EXTENDED DESIGN METHOD FOR MULTI-ROW STABILIZING PILES AGAINST LANDSLIDE

Tomio Ito*, Tamotsu Matsui** and Won Pyo Hong***

ABSTRACT

Row of piles may often be used to stabilize a sliding mass, in which case, the stabilizing piles should be designed so as to insure not only the stability of each pile row, but also the slope stability with regard to all the pile rows. In this paper, a method of designing several rows of piles to prevent a large landslide has been investigated. By extending the method, established in a previous paper, of designing one row of stabilizing piles, the stabilizing effect of two rows of piles is firstly studied and a method of designing several rows of stabilizing piles is proposed.

In the design method proposed in this paper, the ground conditions of a slope are fixed, and the selections of the fixity condition of pile head, the number of pile rows, the position of pile rows, and the pile length above sliding surface are carried out, followed by the systematic selections of factors of mobilization of lateral force, pile diameters, intervals between piles, and pile stiffnesses. An example of the design is presented, with figures to illustrate important factors in the design of multi-row stabilizing piles.

Key words: design, earth pressure, horizontal load, landslide, pile group, safety factor, slope stability, stability analysis, stabilizing pile (IGC: E6/E4/E5)

INTRODUCTION

To carry out a design for stabilizing piles against landslides using their capability effectively, it is necessary to correctly understand the stabilizing mechanism of the piles. The authors have clarified the mechanism through studies of the effect of many factors on stabilizing piles, and have established a basic method of analysis of the stability of a landslide slope containing stabilizing piles in a row (Ito, Matsui and Hong, 1981), in which a theoretical equation is used to estimate the lateral force acting on the piles (Ito and Matsui, 1975, 1977, 1978). Based on the results of the studies, the authors have proposed a new design method for the case of one row of stabilizing piles, in which the systematic analysis for the stabilities of both piles and the slope can be carried out.

To prevent a large scale landslide, however, multiple rows of stabilizing piles may often

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Manuscript was received for review on November 28, 1980.

Written discussions on this paper should be submitted before January 1, 1983.
be used (De Beer and Wallays, 1970; Broms, 1972; Fukumoto, 1976). In this case, it is important that not only the pile stability of stabilizing piles for each pile row but also the slope stability with the effect of all stabilizing piles should be simultaneously ensured. In the present paper, a basic method for stability analysis of a slope containing multiple rows of piles is firstly described with the effect of two rows of stabilizing piles being subsequently studied in relation to a landslide slope. Thereafter, an extended design method of stabilizing piles against a large scale landslide by using multiple rows of piles is proposed, and a design example is finally shown for an existing large scale landslide.

BASIC METHOD FOR STABILITY ANALYSIS OF SLOPE CONTAINING MULTI-ROW STABILIZING PILES

Stability Analysis Method

It has been demonstrated that, in the case of a slope containing piles in a row, two kinds of analyses, one of the slope stability, and another of the pile stability, should be carried out (Ito and Matsui, 1977; Ito, Matsui and Hong, 1979). Furthermore, the basic method for the stability analysis of the slope containing one row of stabilizing piles has been already proposed, when the lateral force acting on the pile (or the lateral force reaction against a landslide) is known (Ito, Matsui and Hong, 1981).

Where multi-rows of piles are installed to prevent a landslide, not only the pile stability for each pile row but also the slope stability with regard to all the pile rows should be analyzed. To facilitate the analyses for multi-row stabilizing piles, the basic method proposed in the previous paper has been modified, particularly by the introduction of the mobilization factor of lateral force, which is described in the next section. This modification was carried out so as to be applicable even to the analyses of a single row of piles. If the lateral forces acting on each pile row are known, an analytical method for stabilizing the piles subjected to horizontal loads can be employed. Slope stability can be examined by using conventional stability analysis in which the total lateral force reactions of all pile rows are added to the resisting force due to the shear resistance along the sliding surface. This approach is possibly given by the assumption that each pile row is located apart from adjacent ones and consequently that the interaction between them can be neglected. Other detailed techniques of stability analysis have been presented by the authors (1981).

Lateral Force Used for Stability Analysis

The lateral force may vary from zero, in the case of no movement of the landslide mass, to an ultimate value in the case of passive failure and resultant large movements of land mass. Therefore, in order to effectively design stabilizing piles, one has to determine the applicable lateral force. In the design of stabilizing piles, it may be reasonable to assume a lateral force produced when the shear resistance along the sliding surface is not reduced by a strain softening with the advance of landslide. To estimate the critical lateral force on conditions as described above, a theoretical equation has been derived, which is based on consideration of the interval between the piles and also assumes that the Mohr-Coulomb's plastic condition occurs only in the ground just around the piles (Ito and Matsui, 1975, 1977, 1978). An important point in this assumption is that the lateral force acting on the piles can be estimated regardless of the state of equilibrium of the whole slope. Thus, the mobilized lateral force may be generally represented by multiplying the critical value with a coefficient that varies from zero to unity. This coefficient is designated by the mobilization factor \( \alpha_m \) of the lateral force. In the design of passive piles, the mobilization factor can be dealt with as a parameter, varying between two values; the first being a value determined from the maximum lateral force and from which the pile stability can be obtained, with the second being determined from the minimum lateral force reaction needed to prevent
a landslide.

Comparison between Behavior of Piles Subjected to Distributed and Concentrated Lateral Forces

Although the lateral force acting on a passive pile is a distributed one, it is often approximated by a concentrated one to facilitate calculations in the analysis of pile stability. The validity of this approximation will be discussed below.

Fig.1 shows an example of aligned stabilizing piles with soil parameters, a cross sectional view, layout and pile dimensions being given. The lateral force acting on piles is also shown, assuming that the mobilization factor $\alpha_m$ is unity.

Fig.2 shows the distribution of deflection, shearing force and bending moment calculated for the stabilizing piles shown in Fig.1, where $L_p$ is the pile length, $z_p$ is the depth from the pile top, and an unrotated head is adopted as the condition of pile head fixity. The solid lines in Fig.2 represent the analytical results for stabilizing piles subjected to a distributed lateral force with the broken lines representing those for a concentrated lateral force approximating the distributed case.

It can be seen in Fig.2 that the deflection of the pile head in the concentrated case is slightly larger than that in the distributed one, and that the distributions of shearing forces and bending moments above the sliding
Table 1. Safety factors of pile stability

<table>
<thead>
<tr>
<th>Fixity condition of pile head</th>
<th>Safety factor of pile stability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bending stress</td>
</tr>
<tr>
<td></td>
<td>Dist.*</td>
</tr>
<tr>
<td>Free head</td>
<td>0.58</td>
</tr>
<tr>
<td>Unrotated head</td>
<td>0.91</td>
</tr>
<tr>
<td>Hinged head</td>
<td>1.84</td>
</tr>
<tr>
<td>Fixed head</td>
<td>1.52</td>
</tr>
</tbody>
</table>

Dist.*: Distributed case
Con.*: Concentrated case

surface in both cases are very different from each other. The maximum values of shearing force in both cases coincide at the sliding surface, but the maximum value of bending moment in the distributed case is slightly larger than that in the concentrated one.

Assuming allowable bending and shearing stresses of $1.57 \times 10^6$ kN/m$^2$ and $0.98 \times 10^6$ kN/m$^2$, respectively, Table 1 gives the safety factor of pile stability for the piles shown in Fig. 1 in terms of four fixity conditions, i.e., free head, unrotated head, hinged head and fixed head. It can be seen from this table that the safety factors for bending stresses are much less than those for shearing stresses, and that the stronger the fixity condition of the pile head, the larger the safety factor. It will be further noted that the safety factors for shearing and bending stresses on the concentrated case coincide with those in the distributed case only for the free head condition. The safety factors for shearing stress in both concentrated and distributed cases in this table are almost the same for each pile head fixity condition. On the other hand, the safety factor for bending stress for the unrotated head in the concentrated case is 9 percent greater than that in the distributed one, but 40 percent and 19 percent less for the hinged and fixed heads, respectively.

Finally, it should be noted that the stability of the piles has to be checked by the bending stress, except in cases such as rock slides, and that the approximation of a distributed lateral force by a concentrated one incurs comparatively large errors in cases where the pile head is restrained. Thus, approximation by concentrated lateral forces should not be used, except in cases where free head conditions are employed or a rough estimate of other fixity conditions is being made.

EFFECT OF TWO ROWS OF STABILIZING PILES AGAINST LANDSLIDES

General Remarks

In cases where stabilizing piles are placed in two rows to prevent landslides, it is important that not only the pile stability for each row but also the slope stability for the combined effect of both rows is insured simultaneously.

Fig. 3 shows a cross section of a landslide slope, upon which a road is planned. The boring log, $N$-value and soil parameters are also shown in Fig. 3. The safety factor of the designed slope along the sliding surface shown is 0.92, which was obtained by the

![Fig. 3. Cross section of a landslide slope](image-url)
slice method, so that the stability of this slope is not insured. The two rows of stabilizing piles, as shown in this figure, can be used as a countermeasure against a possible landslide movement. Both rows No.1 and No.2 are placed outside the relaxation zone of the tunnel which is delineated by a dotted line. In the present chapter, the preventative effects of these two rows of stabilizing piles are examined using the method described in the previous chapter.

In order to carry out this study, the following assumptions were made:
1) The modulus of elasticity of steel pile, \(E_p\), is \(2.06 \times 10^8\) kN/m².
2) The allowable bending and shearing stresses of steel pile are \(1.57 \times 10^5\) kN/m² and \(0.98 \times 10^5\) kN/m², respectively.
3) The soil modulus below the sliding surface, \(E_s\) (kN/m²), is \(4 \times 10^4\) kN/m², based on the N-value.
4) The pile length is infinite.
5) The required safety factors of the pile stability and the slope stability are 1.0 and 1.2, respectively.

**Effect of Mobilization Factor of Lateral Force**

Figs. 4(a) and (b) show the effects of the mobilization factor, \(\alpha_m\), of lateral force on the stabilities of the pile and the slope, respectively, where steel pipe piles having a diameter of 711.2 mm, a thickness of 22 mm, a pile length above the sliding surface of 3 m and an unrotated head are installed in the position of pile row No.2 shown in Fig. 3. In this case, it is assumed that the lateral force acting on the piles (or the lateral force reaction against a landslide) can be estimated by the theoretical equation multiplied by the mobilization factor as described in the previous chapter. Solid lines in Fig. 4(a) show variations of the safety factor for pile stability, \(F_s/pile\), in terms of the interval ratio, \(D_h/D_s\), using \(\alpha_m\) as a variable parameter. Broken lines and the chain–dot line in Fig. 4(b) show the safety factors for slope stability \(F_s/slope\), for cases where consideration and nonconsideration of the pile effect have been made, respectively. In the cases where pile stability is insured, the pile effect has been calculated by the difference between the broken and chain–dot line as estimated in terms of the safety factor.

It can be seen from Figs. 4(a) and (b) that the safety factor for pile stability gradually decreases with an increase in the mobilization factor of lateral force, while the safety factor for slope stability increases, when the interval ratio, \(D_h/D_s\), is held constant. Therefore, it can be said that the variation of the mobilization factor of lateral force has a converse effect on pile and slope stabilities.

Based on the results of Fig.4, the relation
between the allowable interval ratio, \(D_2/D_1\) allow., and the mobilization factor, \(\alpha_m\), can be obtained as shown in Fig.5. The solid line in this figure represents the minimum interval ratio, over which pile stability can be insured and the broken line represents the maximum interval ratio, under which slope stability can be insured. Consequently, the hatched portion in Fig.5 represents the range in which the overall stability of the slope containing the stabilizing piles can be insured. Thus, the allowable interval ratio has a tendency to increase with an increase in the mobilization factor.

**Effect of Two Rows of Stabilizing Piles**

Fig. 6 shows analytical results for the two rows of stabilizing piles installed in the positions shown in Fig.3. The depths from the ground surface to the sliding surface are 2.9 m and 5.0 m at the No.1 and No.2 pile row positions, respectively. At the No.1 position, steel pipe piles having a diameter of 355.6 mm, a thickness of 11.1 mm and a pile length above the sliding surface of 2.0 m are used at regular intervals of 2.0 m. At the No.2 position, steel pipe piles having a diameter of 609.6 mm, a thickness of 22 mm, a pile length above the sliding surface of 3 m are also at regular intervals of 2 m. It is assumed that the pile heads are unrotated and that the mobilization factor of lateral force is unity.

Fig. 6(a) shows the relation between the safety factors of both pile and slope stabilities and the interval ratio for the row No.1 piles. Because the interval \(D_1\) between piles is 2 m, the interval ratio, \(D_2/D_1\), becomes 0.822. As shown in Fig. 6(a), pile stability can be insured at the interval ratio, while the safety factor of the slope stability increases from 0.92 to 0.99 with the consequence that the overall stability of this slope can not be insured by only the row No.1 stabilizing piles.

Fig. 6(b) shows the effects of No.2 stabilizing piles, where the chain line with two dots represents the safety factor of the slope stability with the pile effect of No.1 stabiliz-
ing piles as described above. As the interval between piles $D_i$ is 2 m ($D_i/D_s=0.695$), the safety factor of the pile stability is 1.03 and the safety factor of the slope stability increases from 0.99 to 1.20, as shown in Fig. 6(b). Therefore, the overall stability of this slope can be insured, and a landslide may be prevented by using these two rows of stabilizing piles.

**DESIGN METHOD USING MULTI-ROW STABILIZING PILES AGAINST LARGE LANDSLIDES**

A new design method has already been proposed in a previous paper for single row stabilizing piles, based on factors such as the interval between piles, the fixity condition of pile heads, the pile length above the sliding surface, the pile diameter, the pile stiffness, etc. (Ito, Matsui and Hong, 1981). In the present chapter, an extended design method is proposed for preventing large landslides with multi-row stabilizing piles as based on the study in the previous chapter.

In cases where multi-row piles are used, it is necessary to adopt a design that insures not only the stability of each pile row but also the slope stability taking into consideration the total effect of all pile rows.

The procedure for the design of multi-row stabilizing piles is shown as a block chart in Fig. 7. First, the condition of the ground is ascertained through field and laboratory testing with final determination leading to the selection of the required safety factors for slope stability and allowable pile stresses.

As to the fixity of pile heads, it is more effective to select a fixity condition in which deflection and/or rotation are restrained at the pile head. This may be effected by connecting the pile heads to a buried beam with tie-rods or tension anchors. The decision as to selection of fixity, however, should be based on construction conditions. In general, unrotated pile heads are widely used and may be constructed by connecting the pile heads to a buried reinforced concrete beam.

Upon determination of the aforementioned, the number of pile rows, their position, and the pile length above the sliding surface may be decided. The numbers of pile rows should be determined in conjunction with the selection of their position. The position of the pile rows should be selected so as to assure slope stability against not only the existing sliding surface but also potential sliding surfaces after installation of the piles. The pile length above the sliding surface should be selected based on the convenience of construction with regard to the stabilizing piles.

Finally, the mobilization factor of lateral force, the pile diameter, the interval between piles and the pile stiffness should be selected so as to assure both the stability of each pile row and stability of the whole slope. In the selection of these four factors as shown in Fig. 7, it is convenient to use schematic diagrams such as these found in Fig. 8 and Fig. 9. The mobilization factor of lateral force can be determined by using Fig. 8, which represents the relation between the total resisting force of piles, $F_{rp}$, above the sliding surface per unit width for all pile rows and the mobilization factor, $\alpha_m$, of lateral force. In cases where the interval ratio equals
in Fig. 8.

On the other hand, in cases where the mobilization factor and the interval ratio are $\alpha_{m1}$ and $(D_2/D_1)_1$, respectively, a convenient diagram to select the pile stiffness for each pile row is shown in Fig. 9. This figure shows the relation between the allowable interval ratio, $(D_2/D_1)_{allow}$, and the pile diameter, $d$, by choosing the pile stiffness as a parameter. The allowable interval ratio represents the minimum interval ratio by which pile stability can be obtained. In Fig. 9, the broken line represents the maximum allowable interval ratio, $(D_2/D_1)_{allow}$ for slope stability. Curve I shows the variation of the pile diameter with a thickness of $t_1$ with an allowable interval ratio. In this case, there is no suitable pile stiffness as values for curve I are located above the broken line and within the region below the maximum available pile diameter, $d_m$. Curve II represents piles having a thickness of $t_2$ larger than $t_1$, in which it is necessary to use piles with values as shown in the hatched portion in Fig. 9. Again, from the viewpoint of economy, it may be favorable to select a smaller pile diameter. If piles having a diameter of $d_2$ smaller than $d_1$ are used, the pile thickness should be increased by using a larger thickness of $t_2$, as shown by curve III in Fig. 9.

If an adequate result cannot be obtained by the procedure described above, it is possible to reselect the number and position of the pile rows and the pile length above the sliding surface according to the feedback line in Fig. 7. It is also possible to reselect the fixity condition of pile heads or to change the condition of ground by altering the cross section of landslide.

**DESIGN EXAMPLE FOR MULTI-ROW STABILIZING PILES**

In order to implement the design of multi-row stabilizing piles according to the procedure in the previous chapter, Shiranozawa slope, located in the Higashinomoyo landslide area in Niigata Prefecture, is taken up as an example.
Table 2. Design examples of stabilizing piles in eight rows

<table>
<thead>
<tr>
<th>Row No.</th>
<th>H (m)</th>
<th>H' (m)</th>
<th>DESIGN I</th>
<th>DESIGN II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>d (mm)</td>
<td>D1 (m)</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>9</td>
<td>1016</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>9</td>
<td>1016</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>9</td>
<td>1016</td>
<td>2.5</td>
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<tr>
<td>4</td>
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<td>1016</td>
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<tr>
<td>5</td>
<td>11</td>
<td>10</td>
<td>1016</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>9</td>
<td>1016</td>
<td>2.5</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>9</td>
<td>1016</td>
<td>2.5</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>8</td>
<td>1016</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The cross section of this slope and the N-value of the ground are shown in Fig. 10 (Fukumoto, 1977). This landslide slope is about 250 m long and 50 m wide, and has been slowly moving for a long period of time. The strength parameters $c$ and $\phi$ of the soil along the sliding surface are 9.8 kN/m^2 and 7 degree, respectively, and were obtained by the $c - \phi$ method. The unconfined compressive strength, $q_u$, and the unit weight, $\gamma$, of the soil above the sliding surface are estimated at 64.7 kN/m^2 and 17.7 kN/m^3, respectively. Under conditions where the water level is equal to the ground surface during thawing, the safety factor of this slope is 0.78 along the sliding surface shown in Fig. 10, as based on the slice method. If the required safety factor of slope stability is 1.1, the stability of this slope may not be insured. The other assumptions made under General Remarks in the previous chapter are also applied to the following design. The fixity of pile heads is assumed to be unrotated.

Eight rows of stabilizing piles are installed at various positions as shown in Fig. 10. The depth, $H$, from the ground surface to the sliding surface consists of 9 m, 10 m and 11 m as shown in Table 2. The pile length, $H'$, above the sliding surface also consists of three lengths as the fixed position of the pile heads is assumed to be one meter below the ground surface.

Figs. 11 (a), (b) and (c) for these three kinds of pile rows show the variation of the lateral force reaction per unit width, $P/D$, with the interval ratio, $D_1/D$, by choosing the mobilization factor, $\alpha_m$, of lateral force as a parameter. Based on Figs. 11 (a), (b) and (c), a diagram such as Fig. 8 can be obtained as shown in Fig. 12, in which three interval ratios of 0.59, 0.66 and 0.73 are examined. Fig. 12 shows the relation of the total resisting force per unit width, $F_{rp}$, for all pile rows to the mobilization factor, $\alpha_m$. 
By back calculation, an additional resisting force of 1.87 MN/m is found to be necessary to insure slope stability. Therefore, the minimum allowable value of the mobilization factor is 0.35, 0.44 or 0.58, in cases where the interval ratio is 0.59, 0.66 or 0.73, respectively, as shown in Fig. 12.

Figs. 13 (a), (b) and (c) show such diagrams as in Fig. 9 for the above-mentioned three kinds of pile rows for cases where the mobilization factor equals 0.35, i.e. an interval ratio of 0.59. Fig. 14 and Fig. 15 also show similar diagrams in cases where the mobilization factors equal 0.44 and 0.58, respectively, i.e. interval ratios of 0.66 and 0.73. The points shown by open circles in these figures correspond to available steel pipe piles in Japan. When located under the broken lines in each figure, these points indicate that pile stability can be insured.

Using the above-mentioned figures, the design of stabilizing piles can be easily carried out. For example, let us select a pile diameter of 1016 mm with an interval ratio of 0.59 for all pile rows as DESIGN I, in which the interval between piles becomes 2.5 m. In cases where the depth, $H$, from the ground surface to the sliding surface is 9 m, 10 m and 11 m, it is necessary to use piles having a thickness of 16 mm, 19 mm and 22 mm, respectively, as shown in Fig. 13.

If a pile diameter of 812.8 mm with an interval ratio of 0.59 is selected as DESIGN II, the interval between piles becomes 2 m.
In cases where the depth, \( H \), is 9 m and 10 m, it is possible to use piles having a thickness of 16 mm and 19 mm, respectively, as shown in Figs.13(a) and (b). In the event that the depth, \( H \), equals 11 m, however, it is necessary to use piles having a thickness

![Diagram showing relation between allowable interval ratio, \( \frac{D_2}{D_1} \), pile diameter, \( d \), and pile stiffness (\( \alpha_m = 0.35 \))](image1.png)

Fig. 13. Relation between allowable interval ratio, \( \frac{D_2}{D_1} \), pile diameter, \( d \), and pile stiffness (\( \alpha_m = 0.35 \))

![Diagram showing relation between allowable interval ratio, \( \frac{D_2}{D_1} \), pile diameter, \( d \), and pile stiffness (\( \alpha_m = 0.44 \))](image2.png)

Fig. 14. Relation between allowable interval ratio, \( \frac{D_2}{D_1} \), pile diameter, \( d \), and pile stiffness (\( \alpha_m = 0.44 \))

<table>
<thead>
<tr>
<th>Row</th>
<th>DESIGN III</th>
<th>DESIGN IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>( d (\text{mm}) )</td>
<td>( D_1 (\text{mm}) )</td>
</tr>
<tr>
<td>1</td>
<td>1016</td>
<td>3.0</td>
</tr>
<tr>
<td>2</td>
<td>1016</td>
<td>3.0</td>
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<td>1016</td>
<td>3.0</td>
</tr>
<tr>
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<td>1016</td>
<td>3.0</td>
</tr>
<tr>
<td>7</td>
<td>1016</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 3. Design examples of stabilizing piles in eight rows.
between piles is increased without changing the pile diameter, the pile stiffness should also be increased. This is based on the fact that the total lateral force, \(P\), acting on a pile increases as the interval between piles, \(D_1\), increases, if the lateral force reaction per unit width, \(P/D_1\), is constant.

CONCLUSIONS

In a previous paper, a design method was proposed for single row stabilizing piles for a slope containing a fixed sliding surface. The present paper has extended this method for the design of stabilizing piles in multiple rows through a sliding mass. This extension was carried out so as to be applicable for even single row piles.

In the case of the multi-row piles, the stabilizing piles should be designed so as to insure not only the pile stability for each pile row but also the slope stability with regard to all pile rows. In the extended design method proposed in this paper, the ground conditions of a slope were established, the selection of pile head fixity, the number of pile row, the position of pile rows and the pile length above the sliding surface were carried out, followed by the systematic selection of factors of mobilization of lateral force, pile diameters, intervals between piles and pile stiffnesses. If any of the eight factors are known in advance, the design process, of course, becomes simpler.

Finally, design example of a large scale landslide slope with eight rows of stabilizing piles was shown, with convenient figures to illustrate important factors in the design of multi-row stabilizing piles.

The design example in this paper employed visual forms through the use of figures for purposes of illustrating the design procedure in detail. In the practical design of stabilizing piles, however, the extended design method proposed herein may be applied without the use of these figures by the aid of computer programming. Studies on interaction between multi-rows of piles in cases where they are in close proximity have been left.
in further investigations.

ACKNOWLEDGMENTS
The authors are indebted to Mr. Y. Fukumoto for the kind provision of his data on the Shiranozawa landslide slope.

NOTATIONS
\[ c = \text{cohesion of soil} \]
\[ d, d_1, d_2 = \text{pile diameters} \]
\[ d_m = \text{maximum available pile diameter} \]
\[ D_1 = \text{center-to-center interval between piles in a row} \]
\[ D_2 = \text{clear interval between piles in a row} \]
\[ D_0/D_1 = \text{interval ratio of piles in a row} \]
\[ (D_0/D_1)_{\text{allow.}} = \text{allowable interval ratio of piles in a row} \]
\[ E_p = \text{modulus of elasticity of pile} \]
\[ E_s = \text{soil modulus} \]
\[ F_{tp} = \text{total resisting force of piles above the sliding surface per unit width} \]
\[ (F_s)_{\text{pile}} = \text{safety factor of the pile stability} \]
\[ (F_s)_{\text{slop}} = \text{safety factor of the slope stability} \]
\[ H = \text{depth from the ground surface to the sliding surface} \]
\[ H' = \text{length from the pile top to the sliding surface} \]
\[ L_p = \text{pile length} \]
\[ \phi(x) = \text{lateral force acting on piles in a row} \]
\[ P = \text{total lateral force above the sliding surface acting on a pile} \]
\[ q_u = \text{unconfined compressive strength of soil} \]
\[ t, t_1, t_2, t_3 = \text{thicknesses of pipe pile} \]
\[ z, z_p = \text{depths from ground surface and pile top, respectively} \]
\[ \alpha_m = \text{mobilization factor of lateral force} \]
\[ \tau = \text{unit weight of soil} \]
\[ \phi = \text{angle of internal friction of soil} \]

REFERENCES