pipe is insufficient to resist the force of the soft soil, so the pipe deforms along with the soft soil. Due to the embedment and stiffness characteristics of the pipe, its deformation can only partially reflect the actual lateral deformation of the soft soil. When the measured deflection is greater than (or equal to) the critical deflection, ω_0 , the inclinometer pipe no longer deforms along with the soft soil and the inclinometer measurements are completely distorted. At this point, the deformation of the inclinometer pipe cannot reflect the actual lateral deformation of the soft soil.

3.2. Improvement of the Soft Soil Deformation Measurement Method. According to equations (7), (10), and (12), the critical deformation, ω_0 , of the inclinometer can be calculated under different geological conditions. If the measured maximum deflection is less than the critical deflection ($\omega_0 < \omega'_0$), the deformation of the inclinometer pipe is synchronous with the lateral deformation of the soft soil, and the measurement result is true. If the measured maximum deflection is greater than (or equal to) the critical deflection ($\omega_0 \geq \omega'_0$), the soft soil completely bypasses the inclinometer pipe, and the result of the measurement is distorted.

To solve the problem of the distortion of the testing method, it is necessary to know the portion of the soft soil lateral deformation that bypasses the pipe. A new pipe should be installed near the original inclinometer pipe before the deflection of the test pipe reaches its critical deformation. Because the newly buried pipe has no initial deformation, it will not produce a reaction force, and the lateral deformation will occur along with the soft soil. If the new pipe reaches its maximum critical deflection, these steps can be repeated, and another new inclinometer pipe can be embedded.

If the measured deflections of the original inclinometer pipe and the newly buried inclinometer pipe are ω_{h1} and ω_{h2} at a certain depth, the lateral deformation of the soft soil at this depth can be calculated as follows:

$$\omega_h = \omega_{h1} + \omega_{h2}. \quad (13)$$

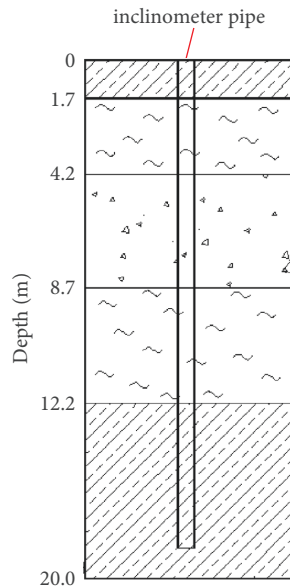


FIGURE 7: Section stratum section diagram.

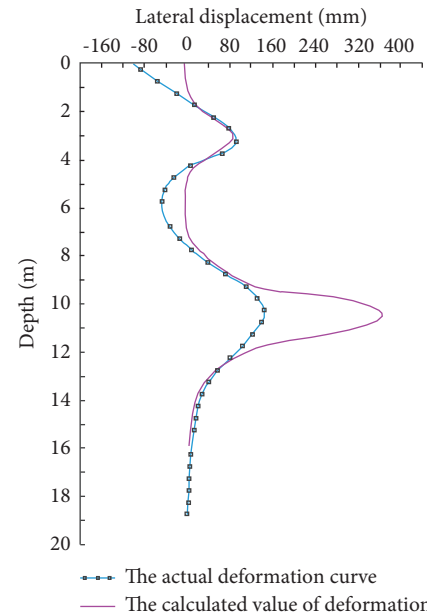


FIGURE 9: Curve of lateral deformation versus depth.



FIGURE 8: Photograph of the inclinometer used in engineering.

4. Engineering Example

A soft soil layer in a section of the Jiangzhong Port section on the west line of the Guangzhou-Zhuhai Expressway was taken as an example. The stratigraphic column of this area is shown in Figure 7. The stratum is a natural stratum without filling. The inclinometer used in this engineering is HY-196, the accuracy is $\pm 6 \text{ mm}/30\text{m}$, as shown in Figure 8. There were two layers of silt in this area, and the middle portion was a middle coarse sand interlayer. The upper layer thickness was 2.5 m. Its shear strength index was represented by $c = 7.8 \text{ kPa}$ and $\varphi = 5.2^\circ$. The thickness of the lower layer was 3.5 m, and its shear strength index was represented by $c = 7.6 \text{ kPa}$ and $\varphi = 5.0^\circ$. The depth at which the inclinometer pipe was buried was 19 m. The pipe material was polyvinyl chloride. The elastic modulus, E , was $2.94 \times 10^9 \text{ Pa}$, the outer diameter was 90 mm, and the inner diameter was 78 mm. According to the expression for the section inertia of a hollow round, the section inertia of the pipe was taken at $1.4034 \times 10^{-6} \text{ m}^4$. According to (12), the maximum deflection of the inclinometer pipe in the upper layer of silt, ω_{10} , was 84.82 mm, and that of the lower layer, ω_{20} , was 323.92 mm.

In the actual situation, the deformation curve of the inclinometer pipe was S-shaped, and reverse deformation occurred. The measured maximum pipe deflections in the upper and lower layers of soft soil were 85.22 mm and 132.75 mm. The measured deformation curve for the inclinometer pipe and the deformation curve that was calculated using the model are shown in Figure 9.

By comparing the theoretical results and the measured data, two primary conclusions were obtained:

- (1) $\omega_1 > \omega_{10}$, which means that the upper silt completely bypassed the inclinometer pipe during the actual measurement process. The pipe deformation did not reflect the actual lateral deformation of the soft soil.
- (2) $\omega_2 < \omega_{20}$, which means that the lower silt did not completely bypass the inclinometer pipe. The deformation of the inclinometer pipe could reflect the actual displacement of the soft soil.

The deformation of an inclinometer pipe in soft soil primarily depends on its own stress, and it is not directly related to the actual lateral deformation of the soft soil, which is the reason that the deformation of the inclinometer pipe could not reflect the actual lateral deformation of the soft soil. Under loading, the additional stress in the upper soil was relatively large due to its shallow buried depth, and the lateral deformation of the soil was larger than that of the inclinometer pipe. The soft soil completely bypassed the inclinometer pipe; so, the pipe's deformation could not reflect the actual lateral extrusion deformation of the soft soil. In the lower soil, the additional stress and the lateral deformation were both relatively small. The soft soil could not completely bypass the inclinometer pipe, so its deformation could reflect the actual lateral deformation of the soft soil. Therefore, the key to determining whether the soft soil

completely bypasses the pipe is to confirm whether the maximum deflection of the inclinometer is greater than the critical deflection.

5. Conclusions

- (1) Based on an analysis of the forces acting between soft soil and an inclinometer pipe and the difference between the soft soil deformation and the inclinometer pipe deformation, a mechanics model for inclinometer pipe deformation under different geological conditions was developed. The model can be used to calculate the deformation of an inclinometer pipe in the critical state when soft soil is about to bypass the pipe.
- (2) A method for determining whether the soft soil completely bypasses the inclinometer pipe was developed using the inclinometer pipe deflection equation. When the soft soil is about to bypass the inclinometer pipe, there exists a critical deflection. When the measured deflection is less than the critical deflection, the deformation can essentially reflect the lateral deformation of the soft soil. When the measured deflection is greater than (or equal to) the critical deflection, the inclinometer pipe fails.
- (3) When the test pipe fails, a new inclinometer should be installed near the original pipe. The actual lateral deformation of the soft soil is equal to the sum of the deformations of the two inclinometer pipes. The deformation of the inclinometer pipe is not consistent with the lateral deformation of the soft soil, but there is a quantitative relationship between them, and the relationship changes with changes in the boundary conditions. Further research is needed regarding the quantitative relationship between the deformations of the pipe and the soft soil.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

- [1] Z. X. Liu and L. S. Tang, "Analysis on lateral squeeze settlement of soft clay foundation under embankment," *Geotechnical Investigation & Surveying*, vol. 2, pp. 1–4, 2003.
- [2] R. J. Finno and L. S. Bryson, "Response of building adjacent to stiff excavation support system in soft clay," *Journal of Performance of Constructed Facilities*, vol. 16, no. 1, pp. 10–20, 2002.
- [3] F. Tavenas, C. Mieussens, and F. Bourges, "Lateral displacements in clay foundations under embankments," *Canadian Geotechnical Journal*, vol. 16, no. 3, pp. 532–550, 1979.
- [4] G. W. Li, X. Li, Y. H. Ruan, and J. Yin, "Creep model of over-consolidated soft clay under plane strain," *Chinese Journal of Rock Mechanics and Engineering*, vol. 35, no. 11, pp. 2307–2315, 2016.
- [5] S. S. Lin, J. C. Liao, J. T. Chen, and L. Chen, "Lateral performance of piles evaluated via inclinometer data," *Computers and Geotechnics*, vol. 32, no. 6, pp. 411–421, 2005.
- [6] J. S. Chiou, C. H. Chen, and Y. C. Chen, "Deducing pile responses and soil reactions from inclinometer data of a lateral load test," *Soils and Foundations*, vol. 48, no. 5, pp. 609–620, 2008.
- [7] A. N. Li and J. L. Liu, "Study on the limitation of lateral displacement measuring with side piling," *Anhui Architecture*, vol. 15, no. 4, p. 174, 2008.
- [8] X. B. Lei, "Observation method of settlement and stability dynamic displacement in embankment construction," *Jiangxi Building Materials*, vol. 1, pp. 108–112, 2018.
- [9] D. W. Ha, J. M. Kim, Y. Kim, and H. S. Park, "Development and application of a wireless MEMS-based borehole inclinometer for automated measurement of ground movement," *Automation in Construction*, vol. 87, pp. 49–59, 2018.
- [10] S. J. Guo, "Application of finite element strength reduction method in slope stability analysis," *Subgrade Engineering*, vol. 6, no. 4, pp. 25–29, 2018.
- [11] Y. L. Sun and H. Y. Sun, "Research on deformation monitoring and determination of displacement of anti-slide piles," *Chinese Journal of Rock Mechanics and Engineering*, vol. 32, no. 10, pp. 2147–2153, 2013.
- [12] G. H. Lei, Y. B. Ai, and J. Y. Shi, "The interpretation of pendulum-type inclinometer readings," *Canadian Geotechnical Journal*, vol. 43, no. 2, pp. 210–216, 2006.
- [13] G. Li, Y. Wang, Z. Wu, and F. X. Du, "Recognition and correction of large deformation errors of landslide based on flexible inclinometer device," *Yangtze River*, vol. 47, no. 4, pp. 74–78, 2016.
- [14] N. Shentu, G. Qiu, R. Tong, and Q. Li, "Research on a novel mutual inductance-based underground displacement sensor," in *Proceedings of the Wseas International Conference on Instrumentation. World Scientific and Engineering Academy and Society (WSEAS)*, Hangzhou China, May 2009.
- [15] B. X. Jia, F. P. Liu, and L. Zhao, "Influential factors analysis of the new and old roadbed on the differential settlements due to the highway reconstruction and extension," *Journal of Safety and Environment*, vol. 20, no. 1, pp. 67–72, 2020.
- [16] P. E. Mikkelsen, "Advances in inclinometer dataanalysis," in *Proceedings of the 6th International Symposium on Field Measurements in Geomechanics, FMGM 2003*, pp. 555–567, Oslo, Norway, September 2003.
- [17] L. Simeoni and L. Mongiovì, "Inclinometer monitoring of the castelrotto landslide in Italy," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 133, no. 6, pp. 653–666, 2007.
- [18] Q. Wei, M. Huang, and H. J. Zhang, "Comparison of interpolation for inclinometer missing data and modeling analysis," *Industrial Construction*, vol. 43, no. S1, pp. 442–445, 2013.

- [19] G. X. Liu, Y. G. Li, and Y. N. Cao, "Calculation and analysis of lateral deformation of ground under embankment load," *Rock and Soil Mechanics*, vol. 39, no. 12, pp. 4517–4526, 2018.
- [20] N. Loganathan, A. S. Balasubramaniam, and D. T. Bergado, "Deformation analysis of embankments," *Journal of Geotechnical Engineering*, vol. 119, no. 8, pp. 1185–1206, 1993.
- [21] S. S. Lin and J. C. Liao, "Lateral response evaluation of single piles using inclinometer data," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 132, no. 12, pp. 1566–1573, 2006.
- [22] N. Shentu, H. Zhang, Q. Li, H. Zhou, R. Tong, and X. Li, "A theoretical model to predict both horizontal displacement and vertical displacement for electromagnetic induction-based deep displacement sensors," *Sensors*, vol. 12, no. 1, pp. 233–259, 2011.
- [23] T. D. Stark and H. Choi, "Slope inclinometers for landslides," *Landslides*, vol. 5, no. 3, pp. 339–350, 2008.
- [24] G. W. Li, L. S. Hu, and R. Wang, "Testing of slip inclinometer and error treatment methods," *Journal of Hohai University (Natural Sciences)*, vol. 41, no. 6, pp. 511–517, 2013.
- [25] Z. Y. Zhao, "Error analysis of an inclinometer based on numerical analysis," *Hydrogeology & Engineering Geology*, vol. 48, no. 3, pp. 157–161, 2021.
- [26] P. S. K. Ooi and T. L. Ramsey, "Curvature and bending moments from inclinometer data," *International Journal of Geomechanics*, vol. 3, no. 1, pp. 64–74, 2003.
- [27] C. H. Dowding and K. M. O. Connor, *Comparison of Tdr and Inclinometers for Slope Monitoring*, Geoinstitute of ASCE, Denver, CO, USA, 2000.
- [28] F. Li, P. H. Chen, H. Y. Shan, and T. Lu, "Testing study on lateral deformation of soft road ground and its control," *Chinese Journal of Rock Mechanics and Engineering*, vol. 23, no. 12, pp. 2114–2117, 2004.
- [29] X. Liu, G. H. Lei, K. Y. Zhang, Y. B. Ai, and J. Shi, "Study of inclinometer data analysis methods for pre-detecting of failure of an inclinometer casing," *Rock and Soil Mechanics*, vol. 33, no. S1, pp. 97–104, 2012.
- [30] C. Foslaau, C. Zet, and D. Petrisor, "Multiaxis inclinometer for in depth measurement of landslide movements," *Sensor Review*, vol. 35, no. 3, pp. 296–302, 2015.