DESIGN METHOD FOR THE STABILITY ANALYSIS OF THE SLOPE WITH LANDING PIER

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ABSTRACT

A basic method for stability analysis of the slope containing piles in a row is described, using the theoretical equation of lateral force acting on piles in a row due to plastically deforming ground, which has already been derived by the authors. Studies of the effect of many factors on pile and slope on the slope-stability are carried out for an example of the foundation piles of landing pier in a harbor and a design method is proposed for the stability analysis of the slope with landing pier.

The results show that such factors as the position of pile's row, the fixity condition of the pile head, the interval between piles, the pile diameter, the thickness of the pipe pile and the slope gradient have much effect on the slope-stability. In the proposed design method, such six factors can be considered systematically. Moreover, an example is shown, in which important factors in pile design are brought out and illustrated.

Key words: design, earth pressure, horizontal load, pile, safety factor, slope stability, stability analysis

IGC: E6/E4/E5

INTRODUCTION

In a slope stability problem, piles in a row may often pass through a sliding surface. One of such cases may be pile foundations of landing piers in harbors, where piles may be expected to prevent extensively slope unstability. In the routine works about the stability analysis of the slope with landing pier, however, it is usual to neglect the effect of piles on preventing the sliding of slope.

Generally speaking, piles subjected to lateral force can be divided into such two classes as "active piles" and "passive piles" (De Beer, 1977). The problem described above, of course, concerns the passive piles, which are subjected to lateral force by horizontal movements of the surrounding soil. The passive piles are more complicated than the active piles, because the lateral force acting on the passive piles results from the interaction between the piles and the soils, while that of the active piles is decided in advance.

The authors have approached the problem of the stability analysis of the slope containing the passive piles in a row, from the view point that it is very important to analyze systematically both stabilities of the pile and the slope, considering the pile interval as accurately as possible (Ito and Matsui, 1975, 1977, 1978).

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In this paper, the authors aim to establish a more reliable design method for the stability analysis of the slope with landing pier. First, a basic method for stability analysis of the slope containing piles in a row is described, using the theoretical equation of lateral force acting on piles in a row due to plastically deforming ground, which has already been derived by the authors. Then, some studies of the effect of many factors on pile and slope are carried out for an example of the foundation piles of landing pier in a harbor. Finally, the authors propose a new design method for the stability analysis of the slope with landing pier, based on the results of the studies.

BASIC METHOD FOR THE STABILITY ANALYSIS OF THE SLOPE CONTAINING PILES IN A ROW

Fig. 1. Stability analysis of slope with foundation piles of landing pier

Generally speaking, for the stability problem of slope containing piles in a row, two kinds of analyses for the slope-stability and the pile-stability have to be carried out individually, as shown in Fig. 1. And the whole stability of slope containing piles in a row can be obtained by the stabilizations for both the slope and the pile. If the lateral forces acting on the pile (or the lateral force reactions) are known, both analyses can be carried out in the following manner (Ito and Matsui, 1977).

Theoretical Equation of Lateral Forces Acting on Piles in a Row through Soil Mass above the Sliding Surface

The lateral force $p(z)$ acting on a pile per unit depth of soil layer can be obtained by the following equations, which are derived considering the interval between piles and also assuming that the Mohr-Coulomb's plastic condition occurs in the surrounding ground just around the piles (Ito and Matsui, 1975, 1977, 1978).

$$\begin{aligned}
 p(z) = & cD_1 \left(\frac{D_1}{D_2} \right)^{(N_\phi^{1/2} \tan \phi + N_\phi - 1)} \left[\frac{1}{N_\phi \tan \phi} \left\{ \exp \left(\frac{D_1 - D_2}{D_2} N_\phi \tan \phi \right) \right. \right. \\
 & \times \tan \left(\frac{\pi}{8} + \frac{\phi}{4} \right) - 2N_\phi^{1/2} \tan \phi - 1 \left. \right\} + \frac{2 \tan \phi + 2N_\phi^{1/2} + N_\phi^{-1/2}}{N_\phi^{1/2} \tan \phi + N_\phi - 1} \left. \right] \\
 & - c \left\{ D_1 \frac{2 \tan \phi + 2N_\phi^{1/2} + N_\phi^{-1/2}}{N_\phi^{1/2} \tan \phi + N_\phi - 1} - 2D_2 N_\phi^{-1/2} \right\} + \frac{\gamma z}{N_\phi} \left\{ D_1 \left(\frac{D_1}{D_2} \right)^{(N_\phi^{1/2} \tan \phi + N_\phi - 1)} \right. \\
 & \times \exp \left(\frac{D_1 - D_2}{D_2} N_\phi \tan \phi \tan \left(\frac{\pi}{8} + \frac{\phi}{4} \right) \right) - D_2 \left. \right\} \quad (1)
 \end{aligned}$$

where $N_\phi = \tan^2(\pi/4 + \phi/2)$, D_1 is the center-to-center interval between piles in a row, D_2 the clear interval between piles, c the cohesion of soil, ϕ the angle of internal friction of soil, γ the unit weight of soil and z an arbitrary depth from the ground surface. In case of cohesionless soil, the lateral force can be obtained, replacing c by zero in Eq. (1). In case of cohesive soil ($\phi=0$), however, the lateral force $p(z)$ is obtained by the following equation ;

$$p(z) = c \left\{ D_1 \left(3 \log \frac{D_1}{D_2} + \frac{D_1 - D_2}{D_2} \tan \frac{\pi}{8} \right) - 2(D_1 - D_2) \right\} + \gamma z (D_1 - D_2) \quad (2)$$

It is shown elsewhere that for the condition of restrained pile head, the lateral force acting on piles in a row may be estimated with good accuracy by this theory (Ito and Matsui, 1975).

Pile-Stability Analysis

As for the pile-stability, an analytical method of piles subjected to horizontal loads can be applied, considering that the lateral force acts on piles through the soil mass above the sliding surface, as shown in Fig. 1(b). Assuming that the distributed lateral load $p(z)$ acting on a pile above the sliding surface, as shown in Fig. 2, can be obtained by Eq. (1) or (2), and that the lateral reaction force on piles below the sliding surface is proportional to the pile deflection, the basic equations can be obtained as follows ;

$$E_p I_p \frac{d^4 y_1}{d \bar{z}^4} = p(\bar{z}) \quad (-H' \leq \bar{z} \leq 0)$$

$$E_p I_p \frac{d^4 y_2}{d \bar{z}^4} = -E_s y_2 \quad (\bar{z} \geq 0) \quad (3)$$

where $\bar{z}$ is equal to $(z-H)$, H is the depth from the ground surface to the sliding surface, H' the length from the pile top to the sliding surface, y_1 and y_2 the pile deflections above and below the sliding surface, respectively, E_p the modulus of elasticity of pile, I_p the moment of inertia of pile, and E_s the soil modulus.

By solving Eq. (3) under the condition of $y_2=0$ at $\bar{z} \rightarrow \infty$, the general solutions of pile deflections can be obtained as follows ;

$$\begin{aligned} y_1 &= a_0 + a_1 \bar{z} + a_2 \bar{z}^2 + a_3 \bar{z}^3 + f(\bar{z}) \\ y_2 &= e^{-\beta \bar{z}} (A \cos \beta \bar{z} + B \sin \beta \bar{z}) \end{aligned} \quad (4)$$

where a_0 , a_1 , a_2 , a_3 , A and B are integral constants, which are decided by both conditions of pile-head fixity and continuity of pile at the sliding surface. $f(\bar{z})$ is an expression containing the remainder of the solution and excluding the integral constants a_0 , a_1 , a_2 , and a_3 in the quadruple indefinite integral of $p(\bar{z})/E_p I_p$, and β is $\sqrt[4]{E_s/4E_p I_p}$.

The distributions of deflection, shearing force and bending moment on the pile can be generally calculated using the above equations. Because the safety factor for bending moment is considerably smaller than that for shearing force for the steel piles (Ito and Matsui, 1977), the safety factor $(F_s)_{\text{pile}}$ of the pile-stability can be obtained by comparing the allowable bending stress $\sigma_{\text{allow.}}$ with the maximum induced one $\sigma_{\text{max.}}$ as follows ;

$$(F_s)_{\text{pile}} = \sigma_{\text{allow.}} / \sigma_{\text{max.}} \quad (5)$$

If the safety factor in Eq. (5) is larger than unity, the pile-stability is insured.

As for the fixity conditions of the pile head, such four cases can be considered as free head (rotation and displacement), unrotated head (displacement without rotation), hinged head (rotation without displacement) and fixed head (neither rotation nor displacement). It is apparent that the smaller the deflection at the pile head is, the larger the safety factor on the pile-stability becomes.

Slope-Stability Analysis

As for the slope-stability, some analytical methods can be considered, but the following one may be most reasonable in case of the stability analysis of the slope with landing pier. That is, the slope-stability analysis can be carried out by making a comparison between the resisting and driving moments, M_r and M_d , acting on the soil mass DBCAD above the sliding surface in Fig. 1(a). The resisting moment may be obtained as the sum of both the resisting moments, M_{rs} and M_{rp} , due to the shearing resistance along the sliding surface DAC and the reaction force of piles in a row at the plane AB, respectively. This

Fig. 2. Analysis of the pile-stability

is an approximation, since the soil masses at the both sides of the position of pile's row, i.e. ABCA and ABDA in Fig. 1(a), will deform as one body in the region between the piles, while only the soil just around the piles in a row will reach a plastic state.

Thus, one can get the safety factor $(F_s)_{\text{slope}}$ of the slope-stability in the case where the resistance of the piles is included as follows ;

$$(F_s)_{\text{slope}} = \frac{M_r}{M_d} = \frac{M_{rs} + M_{rp}}{M_d} \quad (6)$$

Using the circular arc analysis, the values of M_{rs} and M_d can be obtained by such an ordinary method as the slice method in the stability of slope. On the other hand, the value of M_{rp} can be calculated, using the reaction force of a pile divided by the center-to-center interval between piles in a row. If the safety factor in Eq. (6) is larger than the required one, the slope-stability is insured.

EFFECT OF FOUNDATION PILES FOR LANDING PIER ON SLOPE-STABILITY

General Remarks

The effect of foundation piles of landing pier against the sliding of slope is studied by adopting an example of landing pier which exists in Japan. The cross section and plan of this landing pier, the soil parameters and the dimensions of piles are shown in Fig. 3. This landing pier is constructed in a gentle gradient slope and its foundation is composed of long steel pipe piles in eight rows. A clay layer of 21 m thickness lies between the sand and the sandy gravel layers. The tips of the foundation piles are driven down to the dense sandy gravel layer that provides high bearing capacity. Fig. 4 shows the contour lines of the safety factor of this slope obtained by means of the circular arc analysis, neglecting the pile effect. Its minimum value is 1.17 for the circular sliding surface having

Fig. 3. Cross section and plan of a landing pier

Fig. 4. Contour lines of the safety factor without the pile effect

Fig. 5. Relation between the minimum safety factor of the slope-stability without the pile effect $(F_{s,min})_{slope}$ and the slope gradient L_V/L_H

its center at point O and a radius of 20.2 m.

Fig. 5 shows the variation of the minimum safety factor of the slope-stability $(F_{s,min})_{slope}$, with the slope gradient L_V/L_H , in case where the pile effects are neglected. For these cases, only the horizontal length of slope L_H is varied, while the vertical length L_V is kept constant. The minimum safety factor of the slope-stability decreases from 1.17 to 0.89, as L_V/L_H increases from 0.33 to 0.67.

As the required safety factor of the slope-stability in the design of this landing pier was set at 1.17, the stability of slopes of $L_V/L_H > 1/3$ may not be insured. But even in some of those unstable cases of slope, the minimum safety factor of the slope-stability will be able to exceed the required one by considering the pile effect against sliding of slope. The stability of slope can be studied, considering the effect of foundation piles of landing pier, by using both the methods of the pile-stability and the slope-stability analyses described in the previous chapter. That is, first, the pile-stability is studied for a certain sliding surface. Then, when the safety factor of the pile-stability is greater than unity, that of the slope-stability can be calculated. On the other hand, when the safety factor of the pile-stability is smaller than unity, that of the slope-stability can be calculated in the same manner, with a proportional reduction in the lateral force so as to satisfy the pile-stability.

In order to facilitate this study, the following assumptions are made ;

- 1) The modulus of elasticity of steel pile E_p is 2.06×10^8 kN/m².
- 2) The allowable bending and shearing stresses of steel pile are 1.57×10^5 kN/m² and 0.98×10^5 kN/m², respectively.
- 3) The soil modulus E_s below the sliding surface is 40 times the undrained shear strength of the clay (Poulos, 1971).
- 4) The pile length is infinite.
- 5) The soil modulus E_s below the sliding surface has the same value as that of the clay layer.
- 6) The piles are subjected to lateral forces only by horizontal deformations of surrounding soil.

Such factors as the position of pile's row, the fixity condition of the pile head, the interval between piles, the pile diameter and the thickness of the pipe pile are considered to

have influence on the effect of piles against the sliding of slope. Thus, for the gradient slope $L_V/L_H=1/3$, those five factors mentioned above are studied respectively in the following manner. First of all, the effect of position of pile's row is studied, in which steel pipe piles having a diameter of 812.8 mm, a thickness of 22 mm, a regular interval of 2.32 m between piles ($D_2/D_1=0.65$) and an unrotated pile head are used. Then, the studies of the other four factors are carried out by varying both the position of pile's row and one of the factors, respectively.

Effect of the Position of Pile's Row

The piles are effective against sliding when they are placed through the sliding surface resulting in the minimum safety factor of slope. Thus, it is sufficient that the effect of position of pile's row is considered only for the cases that the piles are located between the positions C and D in Fig. 4, i.e. for the cases that the horizontal length X from the toe of the slope to the position of pile's row is between 17 m ($X/L_H=0.64$) and 51 m ($X/L_H=1.45$) in this example.

Fig. 6. Contour lines of the safety factor with the pile effect

When the pile's row is located at the positions $X=27$ m ($X/L_H=0.74$), 35 m ($X/L_H=0.96$) or 43 m ($X/L_H=1.17$), the contour lines of the safety factor of the slope-stability with the pile effect are illustrated in Fig. 6(a), (b) or (c), respectively. From these figures, it is seen that the minimum safety factor of each case is obtained for the almost same circular sliding surface, and also that the pattern of contour lines resembles each other.

Moreover, comparing Fig. 6 with Fig. 4, it is shown in this example that both the pattern of contour lines and the circular sliding surface of the minimum safety factor are similar, whether the pile effect is considered or not.

Fig. 7 shows the relation between the minimum safety factor $(F_{s,min})_{slope}$ of the slope-stability with the pile effect and the position of pile's row which is represented by the parameter X/L_H . In this figure, the solid line and the chain line with one dot show the cases of considering and neglecting the pile effect, respectively, and the pile effect against the sliding of slope is represented by the difference between these two lines, estimated in terms of the safety factor.

From this figure, it is seen that the solid curve has a minimum near the position of pile's row $X/L_H=1.0$. This may be explained mainly by the fact that the piles receive the maximum lateral force from the soil mass above the sliding surface near that position, i.e. the safety factor of the pile-stability decreases.

In this example, the maximum effect of piles is about 0.16 ($=1.33-1.17$) in terms of safety factor, when the piles are located at $X/L_H=0.74$.

Effect of the Fixity Condition of Pile Head

Fig. 8 shows the pile effect represented in terms of the safety factor of the slope-stability in the same manner as in Fig. 7, with the fixity condition of pile head as a variable parameter. As for the fixity condition of pile head, such four cases as described in the previous chapter will be considered. That is, the unrotated head is drawn by a solid line, the hinged head by a broken line, the fixed head by a dotted line and the free head by a chain line with two dots, as in Fig. 8. From this figure, it is seen that the pile effect can be changed considerably depending on the fixity conditions of pile head in a certain position of the pile's row, but there is not necessarily a prevailing tendency of any fixity condition of pile head. This may be also confirmed by Fig. 9, in which only the parameter D_2/D_1 is changed from 0.65 to 0.75.

Thus, it will be very difficult to generally describe which fixity condition of pile head is the most effective one. But, if all other parameters are held constant, it can be decided. For example, in the cases of Fig. 8 and Fig. 9, the most effective fixity condition is the unrotated and the hinged ones, respectively, at the position of pile's row $X/L_H=0.74$.

Effect of the Interval between Piles

In order to study the effect of interval between piles, only the interval ratio D_2/D_1 is varied as a parameter as shown in Fig.

Fig. 7. Relation between the minimum safety factor of the slope-stability $(F_{s,min})_{slope}$ and the position of the pile's row X/L_H

10, while the other parameters are the same as those in Fig. 7. The intervals studied cover six values of D_2/D_1 .

Generally speaking, in Fig. 10, the pile effect increases gradually, as the interval ratio D_2/D_1 decreases from 0.95 to 0.45. But, it decreases slightly for the piles of smaller D_2/D_1 , when X/L_H is about 0.8. The maximum value of the minimum safety factor of the slope-stability is obtained at the position of piles $X/L_H=0.74$ in the cases of the smaller D_2/D_1 , but the value of X/L_H at the position of maximum effect becomes larger as the interval ratio D_2/D_1 increases.

Fig. 11 shows the relation between the minimum safety factor and the interval ratio D_2/D_1 . It is also seen that the same tendency on the effect of interval between piles exists as described above, i.e. the effect of piles decreases linearly as D_2/D_1 increases over the vicinity of 0.7, but the ratio of its increment decreases gradually as D_2/D_1 decreases under the vicinity of 0.7. This means that a limiting value exists in the pile effect as the interval between piles is narrowed. This will be caused by increasing the lateral force, i.e. by decreasing relatively the pile-stability with the decrease of D_2/D_1 . In this example, the maximum effect of pile can be obtained in case of $D_2/D_1=0.65$.

On the other hand, when the piles are located at $X/L_H=1.28$, the minimum safety factor is always constant in case of $D_2/D_1 \leq 0.75$, as shown in Fig. 11. This comes from the fact that the sliding surface of the minimum safety factor does not intersect with the pile's row in those cases.

Effect of the Pile Diameter

Fig. 12 shows the effect of the diameter of pile by choosing $d(=D_1-D_2)$ as a parameter. Five values of pile diameter are considered and the other conditions are the same as those in Fig. 7. In this study, it should be noted that the pile diameter is varied while D_2/D_1 is kept constant, i.e. the center-to-center interval of pile is also varied with the variation of the pile diameter.

It is seen in Fig. 12 that the effect of piles increases almost linearly with increasing the

Fig. 8. Relation between the minimum safety factor of the slope-stability $(F_{s,min})_{slope}$, the position of pile's row X/L_H and the fixity condition of the pile head

Fig. 9. Relation between the minimum safety factor of the slope-stability $(F_{s,min})_{slope}$, the position of pile's row X/L_H and the fixity condition of the pile head

Fig. 10. Relation between the minimum safety factor of the slope-stability $(F_{s,min})_{slope}$, the position of pile's row X/L_H and the interval ratio of piles D_2/D_1

Fig. 11. Relation between the minimum safety factor of the slope-stability $(F_{s,min})_{slope}$ and the interval ratio of piles D_2/D_1

Fig. 12. Relation between the minimum safety factor of the slope-stability $(F_{s,min})_{slope}$, the position of pile's row X/L_H and the pile diameter d

Fig. 13. Relation between the minimum safety factor of the slope-stability $(F_{s,min})_{slope}$ and the pile diameter d

diameter. But, it is always constant when the piles are located in a position greater than $X/L_H=1.28$. This comes from the fact that the sliding surface of the minimum safety factor does not intersect with the pile's row in those cases, as described in the previous section. In this example, the maximum value of the minimum safety factor is obtained in the vicinity of the position of pile's row $X/L_H=0.74$.

Fig. 13 shows the relation between the minimum safety factor and the pile diameter. It is seen in this figure that the minimum safety factor increases linearly, but that in case of $X/L_H=0.74$, the ratio of its increment decreases gradually as the pile diameter becomes larger.

Effect of the Thickness of Pipe Pile

Fig. 14 shows the effect of the thickness t of pipe pile by choosing t as a parameter. The thicknesses studied are four values and the other conditions are the same as those in Fig. 7.

It is seen in Fig. 14 that the pile effect increases linearly with increasing the thickness of pipe pile. However, only at the position of pile's row $X/L_H=1.28$, the pile effect does not increase when the thickness increases from 16 mm to 22 mm. This comes from the same fact as described in the previous two sections. In this example, the maximum value of the minimum safety factor is also obtained in the vicinity of the position of pile's row $X/L_H=0.74$.

Fig. 15 shows the relation between the minimum safety factor and the thickness of pile. It is seen in this figure that the minimum safety factor increases almost linearly with increasing the thickness of pile.

DESIGN METHOD FOR THE STABILITY ANALYSIS OF THE SLOPE WITH LANDING PIER

As the previous chapter has demonstrated, it can be seen that the position of pile's row,

Fig. 14. Relation between the minimum safety factor of the slope-stability $(F_{s,min})_{slope}$, the position of pile's row X/L_H and the pile thickness t

Fig. 15. Relation between the minimum safety factor of the slope-stability $(F_{s,min})_{slope}$ and the pile thickness t

the fixity condition of the pile head, the interval between piles, the pile diameter and the thickness of the pipe pile are very important factors in the slope-stability problems.

In this chapter, a design method is proposed for the stability analysis of the slope with landing pier, based on those results.

Design Method

A procedure of design for the stability analysis of the slope with landing pier is shown in Fig. 16 as a block chart. First of all, both the conditions of ground and structure of a landing pier are established, including the required safety factor on the slope-stability, the allowable stress of pile and so on.

Then, the selections of the fixity condition of the pile head and the position of pile's row may be carried out. Generally speaking, these selections can not be decided arbitrarily, as it is the tendency to choose the unrotated in ordinary landing piers, and the position of pile's row is normally decided in advance by the condition of the landing pier structure. If these two factors can be selected arbitrarily, one can choose the most effective ones corresponding to a situation, using results such as Fig. 8.

Next, the selection of the slope gradient may be carried out. This factor has been decided in advance or can be selected so as to be able to obtain a situation such that the safety factor of the slope-stability without the pile effect is smaller than the required safety factor for design.

Finally, such three factors about piles as the interval between piles, the pile diameter and the thickness of the pipe pile have to be selected, so as to satisfy the required safety factor of the slope-stability with the pile effect. Judging from the characteristics of these three factors obtained before, it will be the best method that they are selected simultaneously by using such a schematic diagram as in Fig. 17, which is represented as the relation between the minimum safety factor of the slope-stability and the interval ratio D_2/D_1 . For example, let us consider the minimum safety factor without the pile effect and the required safety factor are 1.1 and 1.2, respectively, which are represented by a chain line with one dot and a solid line in Fig. 17. When pipe piles having a diameter of d_1 and a thickness of t_1 are used as the piles in a row, a relation between the minimum safety factor of D_2/D_1 may be obtained by the curve I in Fig. 17. In such case, there is no suitable interval between piles for the required safety factor, and the slope-stability can not be obtained, even if many piles are used by decreasing the interval ratio D_2/D_1 . When the curve II in Fig. 17 is obtained, in which the (d_2, t_2) piles of larger stiffness than the (d_1, t_1) piles are used, it is possible to use the piles in a row having the interval ratios between $(D_2/D_1)_1$ and $(D_2/D_1)_2$, in order to satisfy the slope-stability. In the case of the curve III, in which the (d_3, t_3) piles of still larger stiffness than the (d_2, t_2) piles are used, it is possible to use them having smaller interval ratios than $(D_2/D_1)_3$. Judging from the economic point of view, it may be favorable to select a larger interval ratio of (D_2/D_1) , i.e. $(D_2/D_1)_2$ or $(D_2/D_1)_3$ in the above

Fig. 16. Procedure of design for the stability analysis of the slope with landing pier

Fig. 17. Schematic diagram for a design of piles

Fig. 18. Relation between the minimum safety factor of the slope-stability $(F_{s,min})_{slope}$, the interval ratio of piles D_2/D_1 , the pile diameter d , and the pile thickness t

two cases, respectively.

It is possible to return again to the selection of another slope gradient according to the feed back line in Fig. 16, when an adequate result can not be obtained by the method described above. For example, if only the slope gradient is changed into a gentler one in the case of the curve III in Fig. 17, one can get the curve III', and then, it is possible to design even for the required safety factor of 1.3.

Also, it is possible to return to the selections of both the fixity condition of the pile head and the position of pile's row according to the feed back broken line in Fig. 16, but such a case will be very rare.

Design Example

A design for the gradient slope $L_V/L_H=1/2.5$ with the landing pier in Fig. 3 is carried out as follows. The minimum safety factor of this slope stability without the pile effect is 1.08, as in Fig. 5. It is assumed that the fixity condition of the pile head is the unrotated one and that the piles are located at $X/L_H=0.8$ (in this case, $L_H=30.5$ m).

Fig. 18 shows a diagram for this example, corresponding to Fig. 17, in which both three values of diameter (812.8 mm, 914.4 mm, 1016.0 mm) and thickness (12 mm, 16 mm, 22 mm) of pile are combined. From this figure, it is seen that if the required safety factor is 1.15 or 1.18, one can select the allowable interval between piles for each of all these nine types of piles or the six types of piles having the thicknesses of 16 mm and 22 mm, respectively. But, if the required safety factor is 1.20, one can select it only for each of the two types of piles having diameters of 914.4 mm and 1016.0 mm with the 22 mm thickness.

Fig. 19 illustrates the relation between the required safety factor, the most suitable bending stiffness $E_p I_p$ of pile and the interval ratio D_2/D_1 , using the results of Fig. 18. The most suitable bending stiffness of pile is considered to be that which produces the largest interval between piles among the allowable ones. From this figure, it is seen that the interval

Fig. 19. Relation between the interval ratio of piles D_2/D_1 , the bending stiffness of piles $E_p I_p$ and the minimum safety factor of the slope-stability $(F_{s,min})_{slope}$

Fig. 20. Relation between the minimum safety factor of the slope-stability $(F_{s,min})_{slope}$, the interval ratio of piles D_2/D_1 and the slope gradient L_V/L_H

ratio D_2/D_1 increases with increasing bending stiffness of the pile.

Fig. 20 shows the relation between the minimum safety factor of the slope-stability and the interval ratio D_2/D_1 , using the slope gradient as a variable parameter. From this figure, it is seen that the minimum safety factor increases with decreasing the slope gradient L_V/L_H , and that the amount of increment is almost constant no matter what the value of D_2/D_1 is. When the required safety factor of the slope-stability is 1.20, it is possible to design for the gradient slope $L_V/L_H = 1/2.5$. But, if the required safety factor is set up to 1.30, it is impossible to design for the same slope. But in this case, one can satisfy the slope-stability by decreasing the slope gradient to the value of $L_V/L_H = 1/3$. When the required one is 1.10, one can satisfy the slope-stability even for the gradient slope $L_V/L_H = 1/2$.

CONCLUSIONS

The pile foundation of landing pier is one of typical passive piles. In the stability analysis of the slope with landing pier, the circular arc analysis is generally used, in which many circular arcs have to be checked for the whole stability of slope. Thus, it is necessary to analyze systematically such a problem in which there are many factors.

In this paper, the authors examined the effect of many factors on the pile and the slope on the slope-stability, and proposed a design method for the stability analysis of the slope with landing pier. If both conditions on the structure of landing pier and the surrounding ground are given, such factors as the position of pile's row, the fixity condition of the pile head, the interval between piles, the pile diameter, the thickness of the pipe pile and the slope gradient have considerable effect on the slope-stability. In the proposed design method, such six factors can be decided systematically. Moreover, an example of design is shown, with a convenient figure to show important factors of pile design.

If some factors of the pile and the slope are given in advance, the design method, of course, becomes simpler. The case of a sliding surface containing more than two rows of

piles in a row is left out for further investigations.

NOTATION

a_0, a_1, a_2, a_3, A, B =integral constants

c =cohesion of the soil

d, d_1, d_2, d_3 =pile diameters

D_1 =center-to-center interval between piles in a row

D_2 =clear interval between piles in a row

E_p =modulus of elasticity of the pile

E_s =soil modulus

$(F_s)_{\text{pile}}$ =safety factor of the pile-stability

$(F_s)_{\text{slope}}$ =safety factor of the slope-stability

$(F_{s,\min})_{\text{slope}}$ =minimum safety factor of the slope-stability

$f(\bar{z})$ =remainder of the solution excluding the integral constants a_0, a_1, a_2 and a_3 in quadruple infinite integral of $p(\bar{z})/E_p I_p$

H =depth from the ground surface to the sliding surface

H' =length from the pile top to the sliding surface

I_p =moment of inertia of the pile

L_H =horizontal length of the slope

L_V =vertical length of the slope

M_d =driving moment acting on the soil mass above the sliding surface

M_r =resisting moment acting on the soil mass above the sliding surface

M_{rp} =resisting moment due to the reaction force of piles in a row above the sliding surface

M_{rs} =resisting moment due to the shearing resistance along the sliding surface

N_ϕ =flow value ($=\tan^2(\pi/4+\phi/2)$)

O =center of circular sliding surface of the minimum safety factor of the slope-stability without the pile effect

O' =center of circular sliding surface of the minimum safety factor of the slope-stability with the pile effect

$p(z), p(\bar{z})$ =lateral force acting on piles in a row

t, t_1, t_2, t_3 =thicknesses of the pipe pile

X =horizontal length from the slope toe to piles in a row

y_1, y_2 =pile deflections above and below the sliding surface, respectively

z =depth from the ground surface

$\bar{z}$ =depth from the sliding surface ($=z-H$)

$\beta = \sqrt[4]{E_s/4E_p I_p}$

γ =unit weight of the soil

$\sigma_{\text{allow.}}$ =allowable bending stress of the pile

$\sigma_{\text{max.}}$ =maximum bending stress induced on the pile

ϕ =angle of internal friction of the soil

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