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APPLICATION OF STRAIN-PIPE GAUGE IN THE STUDY OF SLOPE STABILITY

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An attempt is made to interpret the strain measured along a strain-pipe embedded in landslide areas with the aid of a continuous curve fitting by cubic spline functions. The aim of the present research is to identify the slip planes in the particular areas as well as to evaluate the current extent of the sliding movement.

The strain-pipe employed is made of a plastic material with strain gauges attached on its side wall. The pipe is penetrated into stable layers beneath a slope so that the bottom tip is fixed.

The pipe is modeled as a beam lying on an elastic foundation. The theory of beams suggests that the strain measured by gauges are proportional to the bending moment whose first-order derivative is equal to the shear force. The maximum shear force is expected to occur at an elevation close to the slip plane. Furthermore, the lateral displacement of the pipe and surrounding soils can be evaluated by integrating the moment twice along the pipe.

The method described above was used for two case studies at the Er-Jen Mountain and the Lung-Tan District. By comparing the results with those of the limit equilibrium analyses, it was found that both strain-pipe and numerical methods gave very similar locations of slip planes.

Keywords: *strain-pipe gauge, subgrade reaction, modulus of soil K_S, STABL 2, "S" strain shape and bow strain shape*

1. INTRODUCTION

Due to the special natural environment such as steep slopes, weak geology, frequent earthquakes, concentrated downpours, etc., erosion and landslides of a slope are easy to occur in Taiwan. In the investigations from 1964 to 1976, the area of landslides reached 15 000 hectares, about 0.4 % of the area of Taiwan. Because of the high population density in Taiwan, it is inevitable to develop the slopeland. Hence, it is significantly important to study landslides caused by earthquakes and floods. It is urgent to make a technical study on the prevention and treatment of landsliding[13].

Conventional slope stability analysis is made by the methods of limit equilibrium analyses[10),12] and deformation analyses. The limit equilibrium method studies the slope stability by the value of a safety factor. It does not consider the relationship between stress and strain of soil. Hence, we cannot predict the deformation value. On the other hand, the Finite Element Method is a useful tool of deformation analysis. However, the complex subsurface structures as seen in natural slopes may not be realistically modeled by the Finite Element Method. Due to the difficulty in determining soil properties, the probabilistic method is becoming popular. Its shortcoming is that it requires a large amount of experiments to understand the variability of the soil properties.

In recent years, with the development of instrument system, it is possible to observe the soil behavior by means of insitu equipments. Such equipments as inclinometer, pipe strain gauge, extensometer, etc. are commonly used in observations on slopes. In particular, the pipe strain gauge is a simple, economical, and effective apparatus for observations of landsliding. In Taiwan, there are many examples of using pipe strain gauges in the past decade. However, the interpretation of the measured data is not detailed yet. The

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main subject of this study is to analyze the observed data by numerical methods[1),2),4)] and to determine the sliding surface and sliding displacement.

2. INSTRUMENTATION OF PIPE STRAIN GAUGE

Strain gauges of small capacity but high precision are attached to the surface of P. V. C pipe which is called a strain pipe. When this pipe is buried in the ground and loaded with earth pressure, resistant lines of the strain gauges elongate or shrink. This variation of the electric resistance can be measured by a strain indicator.

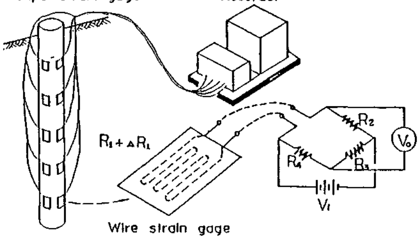

Fig. 1 Pipe strain gauge details (Masami Fukuoka, 1979).

3. INTERPRETATION OF OBSERVED DATA

(1) Cubic spline fit method

Strain gauges are normally placed with an equal interval along a strain pipe. Conventionally it has been practiced that the observed strains are plotted along depth and then connected to form a piecewise linear diagram of strains. Similar diagrams are made at several sites so that the accumulation of strain in the soil with time is understood. Then, the location of the sliding surface is determined by examining a set of log figures of accumulated strain. This method assumes that the strain value of a strain pipe varies with depth in a piecewise linear manner. This assumption may not be accurate, however, and does not give the magnitude of displacement. Due to this reason, the strain value in the present study is approximated by cubic spline functions which may reasonably model the continuous strain variation along a strain pipe. The theory is explained in which follows.

Suppose there are n points along a pipe. Let the strains at those points be denoted as P_1, P_2, ………, and P_n. An attempt is made to find out a cubic equation $Q_k(t)$ between two adjacent points P_k and P_{k+1} like :

$$Q_k(t)=A_k+B_kt+C_kt^2+D_kt^3 \quad (1)$$

where : $k=1, 2, 3,$ ………, $n-1$.

There are four unknown parameters, A_k, B_k, C_k and D_k to be determined.

When $t=0$, this line passes through the point P_k, its differential value being equal to P'_k. When $t=1$, this line passes through the point P_{k+1}, its differential value being equal to P'_{k+1}. The boundary conditions are written as :

(1) $Q_k(0)=P_k$ where $k=1, 2,$ ………, $n-1$

(2) $Q_k(1)=P_{k+1}$ where $k=1, 2,$ ………, $n-1$

(3) $Q'_k(1)=Q'_{k+1}(0)$ where $k=1, 2,$ ………, $n-1$

(4) $Q''_k(1)=Q''_{k+1}(0)$ where $k=1, 2,$ ………, $n-1$

Eqs. (1) and (2) show that $Q_k(t)$ is a set of curved lines which pass through points P_1, P_2, ………, and P_n when $k=1, 2,$ ………, and $n-1$. Eqs. (3) and (4) imply that the first and second derivatives are continuous at points P_2, P_3, ………, and P_{n-1}. Substituting the boundary conditions into Eq. (1) yields,

$$A_k=P_k$$
$$B_k=P'_k$$
$$C_k=3P_{k+1}-P'_{k+1}-3P_k-2P'_k$$
$$D_k=2P_k-2P_{k+1}+P'_k+P'_{k+1}$$

Thus Eq. (1) becomes

$$Q_k(t)=P_k+P'_kt+(3P_{k+1}-P'_{k+1}-3P_k-2P'_k)t^2+(2P_k-2P_{k+1}+P'_k+P'_{k+1})t^3 \quad (2)$$

$Q_k(t)$ is called cubic spline. By differentiating Eq. (2) twice, we obtain

$$Q''_k(1)=2(3P_{k+1}-P'_{k+1}-3P_k-2P'_k)+6(2P_k-2P_{k+1}+P'_k+P'_{k+1})$$

$$=2(3P_k-3P_{k+1}+P'_k+2P'_{k+1}) \quad \cdots\cdots (3)$$

Moreover,

$$Q''_{k+1}(0)=2(3P_{k+2}-P'_{k+2}-3P_{k+1}-2P'_{k+1}) \quad \cdots\cdots (4)$$

It should be noted here that the continuity of Q and Q', i. e. the bending moment and the shear force, is already satisfied. Therefore, the continuity of Q'' or earth pressure is employed to derive a set of equation;

$$\left.\begin{array}{l} Q''_k(1)=Q''_{k+1}(0), \\ P'_k+4P'_{k+1}+P'_{k+2}=-3P_k+3P_{k+2} \end{array}\right\} \quad \cdots\cdots (5)$$

in which $k=1, 2, \cdots\cdots, n-2$

Eq. (5) may be written in matrix form:

$$\begin{bmatrix} 141 & & \\ & \vdots & \\ & \vdots & \\ & & 141 \\ & & 141 \\ & & \end{bmatrix} \begin{bmatrix} P'_1 \\ P'_2 \\ \vdots \\ \vdots \\ P'_{n-1} \\ P'_n \end{bmatrix} = \begin{bmatrix} -3P_1+3P_3 \\ -3P_2+3P_4 \\ \vdots \\ \vdots \\ -3P_{n-2}+3P_n \\ \end{bmatrix} \quad \cdots\cdots (6)$$

Since $P_1, P_2, \cdots\cdots, P_n$ are observed strain values in Eq. (6), we have $n-2$ equations and n unknown variables. Hence, it is needed to find two boundary conditions to solve these equations.

For the boundary conditions of a strain pipe:

① The moment and earth pressure acting on a strain pipe at the slope surface is very small and can be assumed equal to zero. $\cdots\cdots$ that means, P_1 is equal to 0, and the second derivative of Q is equal to 0.

② As the strain pipe is installed, it must be embedded over a sufficient length into an immovable soil layer or rock bed. The bottom part of the strain pipe must be fixed by bentonite or concrete[6)~8)], resulting in zero shear force at the bottom end. Hence, the first derivative value P'_n is equal to zero. Substituting $Q''_1(0)=0$ into Eq. (4), we have $2P'_1+P'_2=3P_2-3P_1$. Appending this equation and $P'_n=0$ into Eq. (6) gives

$$\begin{bmatrix} 21 & & \\ 141 & & \\ & \vdots & \\ & \vdots & \\ & & 141 \\ & & 14 \end{bmatrix} \begin{bmatrix} P'_1 \\ P'_2 \\ \vdots \\ \vdots \\ \vdots \\ P'_{n-1} \end{bmatrix} = \begin{bmatrix} -3P_1+3P_2 \\ -3P_1+3P_3 \\ \vdots \\ \vdots \\ -3P_{n-3}+3P_{n-1} \\ -3P_{n-2}+3P_n \end{bmatrix} \quad \cdots\cdots (7)$$

There are $n-1$ unknown variables with $n-1$ equations in Eq. (7). Therefore, $P'_1, \cdots\cdots, P'_{n-1}$ can be solved and substituted Eq. (2). The cubic spline equation between two adjacent points is thus obtained.

(2) Analysis of slide surface and prediction of lateral displacement

The mechanical model of a strain pipe in estimating landslide is shown in **Fig. 2**. The external load acting on the strain pipe is an unbalanced force of soil embankment or a force caused by earthquake[4), 5)]. The external load results in the displacement of a strain pipe in the downslope direction. If the strain pipe has a displacement, y, then the soil around the pipe generates a resistant force of $K_s y$. The relationship may be written as:

$$EI\frac{d^4y}{dx^4}+K_s y=0 \quad \cdots\cdots (8)$$

where, E : Elastic modulus of the strain pipe,

I : Inertial modulus of the strain pipe,

K_S : Subgrade reaction modulus of soil.

It should be noted that x coordinate is measured from the bottom towards the surface.

K_S varies with the depth of soil layer. Hence, the strain pipe may be treated as an elastic uniformly supported beam. Consequently the bending moment may be written as :

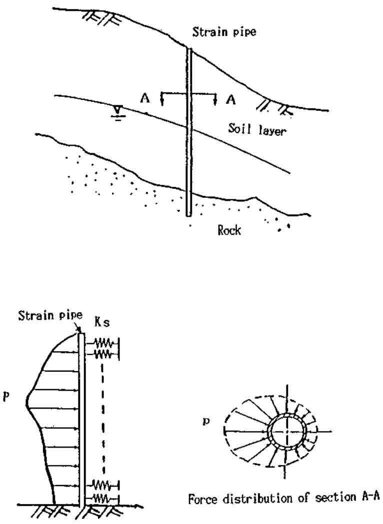

Fig. 2 Mechanic modulus of a strain pipe.

$$EI\frac{d^2y}{dx^2}=-M=-\sigma\cdot Z$$

or

$$\frac{d^2y}{dx^2}=-\frac{\sigma}{E}\cdot\frac{Z}{I} \quad (9)$$

where σ is the pipe stress at its edge and Z is the sectional modulus. The strain ε measured by strain gauges on the strain pipe is related to the stress by

$$\varepsilon=\frac{\sigma}{E} \quad (10)$$

Substituting this in Eq. (9) gives

$$\frac{d^2y}{dx^2}=-\frac{Z}{I}\varepsilon=-\frac{2}{D}\varepsilon(x) \quad (11)$$

where D is the external diameter of the strain pipe.

A continuous strain curve $\varepsilon(x)$ may be obtained by the aforementioned cubic splines.

$$EI\frac{d^2y}{dx^2}=-M(x)=-\frac{2\,EI}{D}\varepsilon(x) \quad (12)$$

In structural mechanics, the curvature of a beam, K, may be derived by

$$K=\frac{di}{dx}=\frac{d^2y/dx^2}{\left[1+\left\{\frac{dy}{dx}\right\}^2\right]^{3/2}} \quad (13)$$

where i is the slope of the lateral-displacement curve.

When the ratio of "y" of a strain pipe to its length is very small, dy/dx can be neglected. Hence, Eq. (13) can be simplified as :

$$\frac{di}{dx}=\frac{d^2y}{dx^2}=-\frac{2}{D}\varepsilon(x) \quad (14)$$

Where $2\varepsilon(x)/D$ represents the curvature distribution of the strain pipe. Eq. (12) reveals that $2EI\varepsilon(x)/D$ is the moment distribution of the strain pipe. The shear force distribution curve $V(x)$ is obtained by differentiating the moment distribution curve :

$$V(x)=EI\frac{d^3y}{dx^3}=\frac{2\,EI}{D}\cdot\frac{d\varepsilon(x)}{dx} \quad (15)$$

The location of the maximum shear force indicates the position of the potential sliding surface. The distribution curve of earth pressure $P(x)$ is obtained by differentiating the shear force $V(x)$:

$$P(x)=EI\frac{d^4y}{dx^4}=\frac{2\,EI}{D}\cdot\frac{d^2\varepsilon(x)}{dx^2} \quad (16)$$

From the distribution curve of earth pressure, we can find out the elevation of the potential sliding surface at which the earth pressure in the sliding mass is replaced by the resistant force in the bottom. The sliding surface thus detected is expected to be in agreement with what is obtained by the maximum ε.

From Eq. (14), the slope of the lateral displacement i can be obtained by integrating Eq. (14) :

$$i=\frac{dy}{dx}=-\frac{2}{D}\cdot\int \varepsilon(x)dx+C_1 \quad (17)$$

The displacement can be obtained by integrating Eq. (14) twice;

$$\begin{aligned} y&=-\int idx+C_2 \\ &=-\int\int\frac{2}{D}\,\varepsilon(x)dxdx+\int C_1dx+C_2 \end{aligned} \quad (18)$$

Because the lowest end of the strain pipe ($x=0$) is fixed, the integration constants C_1 and C_2 in Eqs. (17) and (18) are both equal to zero.

In **Fig.** 3, section (a) represents the accumulated strain distribution curve which was obtained from the observed data of the strain pipe by using the cubic spline method. The shear force can be obtained by differentiating section (a) and multiplying by $2\,EI/D$ (the value of EI is about 29.5 kg/m² for PVC pipe) as shown in section (b). The earth pressure curve of a soil layer can be obtained by differentiating the shear force as shown in section (c). Note that the negative value represents the passive earth force directed downslope. The positive value represents the resistant force of the bottom layer. The inclination of the pipe shown in section (d) is obtained by integrating the strain distribution curve shown in (a) Moreover, the pipe displacement as shown in (a) can be obtained by integrating the inclination of the pipe in (d).

As shown in **Fig.** 3, at the depth of 7.7 m under the slope surface, the strain pipe indicated the maximum positive shear force. The soil layer at this elevation developed the maximum shear force as well. This location indicates the boundary between the zone of the passive earth pressure and the resistant force of the bottom soil layer and is regarded as the location of the sliding surface.

4. TWO TYPICAL EXAMPLES

Discussion is made of two examples in order to examine the proposed method of analysis. The first example is the land sliding in the Er-Jen Mountain which was classified as a shallow layer failure. The second example is the land sliding which occurred in the Lung-Tan district which can be classified as a deep layer failure.

(1) Study on the land sliding in the Er-Jen Mountain

The land sliding of the Er-Jen Mountain occurred at the border of Shui-Li and Chung-Liao districts of

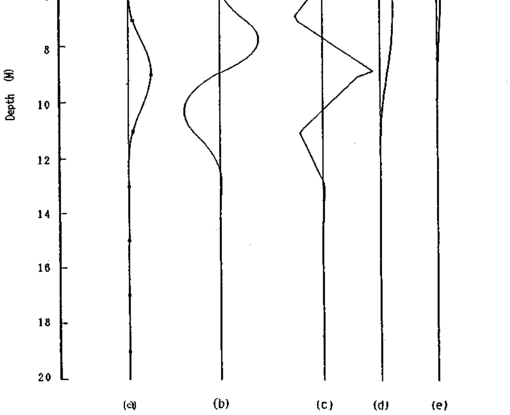

Fig. 3 Analytical diagram of a bow shape.

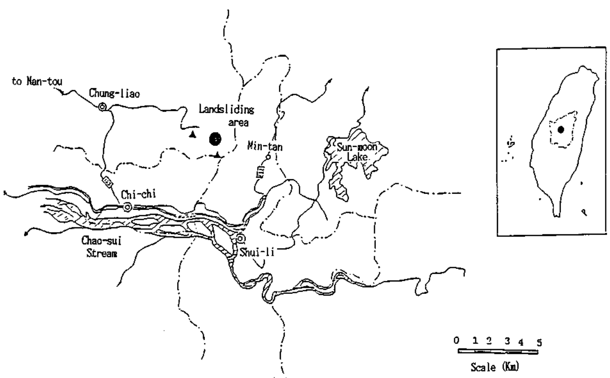

Fig. 4 Location of the landsliding in the Er-Jen Mountain.

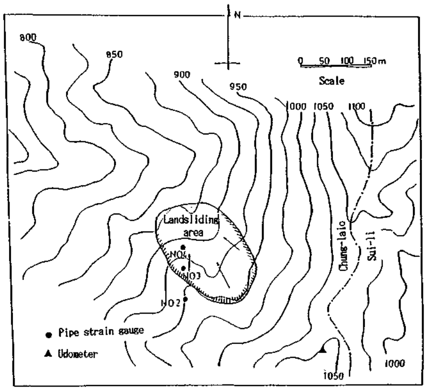

Fig. 5 Geography of the Er-Jen Mountain and location of strain pipes.

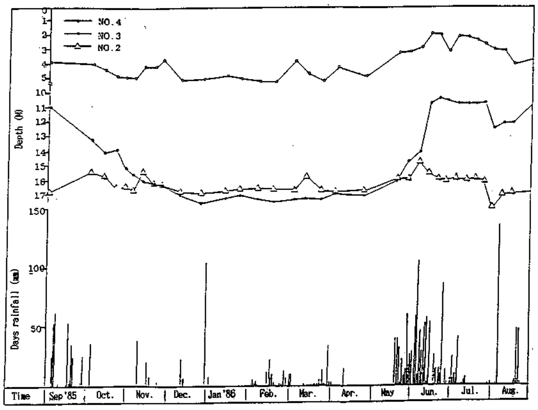

Fig. 6 Days rainfall and ground water level of the Er-Jen Mountain.

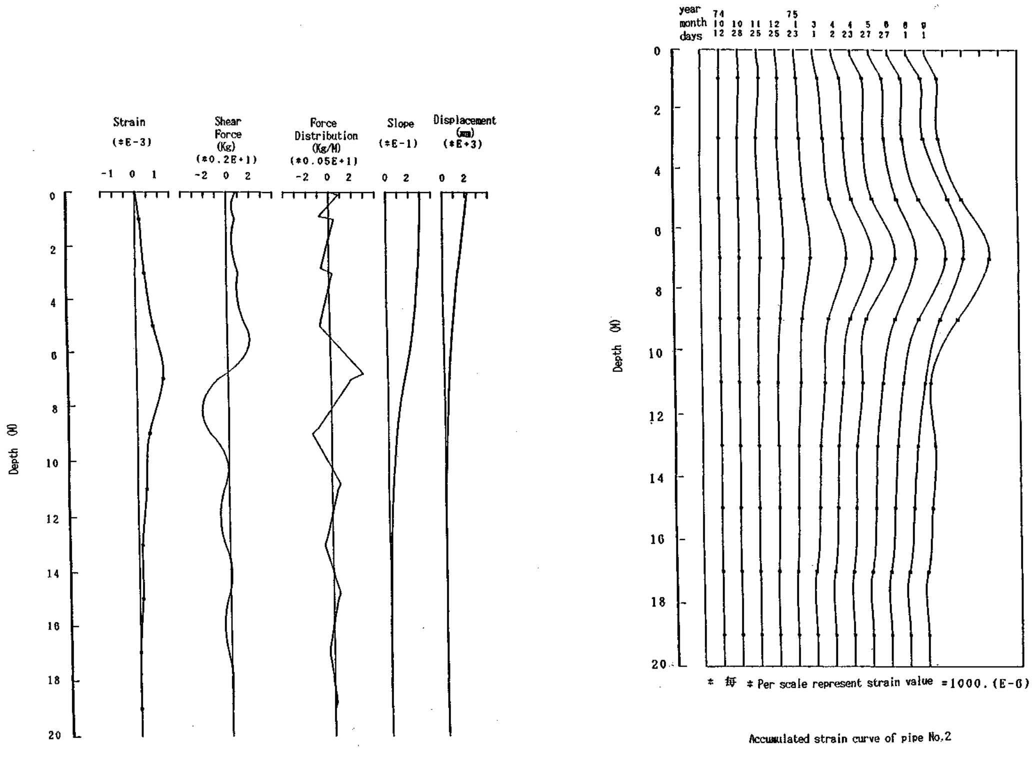

Fig. 7 Prediction of Sliding point and displacement of No. 2.

Nan-Tou county, as shown in Fig. 4 and Fig. 5. It was quite frequent especially during the rainy season. After a continuous torrential rain on June 1, 1985, a landslide caused serious damage to the bamboo groves and structures in this district. The area of the landslide is about one and half hectares on the northern side of this district.

a) The geological and hydrological investigation at the landsliding area

The slope of the ground surface is about 24 degrees. From the records of site borings, the thickness of the top soil is about 4~10 m. It is a mixture of weathered sandstone, shale, and clay. Below this, there are alternating layers of sandstone and shale underlain by mudstone.

According to the records of rain gauges installed in this district, the total amount of the rainfall during May and September was about 79 % of the whole year's amount. The relationship between the total amount of rainfall and the ground water level is shown in **Fig. 6**. Note should be taken of the water level in May and September. This influences the stability of slopes.

b) Analysis of sliding surface and prediction of sliding displacement

There were three strain pipes installed in this area. They were in holes No. 2, No. 3, and No. 4 shown in **Fig. 5**. The observation period were from October, 1985 to September, 1986. The accumulated strain curves depicted in **Fig. 7** were obtained from the observation data of pipe No. 2 by the cubic spline method. The accumulated strain curves show the deformation tendency of the strain pipe. The accumulated strain at 7 meters below the ground surface was greater than $1\,000\times10^{-6}$ on Jan. 23, 1986. Differentiating and integrating the accumulated strain curve yield the analytical diagram of sliding location as shown in **Fig. 7**. By this strain pipe, we can determine that the sliding surface is located at a depth of 5. 4 meters below the ground surface, and find the sliding displacement of the observation points equal to around 2 m (**Fig. 7**).

c) Safety factor of the critical sliding surface

To find out the safety factor by the limit equilibrium method, we should first evaluate the shear strength parameters of soil by laboratory test. In this area, there are too much weathered gravels in undisturbed samples, making laboratory testing difficult. Therefore, it is better to run shear tests on remoulded samples. Samples were prepared by compacting the soil with the trial water content. Compaction was carried out in four layers, each given with 25 blows (**Fig. 8**). Consequently, the shear strength of the soil in this area were found to be $C=0.051$ kg/cm^2 and $\phi=23^\circ$. These parameters were put in the computer program STABL 2[9] and the sliding surface in **Fig. 9** were obtained. The safety factor is equal to 0. 988. (Remark 1)

d) Additional comments on landslides in the Er-Jen Mountain

① In addition to the geological failure, the downpours is another agent that causes the landsliding in the Er-Jen Mountain. As shown in **Fig. 6**, the total amount of rainfall between May and Sep. induced very high ground water level. Normally the shear strength decreases sharply as the soil is saturated (**Fig. 10**). This is another major reason that causes the landsliding in this area.

② The sliding surface identified by the cubic spline method is more or less in agreement with the surface indicated by STABL 2[9]. (Remark 2)

Standard compaction		Optimum moisture content	Maximum dry unit weight	Mean moisture in situ	Mean dry unit weight	Re-compaction		Remold moisture content	Remold dry unit weight
Layer	Blow/per layer					Layer	Blow/per layer		
3	25	13.6	1.87	14.3	1.91	4	25	14.2	1.90

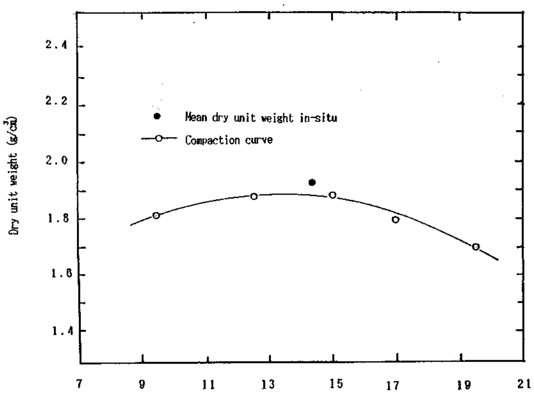

Fig. 8 Remodel Sampling of the Er-Jen Mountain.

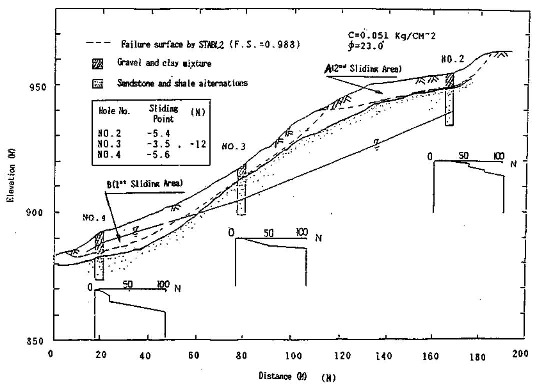

Fig. 9 Stratum section and sliding surface of the Er-Jen Mountain.

REMARK 1

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10  '*****************************************************************
20  '*                                                               *
30  '*           PFROGRAM       CSPSG 1                              *
40  '*                                                               *
50  '*    DRAWS  2-D  CUBIC-SPLINE  FOR  PIPE  STRAIN  GAGE          *
60  '*                                                               *
70  '*     xq,yq :input datas                                        *
80  '*     nn    :numbers of curves                                  *
90  '*     m     :numbers of datas in one curve line                 *
100 '*     ix,iy,xe,yx :boundary of drawing                          *
110 '*                                                               *
120 '*****************************************************************
130 '
140 DEFINT I-N
150 DIM XQ(20,20),YQ(20,20),T(5,50),V(5,50),P(20,20),X(20,200),Y(20,200)
160 KEY OFF
170 SCREEN 2
180 XE=575: YE=300:IX=75:IY=48
190 YY=YE
200 DT=.1
210 OPEN  "file.dat" FOR  INPUT AS #1
220 PRINT "the numbers of curves,nn="  :INPUT NN
230 PRINT "the numbers of datas in one curve,m=" :INPUT M
240  CLS
250 FOR I=1 TO NN
260   XQ(I,1)=75
270   XQ(I,2)=100
280    FOR J=3 TO M
290     XQ(I,J)=XQ(I,J-1)+50
300    NEXT J
310 NEXT I
320 FOR I=1 TO NN
330  FOR J=1 TO M
340   INPUT #1, YQ(I,J)
350   YQ(I,J)=YQ(I,J)/100
360  NEXT J
370 NEXT I
380 CLOSE #1
390 KT=0
400 FOR T=DT TO .90 STEP DT
410  KT=KT+1: T(1,KT)=T: T(2,KT)=T*T:T(3,KT)=T*T*T
420 NEXT T
430 FOR I=1 TO NN
440  FOR K=1 TO M
450   LINE (XQ(I,K)-1,YY-YQ(I,K)-1)-(XQ(I,K)+1,YY-YQ(I,K)+1),,B
460  NEXT K
470  N=0
480  N=N+1: X(I,N)=XQ(I,1)
490  FOR L=1 TO KT
500   N=N+1
510   X(I,N)=25*(N-1)*DT+XQ(I,1)
520  NEXT L
530  FOR K=2 TO M-1
540   N=N+1: X(I,N)=XQ(I,K)
550    FOR L=1 TO KT
560     N=N+1
570     X(I,N)=XQ(I,2)+50*(N-11)*DT
580    NEXT L
590  NEXT K
600  N=N+1: X(I,N)=XQ(I,M)
610  V(1,2)=1:V(2,2)=.25:  P(I,2)=.75*(YQ(I,3)-YQ(I,1))
620  V(1,M-1)=.25: V(2,M-1)=1: P(I,M-1)=.75*(YQ(I,M)-YQ(I,M-2))
630  FOR K=3 TO M-2
640    P(I,K)=3*(YQ(I,K+1)-YQ(I,K-1))
650    V(0,K)=1: V(1,K)=4: V(2,K)=1
660  NEXT K
670 '---------------------GAUSSIAN ELIMINATION----------------------
680  FOR K=3 TO M-1
690    V(1,K)=V(1,K)-V(2,K-1)*V(0,K)/V(1,K-1)
700    P(I,K)=P(I,K)-P(I,K-1)*V(0,K)/V(1,K-1)
710  NEXT K
720  P(I,M-1)=P(I,M-1)/V(1,M-1)
730  FOR K=M-2 TO 2 STEP -1
740   P(I,K)=(P(I,K)-P(I,K+1)*V(2,K-1)/V(1,K))/V(1,K)
750  NEXT K
760  P(I,1)=0 :P(I,M)=0
770  N=0
780  FOR K=1 TO M-1
790   N=N+1: Y(I,N)=YQ(I,K)
800    FOR L=1 TO KT
810     N=N+1
820     Y(I,N)=(2*(YQ(I,K)-YQ(I,K+1))+P(I,K)+P(I,K+1))*T(3,L)-(3*(YQ(I,K)-YQ(I,K
              +1))+2*P(I,K)+P(I,K+1))*T(2,L)+P(I,K)*T(1,L)+YQ(I,K)
830    NEXT L
840  NEXT K
850  N=N+1: Y(I,N)=YQ(I,M)
860  PSET(X(I,1),YY-Y(I,1))
870  FOR K=1 TO N
880   LINE-(X(I,K),YY-Y(I,K))
890  NEXT K
900  YY=YY-14
910 NEXT I
920 LINE (IX,IY)-(XE,YE+14),,B
930 JI=(YE-IY)/14
940 J=JI
950   FOR I=1 TO JI
960    LINE (IX,IY)-(IX+5,IY)
970    IY=IY+14
980   NEXT I
990 LINE (IX,YE+35)-(XE,YE+35)
1000 LINE (IX,YE+30)-(XE,YE+30)
1010 FOR I=1 TO M
1020   LINE (IX,YE+30)-(IX,YE+35)
1030   IX=IX+50
1040 NEXT I
1050   END
```

REMARK 2

```
20 '*****************************************************************
30 '*                                                               *
40 '*                  PROGRAM     CSPSG2                           *
50 '*       ANALYSIS  SLIDING  PLANE  FOR  PIPE  STRAIN  GAGE       *
60 '*                                                               *
70 '*       m:the numbers of datas                                  *
80 '*       xq(n),yq(n):input datas                                 *
90 '*                                                               *
100 '*****************************************************************
110 '
120 DEFINT I-N
130 DIM XQ(50),YQ(50),T(5,50),V(2,50),P(50),X(2000),Y(2000),FY(2000),PY(2000),AY
    (2000),DY(2000)
140 KEY OFF
150 SCREEN 2:CLS
160 XE=575:IX=75:IY=10:YE=340: YY1=300 :YY2=220:YY3=140:YY4=100:YY5=50
170 DT=.1
180 PRINT "the number of datas,M=":INPUT M
190 CLS
200 XQ(1)=IX
210 XQ(2)=XQ(1)+25
220  FOR J=3 TO M
230   XQ(J)=XQ(J-1)+50
240  NEXT J
250 OPEN "file.dat" FOR INPUT AS #1
260  FOR I=1 TO M
270   INPUT #1,YQ(I)
280  NEXT I
290 CLOSE #1
300 KT=0
310 FOR T=DT TO .99 STEP DT
320  KT=KT+1: T(1,KT)=T: T(2,KT)=T*T:T(3,KT)=T*T*T
330 NEXT T
340 N=0
350 N=N+1: X(N)=XQ(1)
360  FOR L=1 TO KT
370   N=N+1
380   X(N)=25*(N-1)*DT+XQ(1)
390  NEXT L
400 FOR K=2 TO M-1
410  N=N+1: X(N)=XQ(K)
420   FOR L=1 TO KT
430      N=N+1
440      X(N)=XQ(2)+50*(N-11)*DT
450   NEXT L
460 NEXT K
470 N=N+1: X(N)=XQ(M)
480 V(1,1)=1: V(2,1)=.5: P(1)=1.5*(YQ(2)-YQ(1))
490 V(0,M)=0: V(1,M)=0:V(2,M)=0: P(M-1)=1.5*(YQ(M)-YQ(M-2))
500  FOR K=2 TO M-1
510     P(K)=3*(YQ(K+1)-YQ(K-1))
520     V(0,K)=1: V(1,K)=4: V(2,K)=1
530  NEXT K
540 '-----------------------------------GAUSSIAN ELIMINATION-------------
550  FOR K=2 TO M
560    V(1,K)=V(1,K)-V(2,K-1)*V(0,K)/V(1,K-1)
570    P(K)=P(K)-P(K-1)*V(0,K)/V(1,K-1)
580  NEXT K
590 P(M-1)=P(M-1)/V(1,M-1)
600 FOR K=M-2 TO 1 STEP -1
610   P(K)=(P(K)-P(K+1)*V(2,K-1)/V(1,K))/V(1,K)
620 NEXT K
630 P(M)=0
640  N=0
650  FOR K=1 TO M-1
660   N=N+1 :Y(N)=YQ(K): AY(N)=0 :DY(N)=0
670    FOR L=1 TO KT
680     N=N+1
690     Y(N)=(2*(YQ(K)-YQ(K+1))+P(K)+P(K+1))*T(3,L)-(3*(YQ(K)-YQ(K+1))+2*P(K)+P(
            K+1))*T(2,L)+P(K)*T(1,L)+YQ(K)
700    NEXT L
710  NEXT K
720 N=N+1:  Y(N)=YQ(M):AY(N)=0:DY(N)=0
730 FOR K=M-1 TO 1 STEP -1
740  FOR L=1 TO KT+1
750   N=N-1
760   AY(N)=AY(N+1)+Y(N)*(X(N+1)-X(N))*2000/50/24*.000001
770   DY(N)=DY(N+1)+AY(N)*(X(N+1)-X(N))*2000/50
780  NEXT L
790 NEXT K
800 LOCATE 2,50: PRINT DY(N):LOCATE 5,50 :PRINT AY(N)
810 KT=0
820 FOR T=DT TO .99 STEP DT
830   KT=KT+1: T(1,KT)=1: T(2,KT)=2*T:T(3,KT)=3*T*T
840 NEXT T
850  N=0
860 FOR K=1 TO M-1
870  N=N+1: FY(N)=P(K)
880  FOR L=1 TO KT
890    N=N+1
900    FY(N)=(2*(YQ(K)-YQ(K+1))+P(K)+P(K+1))*T(3,L)-(3*(YQ(K)-YQ(K+1))+2*P(K)+P(
       K+1))*T(2,L)+P(K)*T(1,L)
910  NEXT L
920 NEXT K
930 N=N+1:FY(N)=P(M)
940 FOR I=1 TO N
950  FY(I)=FY(I)*29.5/.2*.000001/(2.4*.01)
960 NEXT I
970  LOCATE  13,55 :PRINT FY(1)
980  PY(1)=0
990 FOR I=2 TO N-1
1000  PY(I)=-(FY(I+1)-FY(I))/(X(I+1)-X(I))/.2
1010 NEXT I
1020  LOCATE  9,55  :PRINT PY(1)
1030  '
1040  FOR K=1 TO M
1050   YQ(K)=YQ(K)*.02
1060  LINE (XQ(K)-1,YY1-YQ(K)+1)-(XQ(K)+1,YY1-YQ(K)-1),,B
1070 NEXT K
1080  LINE(IX,YY1)-(XE,YY1),,B
1090  LINE(IX,YY2)-(XE,YY2),,B
1100  LINE(IX,YY3)-(XE,YY3),,B
1110  LINE(IX,YY4)-(XE,YY4),,B
1120 LINE (IX,YY5)-(XE,YY5),,B
1130  LINE (IX,330)-(XE,330),,B
1140  LINE (IX,340)-(XE,340),,B
1150  LINE (IX,10)-(IX,50)
1160  LINE (IX,60)-(IX,100)
1170  LINE (IX,110)-(IX,170)
1180  LINE (IX,180)-(IX,260)
1190  LINE (IX,270)-(IX,330)
1200 '---- Y(N), TIMES 2E-2,FY(N) TIMES 5,PY(N) TIMES 20, DY(N) TIMES E-2, AY(N)
 TIMES E+2  AND THEN DRAWING ------
1210 FOR I=1 TO N
1220   Y(I)=Y(I)*.02
1230   FY(I)=FY(I)*5
1240   AY(I)=AY(I)*100
1250   PY(I)=PY(I)*20
1260   DY(I)=DY(I)*.01
1270 NEXT I
1280  PSET(X(1),YY1-Y(1))
1290  FOR K=1 TO N
1300     LINE-(X(K),YY1-Y(K))
1310  NEXT K
1320 PSET(X(1),YY2-FY(1))
1330 FOR K=1 TO N-1
1340  LINE-(X(K),YY2-FY(K))
1350 NEXT K
1360  PSET(X(1),YY3-PY(1))
1370  FOR K=1 TO N
1380     LINE-(X(K),YY3-PY(K))
1390  NEXT K
1400  PSET(X(N),YY4-AY(N))
1410  FOR K=N TO 1 STEP -1
1420    LINE-(X(K),YY4-AY(K))
1430  NEXT K
1440  PSET(X(N),YY5-DY(N))
1450  FOR K=N TO 1 STEP -1
1460    LINE-(X(K),YY5-DY(K))
1470  NEXT K
1480 '----------------------create  axis  scale----------------------
1490 JI=(YE-IY)/10
1500 FOR I=1 TO JI
1510   LINE (IX,IY)-(IX+5,IY)
1520   IY=IY+10
1530 NEXT I
1540 FOR I=1 TO M
1550  LINE(IX,YE)-(IX,YE-5)
1560  IX=IX+50
1570 NEXT I
1580 END
```

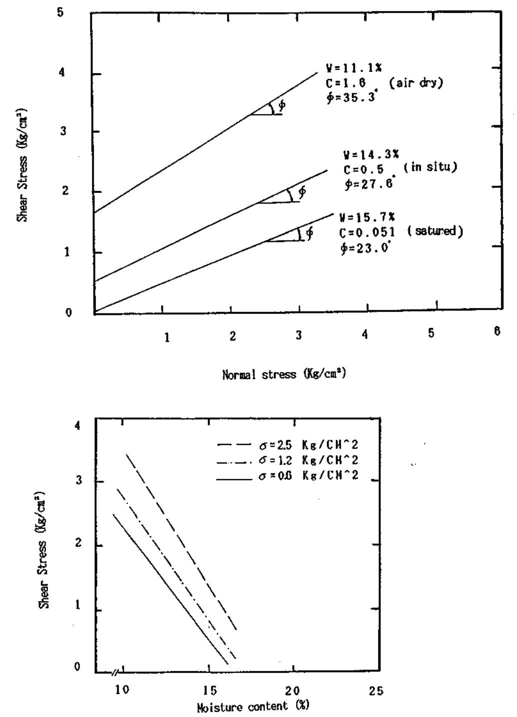

Fig. 10 Relation between shear strength and moisture content.

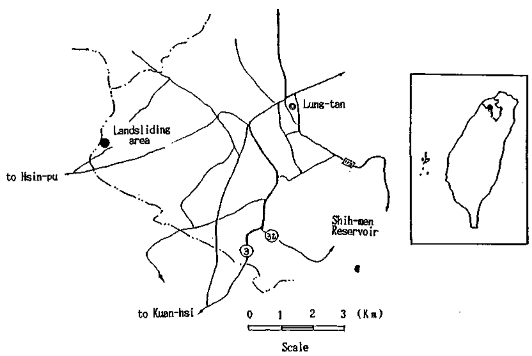

Fig. 11 Location of strain pipes in Lung-Tan district.

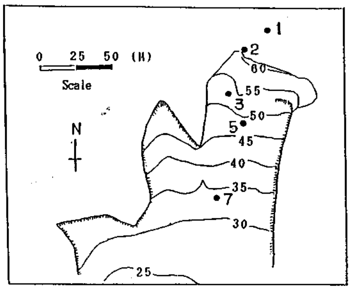

Fig. 12 Distribution of strain pipes in Lung-Tan district.

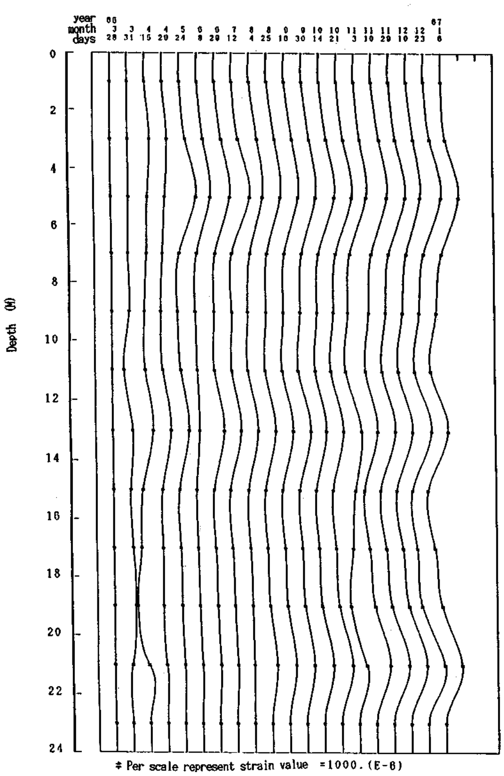

Fig. 13 Accumulated strain curve of No. 1 in Lung-Tan district.

(2) Study on the landslide at Ta-Pei-Keng, Lung-Tan district

(Reference from Chen Hsin-Hsuing 1978)[2)]

The location of this landslide is in Shan-Shui Village, Lung-Tan in Taiwan (Fig. 11). The geology of this district is classified as a deposit of lateritic terrace. Site borings revealed that there is a thick layer of sandy clay. This stratum had a sudden settlement about 12 meters in January, 1975. The range of settlement was about 500 meters long and 150 meters wide. A site investigation showed that there were serious cracks around tube No. 3, and that the top soil was very loose.

a) Analysis of sliding surface and prediction of sliding desplacement

The strain pipes No. 1, 2, 3, 5 and 7 in this area were installed in a linear configuration (Fig. 12). The observation period was from March, 1977 to January, 1978. The accumulated strain curve for pipe No. 1 shown in Fig. 13 was obtained from the observed data which was interpreted by the cubic spline method. The accumulated strain value was greater than $1\,000 \times 10^{-5}$ at 5 meters and 21 meters below the

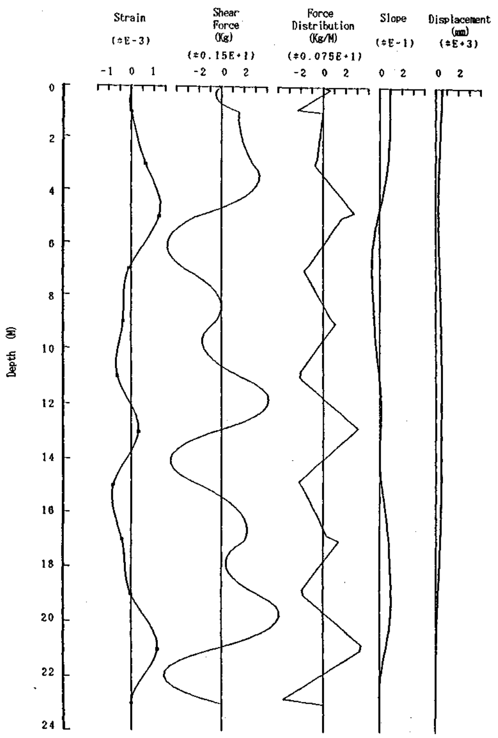

Fig. 14 Prediction of sliding point and displacement of No. 1.

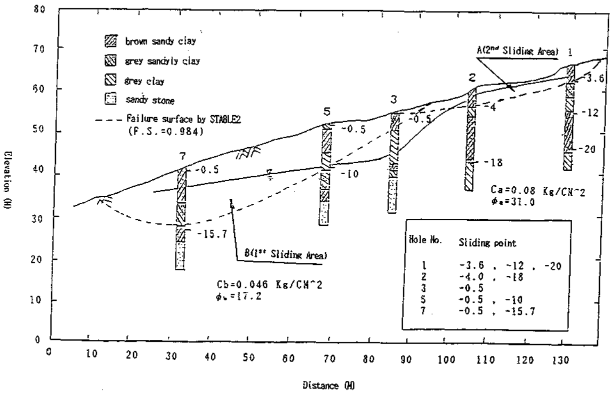

Fig. 15 Stratum section and sliding surface of Lung-Tan district.

ground surface on Nov. 10, 1977. By differentiating and integrating the strain curve, the analytical diagram at the sliding location were obtained (Fig. 14). The sliding surface for the strain pipe No. 1 passes through the depth of 3.6 meters, 12.0 meters, and 20.0 meters below the ground surface as suggested by the peak shear force. Note that these estimated sliding surfaces are situated slightly above or below the locations of peak pipe strain. The sliding displacement at this observation point is calculated below the ground surface as shown in Fig. 14.

b) Safety factor of the critical sliding surface

From the results of laboratory soil testing, we can devide the soil parameters into two groups with the boundary at pipe No. 5. The right-hand side is called area A. Shear parameters are C_a=0.08 kg/cm^2 and ϕ =31°. The left-hand side is called area B. Shear parameters are C_b=0.046 kg/cm^2, and ϕ=17.2°. By using these parameters, the safety factor of critical surface was computed by program STABL 2 to be equal to 0.984. (Remark 3)

c) Discussion on the landslide in Lung-Tan district

① With a reference to Chen Hsin-Hsiung, 1978, we know that the continuous downpours is a major reason which causes the landsliding in this district.

② Generally speaking, the interface of soil has layers below a shear strength. Fig. 15 obtained by the cubic spline method reveals that the failure surfaces are located almost on the interface of layers.

③ The critical failure surfaces computed by program STABL 2 are in good agreement with the sliding point detected by the cubic spline method, as shown in Fig. 15. (Remark 4).

5. CONCLUSIONS

From the analytical method and the two practical examples described above, we can draw the conclusions as followings :

(1) It is feasible to model the continuous strain variation of a strain pipe by the cubic spline method. The results of analysis are similar to those computed by program STABL 2.

(2) The location of the maximum shear force in the strain pipe is accompanied by the transition from the passive earth force to the soil resistant force. This is considered to be the depth where the failure surface is being developed.

REMARK 3

--SLOPE STABILITY ANALYSIS--
MODIFIED BISHOP METHOD OF SLICES
IRREGULAR FAILURE SURFACES

PROBLEM DESCRIPTION ER JEN K.

BOUNDARY COORDINATES

5 TOP BOUNDARIES
5 TOTAL BOUNDARIES

BOUNDARY NO.	X-LEFT (M)	Y-LEFT (M)	X-RIGHT (M)	Y-RIGHT (M)	SOIL TYPE BELOW BND
1	.00	33.00	20.00	41.00	1
2	20.00	41.00	80.00	60.00	1
3	80.00	60.00	100.00	84.00	1
4	100.00	84.00	132.00	100.00	1
5	132.00	100.00	165.00	104.00	1

ISOTROPIC SOIL PARAMETERS

1 TYPE(S) OF SOIL

SOIL TYPE NO.	TOTAL UNIT WT. (Kg/M^3)	SATURATED UNIT WT. (Kg/M^3)	COHESION INTERCEPT (Kg/M^2)	FRICTION ANGLE (DEG)	PORE PRESSURE PARAMETER	PRESSURE CONSTANT (Kg/M^2)	PIEZOMETRIC SURFACE NO.
1	2180.0	2180.0	510.0	23.0	.00	.0	1

1 PIEZOMETRIC SURFACE(S) HAVE BEEN SPECIFIED

UNITWEIGHT OF WATER =1000.00

PIEZOMETRIC SURFACE NO. 1 SPECIFIED BY 4 COORDINATE POINTS

POINT NO.	X-WATER (M)	Y-WATER (M)
1	.00	30.00
2	20.00	37.00
3	80.00	55.00
4	165.00	90.00

SEARCHING ROUTINE WILL BE LIMITED TO AN AREA DEFINED BY 5 BOUNDARIES
OF WHICH THE FIRST 5 BOUNDARIES WILL DEFLECT SURFACES UPWARD

BOUNDARY NO.	X-LEFT (M)	Y-LEFT (M)	X-RIGHT (M)	Y-RIGHT (M)
1	.00	30.00	20.00	31.00
2	20.00	31.00	50.00	43.00
3	50.00	43.00	80.00	63.00
4	80.00	63.00	132.00	92.00
5	132.00	92.00	165.00	98.00

A CRITICAL FAILURE SURFACE SEARCHING METHOD, USING A RANDOM
TECHNIQUE FOR GENERATING IRREGULAR SURFACES, HAS BEEN SPECIFIED.

100 TRIAL SURFACES HAVE BEEN GENERATED.

10 SURFACES INITIATE FROM EACH OF 10 POINTS EQUALLY SPACED
ALONG THE GROUND SURFACE BETWEEN X = .00 M
AND X = 50.00 M.

EACH SURFACE TERMINATES BETWEEN X = 80.00 M.
AND X = 165.00 M.

UNLESS FURTHER LIMITATIONS WERE IMPOSED, THE MINIMUM ELEVATION
AT WHICH A SURFACE EXTENDS IS Y = .00 M.

6.00 FT. LINE SEGMENTS DEFINE EACH TRIAL FAILURE SURFACE.

FOLLOWING ARE DISPLAYED THE TEN MOST CRITICAL OF THE TRIAL
FAILURE SURFACES EXAMINED. THEY ARE ORDERED - MOST CRITICAL
FIRST.

FAILURE SURFACE SPECIFIED BY 24 COORDINATE POINTS

POINT NO.	X-SURF (M)	Y-SURF (M)
1	5.50	35.22
2	11.34	33.63
3	17.17	35.00
4	23.01	36.42
5	28.97	35.73
6	34.23	38.01
7	39.62	41.24
8	45.60	41.77
9	49.40	40.37
10	54.00	49.45
11	60.50	50.58
12	64.80	54.76
13	70.22	57.32
14	73.68	62.23
15	78.60	65.65
16	83.90	68.35
17	89.91	69.13
18	94.41	73.09
19	99.82	75.70
20	104.41	79.55
21	109.98	81.80
22	113.45	86.69
23	116.17	92.04
24	116.22	92.11

*** .988 ***

REMARK 4

--SLOPE STABILITY ANALYSIS--
MODIFIED BISHOP METHOD OF SLICES
IRREGULAR FAILURE SURFACES

PROBLEM DESCRIPTION LUNG-TANG

BOUNDARY COORDINATES

5 TOP BOUNDARIES
6 TOTAL BOUNDARIES

BOUNDARY NO.	X-LEFT (M)	Y-LEFT (M)	X-RIGHT (M)	Y-RIGHT (M)	SOIL TYPE BELOW BND
1	.00	33.00	33.00	44.00	1
2	33.00	44.00	77.00	59.00	1
3	77.00	59.00	85.00	62.00	1
4	85.00	62.00	105.00	72.00	1
5	105.00	72.00	130.00	77.00	2
6	77.00	30.00	105.00	72.00	2

ISOTROPIC SOIL PARAMETERS

2 TYPE(S) OF SOIL

SOIL TYPE NO.	TOTAL UNIT WT. (Kg/M^3)	SATURATED UNIT WT. (Kg/M^3)	COHESION INTERCEPT (Kg/M^2)	FRICTION ANGLE (DEG)	PORE PRESSURE PARAMETER	PRESSURE CONSTANT (Kg/M^2)	PIEZOMETRIC SURFACE NO.
1	2260.0	2260.0	460.0	17.2	.00	.0	1
2	2200.0	2200.0	800.0	31.0	.00	.0	1

1 PIEZOMETRIC SURFACE(S) HAVE BEEN SPECIFIED

UNITWEIGHT OF WATER =1000.00

PIEZOMETRIC SURFACE NO. 1 SPECIFIED BY 6 COORDINATE POINTS

POINT NO.	X-WATER (M)	Y-WATER (M)
1	.00	31.00
2	33.00	40.00
3	77.00	46.00
4	85.00	48.00
5	105.00	62.00
6	130.00	66.00

SEARCHING ROUTINE WILL BE LIMITED TO AN AREA DEFINED BY 2 BOUNDARIES
OF WHICH THE FIRST 2 BOUNDARIES WILL DEFLECT SURFACES UPWARD

BOUNDARY NO.	X-LEFT (M)	Y-LEFT (M)	X-RIGHT (M)	Y-RIGHT (M)
1	.00	18.00	85.00	38.00
2	85.00	38.00	130.00	30.00

A CRITICAL FAILURE SURFACE SEARCHING METHOD, USING A RANDOM
TECHNIQUE FOR GENERATING IRREGULAR SURFACES, HAS BEEN SPECIFIED.

100 TRIAL SURFACES HAVE BEEN GENERATED.

10 SURFACES INITIATE FROM EACH OF 10 POINTS EQUALLY SPACED
ALONG THE GROUND SURFACE BETWEEN X = 10.00 M.
AND X = 30.00 M.

EACH SURFACE TERMINATES BETWEEN X = 90.00 M.
AND X = 130.00 M.

UNLESS FURTHER LIMITATIONS WERE IMPOSED, THE MINIMUM ELEVATION
AT WHICH A SURFACE EXTENDS IS Y = .00 M.

4.00 FT. LINE SEGMENTS DEFINE EACH TRIAL FAILURE SURFACE.

FOLLOWING ARE DISPLAYED THE TEN MOST CRITICAL OF THE TRIAL
FAILURE SURFACES EXAMINED. THEY ARE ORDERED - MOST CRITICAL
FIRST.

FAILURE SURFACE SPECIFIED BY 28 COORDINATE POINTS

POINT NO.	X-SURF (M)	Y-SURF (M)
1	10.00	36.33
2	13.47	34.35
3	16.75	32.05
4	20.65	31.16
5	24.30	29.66
6	27.97	27.95
7	31.96	27.64
8	35.00	30.24
9	38.88	31.19
10	42.84	31.80
11	46.66	30.61
12	50.37	32.09
13	54.30	32.43
14	56.93	35.49
15	59.77	38.31
16	63.20	40.37
17	66.79	42.14
18	70.00	44.53
19	73.45	46.56
20	77.44	46.77
21	80.89	48.79
22	82.36	52.51
23	85.32	55.20
24	87.58	58.50
25	91.15	60.30
26	93.22	63.73
27	95.85	66.74
28	96.74	67.87

*** .984 ***

(3) The distribution curve of strain is classified into two types. A curve which is in bow shape (Fig. 3) exhibits a concave shape on the down-slope side. The sliding surface occurs above the point of the maximum strain. A distribution curve which is in "S" shape (Fig. 14) exhibits a convex type in the down-slope side. The sliding point is either below the point of the maximum negative strain or above that of the maximum positive strain.

(4) Provided that the bottom tip of the pipe is fixed, the prediction of the sliding displacement of pipe is theoretically accurate. In fact, the reliability of the proposed method thoroughly depends on the fixed end at the bottom. When the pipe does not penetrate into the immovable base, the sliding movement of soil makes the bottom displacement greater than the top displacement. If such a situation is found in the cubic spline interpretation, the penetration of the pipe is understood to be insufficient. Thus, for a thick deposit soil layer, the strain pipe must be installed deep into the immovable layer.

(5) The displacement curve of a sliding point suggests a landslide.

(6) The size and the location of the sliding surface was found by the cubic spline method, and they were in good agreement with those by the limit equilibrium method. Thus, the proposed method promotes the understanding of sliding types and the control of landslides.

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