LANDSLIDE MONITORING FOR PRESUMPTION OF UNDERGROUND SLIDE SURFACE

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ABSTRACT

An analytic procedure using the three dimensional displacement vector of ground objects tracked in the landsliding field demonstrates the applicability of photogrammetry to the measures of landslide disaster reduction and to the presumption of underground slide surface geometry.

To obtain the reliable information of ground movement caused by rapidly growing landslide where no field surveying is acceptable, only the aerial photogrammetry can be used safely and effectively. The three dimensional displacement vector,which is considered to represent the characteristics of mass-movement on the underground slide surface,is detected by the positional data of tracking points recorded in the series of photographs taken at different time flights on the landslide area.

Projecting a number of the displacement vectors on a horizontal plane, the direction and velocity of mass-movement,which are important information for planning and accomplishing the measures against the landslide disaster, are analyzed. In this analysis, the influence of errors unavoidably included in each displacement vector is considered to detect acculate behavior of the landslide.

On a vertical projection plane taken parallel to the main direction of the mass-movement, the characteristics of the movement, i.e.,simple rotational slide, translational slide, complicated slide, etc., are judged to select the analytic method for presumption of the geometry of underground slide surface. For this presumption, the author has devised several analytic methods (Yoshizawa,1987,1989,1992). They are applied to actual landslides occurred in Japan. The utility of the photogrammetry in the field of disaster reduction techniques is vrified by practical analyses shown in this paper.

Key Words: photogrammetry, landslide, monitoring, displacement analysis, underground slide surface.

1. INTRODUCTION

The advantages of aerial photogrammetry in the monitoring and the analysis of landslide arise from its economy of time and money and safety of surveying, since it covers a relatively large area in one picture and is the only technique that provides a three dimensional view of the terrain safely.

To reduce the disaster caused by the landslide and to control the development of ground destruction in the landslide area, it is very necessary to get the rapid and reliable information about the following items:
1) moving direction of the landsliding mass;
2) velocity of each individual mass-movement;
3) boundary of influenced field by the landslide;
4) development of surface destruction phenomena;
5) geometry of underground slide surface;
6) behavior of underground water;
7) mechanical characteristics of the sliding mass;
8) geomorphologic and geologic information; etc.

The items 1),2),3) and 4) in the above information are urgently important to take the emergency measures against rapidly growing landslide. Without the aerial photogrammetry, we have no means applicable to such landslide, because the actual field surveying can not be carried on if the movement and destruction of the ground is very dangerous. In such case, the ground movement and destruction can be monitored only by the series of photographs taken at different flight time on the landslide area.

In the above information,the items 5),6),7) and 8) are necessary for the analysis of landslide mechanism and for the measures to control or stabilize the landslide action. In this purpose,exploratory techniques such as field boring, test-pits, sampling of rocks,surveying of temporary outcrops, geophysical measurements, hydrologic researches, etc. have been used (Zaruba & Mencl,1982). It is obvious that delay of data acquisition results in the increase of disaster.

As a new rapid and effective technique to presume the geometric shape of underground slide surface, the author proposes an analytic procedure in this paper. Three dimensional displacement of objects on the landslide area, which is detected by the photogrammetry, is used as the basic data in this analysis. By this technique, the information of item 5) can be provided effectively and safely.

Thus the validity of the aerial photogrammetry is evident, because there are no other means to get the information, from item 1) to item 5), under an urgent condition caused by severe and dangerous landslide.

2. ANALYTIC PROCEDURE

In the following sections, the analytic procedure of this paper is briefly described.

2.1 Surface Displacement Tracking

The tracking points are used to obtain the three dimensional displacement vector of surface points on the landsliding mass. They are selected and placed on the images of various ground objects recorded in the photographs. They must be observed always in the series of photographs, and clearly distinguished in each photograph. From the series of photographs taken at different flight time, the three dimensional coordinates of the tracking points at each flight time are obtained. Detecting the variation of these coordinates related with the elapse of time, we can obtain the three dimensional displacement vector (3DD vector) of the tracking points. This vector is the basic data to obtain the information of the items; from 1) to 5) stated above.

2.2 Application to Emergency Measures

The information of items 1) and 2) are directly given by the 3DD vector. The tracking points are projected on a topographic map using their horizontal coordinates obtained by the photogrammetry of the first flight. The movement direction and velocity of each tracking point can be represented on the map by its own 3DD vector.

To forecast the spread of landslide disaster,under an urgent condition disturbed by suddenly occurred landslide, the direction and velocity of the sliding mass must immediately be discussed on the map related with the local terrain, inhabited region, man-made structures, etc. Thus, fast and suitable measures for prevention and reduction against the landslide disaster can be planned and carried out.

An immediate action for acquisition of the above information is the most important problem in this technique. At the same time, higher accuracy of the 3DD vector must be secured. Hence the first flight must be done as fast as possible, if the landslide phenomena are observed. That is to say, the 3DD vector is obtained by difference of three dimensional coordinates of the tracking points recorded in two photographs taken at different time of flight, and the accuracy of the 3DD vector is governed by this difference (Yoshizawa,1991).

2.3 Judgment of Landslide Characteristics

The preliminary treatment is to distinguish the landsliding mass from the area of observation, and to find the main direction of its movement. For this purpose, the 3DD vectors of tracking points are projected on the topographic map, and examined throughly with consideration of the topographic position of the tracking points and the feature of landslide phenomena such as fractures and scarps. Through this examination, we can distinguish the group of landsliding mass. The main direction of mass-movement is presumed by the weighted mean of horizontal directions of the projected vectors distributed over the distinguished mass.

To judge the characteristics of the landslide, the 3DD vectors of the tracking points are projected on a vertical projection plane taken parallel to the main direction of mass-movement. Observing the grade of projected vectors with geometric consideration of their position on the projection plane, we can judge the characterisitics of mass-movement governed by the geometric condition of underground slide surface. This observational procedure is based on the assumption that the deformation of the sliding mass is very small compared with the displacement of the mass on the underground slide surface.

On a basis of this assumption, the following judgment can be made.

a) If the landslide is rotational, the mass is sliding on a circular surface. In this case, the grade of projected vectors varies gradually, showing a steep grade at head region and a gentle(or sometimes negative) grade at toe region.

b) If the landslide is translational, the mass is sliding on a planar surface. In this case, majority of the projected vectors are parallel to the planar surface. In the vicinity of head scarp and toe of the landslide, rotational behavior will be observed by several vectors.

In the landslide of complex type, the shape of underground slide surface is also complex. However, we can treat the slide surface as an aggregate of various curved and planar surfaces. On a vertical projection plane, sectional shape of this slide surface can be represented by combination of various straight and circular line elements. Thus partial judgments are used to analyze such complex landslide. The above judgments a) and b) are used together in this case.

2.4 Presumption of Underground Slide Surface

After the judgment of landslide characterisitics, an analytic method for presumption of the underground slide surface is chosen from the following methods which have been devised by the author:

A) To presume the shape of rotational slide circle on a projection plane, we find out the position of rotational center of sliding mass by the method of analytic geometry (method A) or the method of least square (method B).

B) The shape of translational slide surface on a projection plane is poresumed by a polygon composed of many line segments. The method of polygon fitting (method C) is used in this case.

C) For presumption of the complex shape of slide surface on a projection plane, the method C is the most simple. The method of compound circle connection (method D) and the method of least square to represent the shape of slide surface by polynomial expression (method E) can also be applied to this presumption.

D) The least square method for three dimensional curved surface fitting (method F) is effectively applied to the presumption of solid geometry of underground slide surface.

3. ALGORITHM

Main procedures of photogrammetry and analysis for monitoring of landslide behavior and presumption of underground slide surface geometry are briefly described as follows:

3.1 Landslide Monitoring by Photogrammetry

(1) Urgent flight: Execute the flight immediately if any symptom of landslide is found.
(2) Next flight: Earlier flight is better,but the timely flight should be decided by growing condition of fractures on the landslide area.
(3) Identification: A surface object recorded on the photographs taken at diffrerent flight time is identified by stereoscopic vision.
(4) Pricking: A tracking point is selected and pricked on the surface object.

(5) Measurement: Stereocomparator gives the three dimensional coordinates of the tracking point.
(6) 3DD vector: Variation of the tracking point coordinates by different time photographs is used to get the three dimensional displacement vector.
(7) Monitoring: The behavior of landslide is monitored by the direction and moved distance of the tracking points. The steps (2) ~(7) are repeated against the landslide.

3.2 Error of Three Dimensional Displacement Vector

The coordinates(X_i, Y_i, H_i) of tracking point (i) is given by $X_{i1}\pm m_{Xi1}, Y_{i1}\pm m_{Yi1}, H_{i1}\pm m_{Hi1}$ at flight time T_1, and $X_{i2}\pm m_{Xi2}, Y_{i2}\pm m_{Yi2}, H_{i2}\pm m_{Hi2}$ at T_2. where m is the notation representing the error. Difference of coordinates is given by the form:

$$dX_i=X_{i2}-X_{i1},\quad dY_i=Y_{i2}-Y_{i1},\quad dH_i=H_{i2}-H_{i1}. \tag{1}$$

The magnitude (S_i) and direction cosine (C_{Xi}, C_{Yi}, C_{Hi}) of the 3DD vector at point (i) are given by:

$$S_i=(dX_i^2+dY_i^2+dH_i^2)^{1/2}, \tag{2}$$
$$C_{Xi}=dX_i/S_i,\quad C_{Yi}=dY_i/S_i,\quad C_{Hi}=dH_i/S_i. \tag{3}$$

Error M_{Si} propagating to S_i is represented as:

$$M_{Si}^2=\{dX_i^2, dY_i^2, dH_i^2\}^T\cdot\{(m_{Xi1}^2+m_{Xi2}^2),(m_{Yi1}^2+m_{Yi2}^2),(m_{Hi1}^2+m_{Hi2}^2)\}/S_i^2. \tag{4}$$

Errors M_{CXi}, M_{CYi}, M_{CHi} propagating to C_{Xi}, C_{Yi}, C_{Hi} are given by the following form:

$$\begin{bmatrix} M_{CXi}^2 \\ M_{CYi}^2 \\ M_{CHi}^2 \end{bmatrix} = \begin{bmatrix} (dY_i^2+dH_i^2)^2, (dX_i\cdot dY_i)^2, (dX_i\cdot dH_i)^2 \\ (dX_i\cdot dY_i)^2, (dX_i^2+dH_i^2)^2, (dY_i\cdot dH_i)^2 \\ (dX_i\cdot dH_i)^2, (dY_i\cdot dH_i)^2, (dX_i^2+dY_i^2)^2 \end{bmatrix} \times \begin{bmatrix} (m_{Xi1}^2+m_{Xi2}^2)/S_i^6 \\ (m_{Yi1}^2+m_{Yi2}^2)/S_i^6 \\ (m_{Hi1}^2+m_{Hi2}^2)/S_i^6 \end{bmatrix}. \tag{5}$$

In this manner, the 3DD vectors of tracking points (i),(j),(k), whose magnitude S_i, S_j, S_k and error M_{Si}, M_{Sj}, M_{Sk}, can be obtained. The reliability of these vectors is represented by the weight W_i, W_j, W_k. Their rerationship is represented by

$$W_i : W_j : W_k = (S_i/M_{Si})^2 : (S_j/M_{Sj})^2 : (S_k/M_{Sk})^2. \tag{6}$$

3.3 Displacement Vector on Topographic Map

Taking $dH_i=0$ in Eqs.1,2,3,we have the displacement vector on a horizontal plane (topographic map). Fig.1 shows the horizontal displacement vector of tracking point (i). The angle θ between Y-axis and this vector is given by the equation:

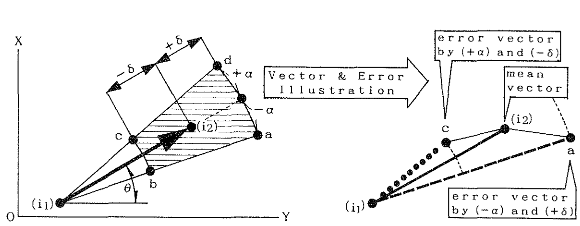


Fig.1 Displacement vector of tracking point (i). Caption; 3DD vector is projected on the horizontal plane. Error of the photogrammetry propagates to the error of the vector. δ = error in magnitude. α = error in direction (Yoshizawa et.al.,1991).

$$\theta = \tan^{-1}(dX_i/dY_i) \tag{7}$$

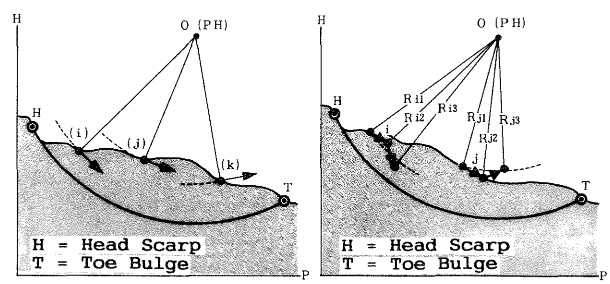
The error of coordinates caused by many steps of the photogrammetry propagates to this vector. δ and α in Fig.1 are given by the equations:

$$\delta^2 = (m_{Xi1}^2+m_{Xi2}^2)\sin^2\theta + (m_{Yi1}^2+m_{Yi2}^2)\cos^2\theta \tag{8}$$
$$\alpha^2 = \{(m_{Xi1}^2+m_{Xi2}^2)\cos^2\theta + (m_{Yi1}^2+m_{Yi2}^2)\sin^2\theta\} / (dX_i^2+dY_i^2). \tag{9}$$

For simplicity, the error of this vector is illustrated by the fan-like hatched area (abcd). This area is considered to be inversely proportional to the reliability of the vector.

3.4 Presumption of Rotational Center

3.4.1 Method of Analytic Geometry (method A)[3]
The rotational slide has a circular slide curve on a vertical projection plane parallel to the moving direction of the landslide. The landsliding mass shows a rotational movement on this circle. Hence the tracking points draw the concentric circles on the plane. The method A is based on this principle as illustrated in Fig.2(a). Direction of the vectors (i),(j),(k) indicate the tangent of the concentric circles. The normals drawn to these vectors locate the position of rotational center.



(a) method A (b) method B
Fig.2 Presumption of rotational center.*

3.4.2 Method of least square (method B)[3]
In Fig.2(b), the broken lines are part of concentric circles passing the tracking points i and j. Observed movement of these points deviates from these circles as illustrated by the dark marks(●). Then the radius of rotation (a function of center coordinates (P,H) and observed coordinates of a tracking point) can not remain constant. To obtain the coordinates of rotational center, we have an objective function:

$$\Omega = W_i\{(R_{i1}-R_{i2})^2+(R_{i1}-R_{i3})^2+(R_{i2}-R_{i3})^2\} + W_j\{(R_{j1}-R_{j2})^2+(R_{j1}-R_{j3})^2+(R_{j2}-R_{j3})^2\}+\cdots, \tag{10}$$

where W_i, W_j = weight of the tracking point vector. The center coordinates P and H can be obtained by solving the following simultaneous equations:

$$\partial\Omega/\partial P = 0,\quad \partial\Omega/\partial H = 0. \tag{11}$$

* The horizontal axis P in Fig.2 is taken parallel to the main direction of the landslide. Then the coordinates of the tracking points are transformed from (X,Y,) into (P) by the equation:
$$P = X\cdot\cos\phi + Y\cdot\sin\phi \tag{a}$$
The tracking points (i),(j),(k) are projected on the vertical plane (PH). To this projection, the coordinates of the first flight is used.

3.4.3 Method of polygon fitting (method C)
On the assumption that individual tracking point moves parallel to the underground slide surface, the shape of slide surface on a projection plane is presumed by a polygon. This method is similar to that proposed by Carter,et al. (Carter,1985).[1] They assumed the rotational movement, contrarily, the author assumed the translational movement.[4]

3.4.4 Compound circle connection (method D)

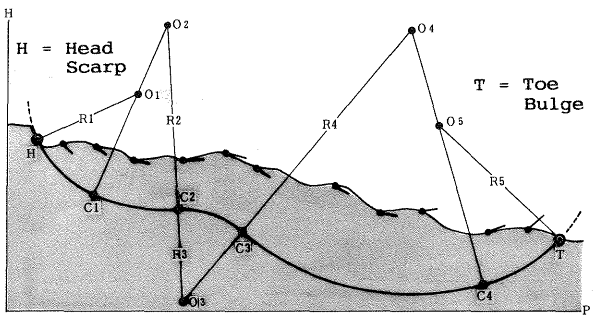


Fig.3 Slide surface presumed by compound circle.

A complicated shape of underground slide surface is presumed by the connection of various circle elements as shown in Fig.3. The center of circles ($O_1, O_2, \cdots, O_5$) is obtained by the method A or B. In this case, consecutive vectors are grouped considering the evidence of partial rotation.

3.4.5 Polynomial curve fitting (method E)[5]
A polynomial function is used to presume the shape of complicated slide curve on a projection plane. This is the two dimensional problem of the method F. These methods are based on the assumption that the variation of depth between tracking point and underground slide surface is negligible compared with the displacement of the tracking point. Then the depth at each point is considered to remain constant as shown in Fig.4.

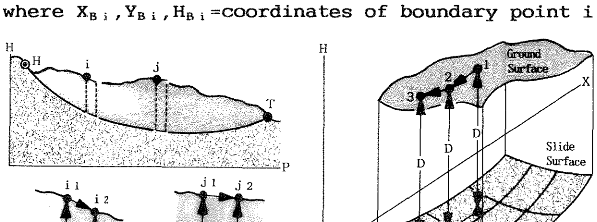
3.4.6 Curved surface fitting (method F)[5,8]
The shape of underground slide surface is presumed by three dimensional curved surface as follows:

$$H = aX^2 + bXY + cY^2 + dX + eY + f. \quad (12)$$

This surface must pass the landslide boundary such as head scarp, toe bulge, side crack,etc. Then we have the equation of residual by the form:

$$V_{Bi} = aX_{Bi}^2 + bX_{Bi}Y_{Bi} + cY_{Bi}^2 + dX_{Bi} + eY_{Bi} + f - H_{Bi}, \quad (13)$$

where X_{Bi}, Y_{Bi}, H_{Bi}=coordinates of boundary point i.



(a) 2-dimensional (E) (b) 3-dimentional (F)
Fig.4 Slide surface presumed by polynomials.

Taking D_j= depth of slide surface under the tracking point j,and $(X,Y,H)_{jt}$= measured coordinates of the tracking point j at flight time t, we have the equation of residual as follows:

$$V_{jt} = aX_{jt}^2 + bX_{jt}Y_{jt} + cY_{jt}^2 + dX_{jt} + eY_{jt} + f - H_{jt} + D_j. \quad (14)$$

To obtain the values of the parameters a,b,c,d,e,f and of the depth D_j ($j=1,2,\cdots,n$), the objective function is written by the form:

$$\Omega = [W_{Bi} \cdot V_{Bi}^2]_1^m + [W_j [V_{jt}^2]_1^p]_1^n \quad (15)$$

where [ ] means the summation, W_{Bi}, W_j are weight of the boundary point i and the tracking point j. The number of boundary and tracking points are m and n, respectively. The tracking point j has data of coordinates measured by p times of flight. The following conditions yield 6+n simultaneous equations to solve the above unknowns.

$$\partial\Omega/\partial a = 0,\quad \partial\Omega/\partial b = 0,\quad \partial\Omega/\partial c = 0,$$
$$\partial\Omega/\partial d = 0,\quad \partial\Omega/\partial e = 0,\quad \partial\Omega/\partial f = 0,$$
$$\partial\Omega/\partial D_1 = 0,\ \ldots\ldots,\ \partial\Omega/\partial D_n = 0. \quad (16)$$

4. APPLICATION TO URGENT MONITORING AND ANALYSIS

Application of the photogrammetry to urgent monitoring and analysis of the landslide behavior is exemplified by a rapidly growing landslide occurred at Hirose in Nagano city, Japan. Cracks discovered in the afternoon,Oct.3,1989 developed very rapidly, so that no field surveying was available.

The photogrammetries were taken at 15:24 Oct.5 and 14:22 Oct.10. But the landslide had entered into a rest condition about noon Oct.7.**

Fig.5 shows a photograph taken at the first flight on the landslide area. Head cracks are developing into the road. The tracking points which can also be distinguished from the second flight photograph are selected as shown in the figure.

Reliable displacement vectors of tracking points and immovable points are shown in Fig.6. They are judged by consideration of the error of vector. In this area, the lower part is covered with forest trees and grassy bush. We had to set the tracking points on the top of trees and the blank of bush. Their accuracy of measurement is low as shown in Fig.8. But, note that, without this method, there are no means to detect the ground movement.

All displacement vectors used for presumption of underground slide surface are shown in Fig.9. The broken line is the presumed boundary of landslide. The method F is used in this analysis.

Presumption of the shape of underground slide surface on a vertical projection plane is illustrated in Figs.10,11 and 12,respectively. Three different methods,C,B,E are used in these figures. Note that observing the vectors in Fig.9, the landslide area is divided into three blocks, and the projection plane is taken parallel to movement of the block. The presumed curve is adjusted to satisfy the head and toe boundary conditions in this analysis.

**The first flight was taken about 50 hours later. It was the deadline to detect the surface movement by the photogrammetry (see Fig.7).

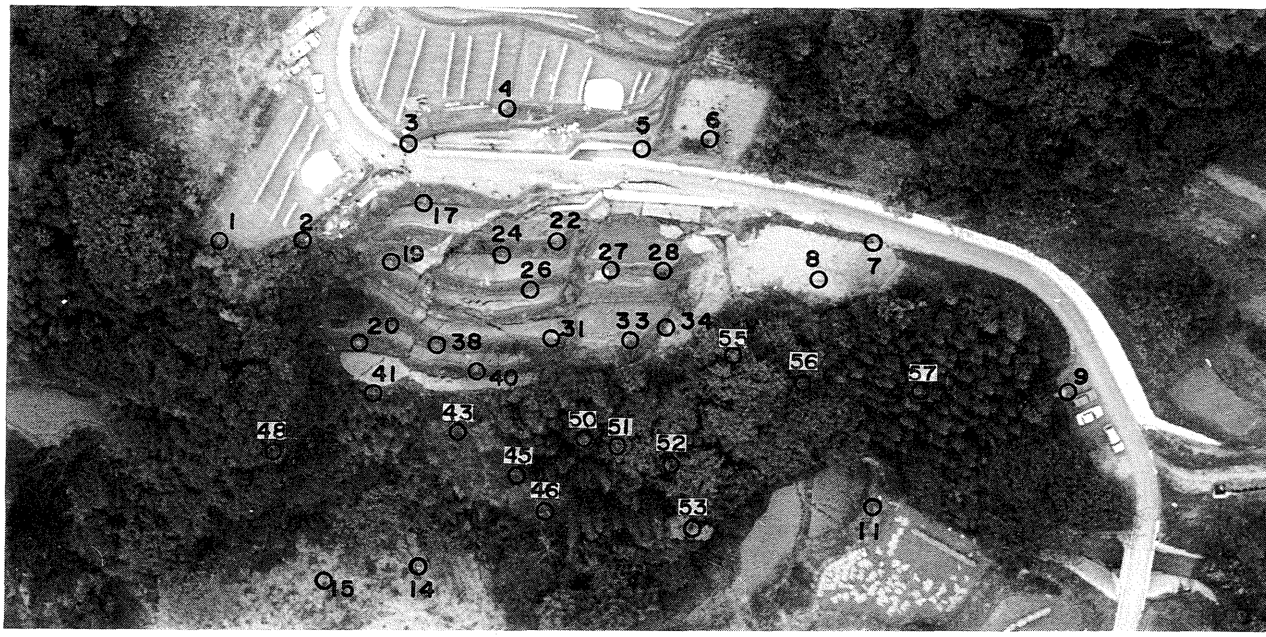


Fig.5 Photograph on landslide area (Hirose in Nagano City,Japan).Caption; This is the photograph of first flight taken at 15:24 Oct.5,1989. About 50 hours passed away after a landslide phnomenon was discovered in the vicinity of the tracking point 22. The tracking point is set in the center of the mark ○.

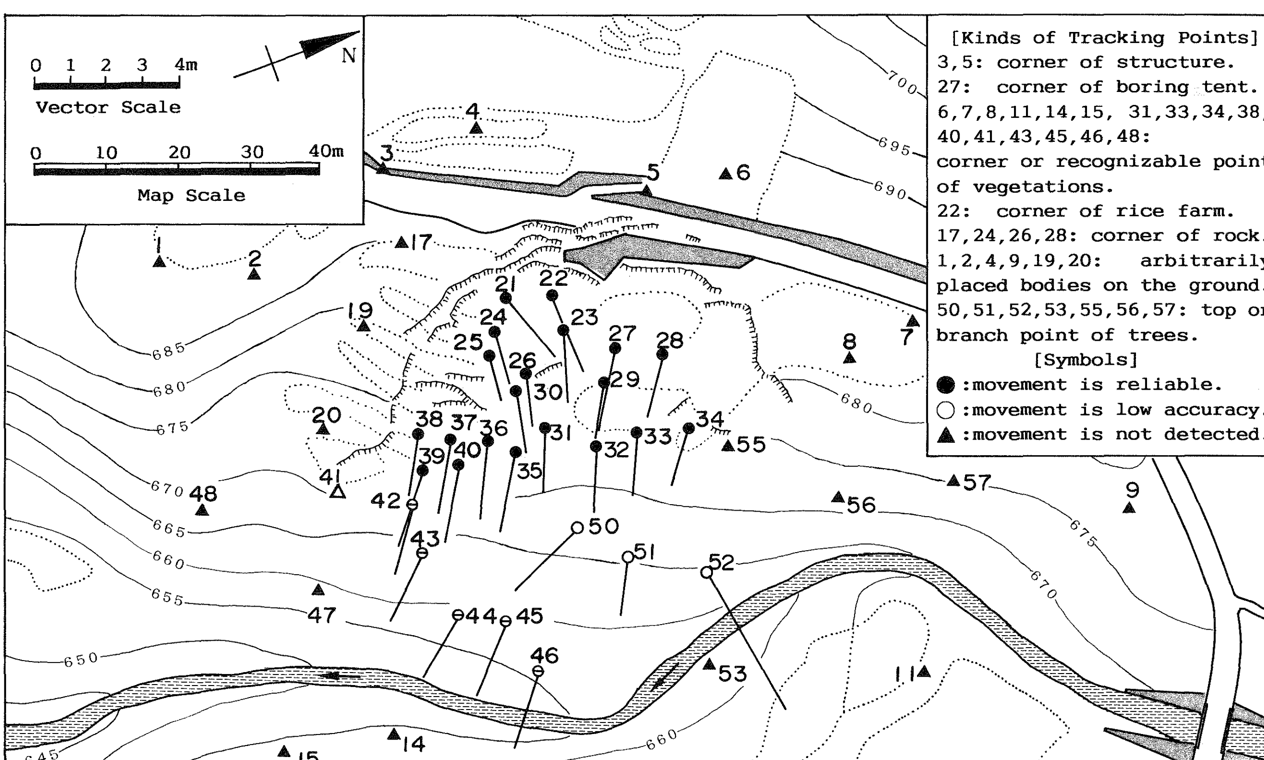


Fig.6 Tracking points projected on a topographic map and their horizontal displacement vectors detected by photogrammetry. Caption; This figure corresponds to Fig.5. Coordinates of the tracking points were measured by the above photograph and that taken at 14:24,Oct.10,1989. The horizontal displacement vectors were obtained by difference of coordinates measured at the different flight time. Tracking points on the road and farm have reliable vector, but those in the grassy bush and forest have low precision one (see Fig.8).

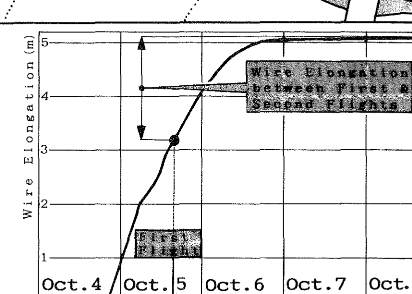


Fig.7 Record of elongation of wire extensometer shown in Fig.9. Caption; Ground movement almost stopped about noon Oct.7.

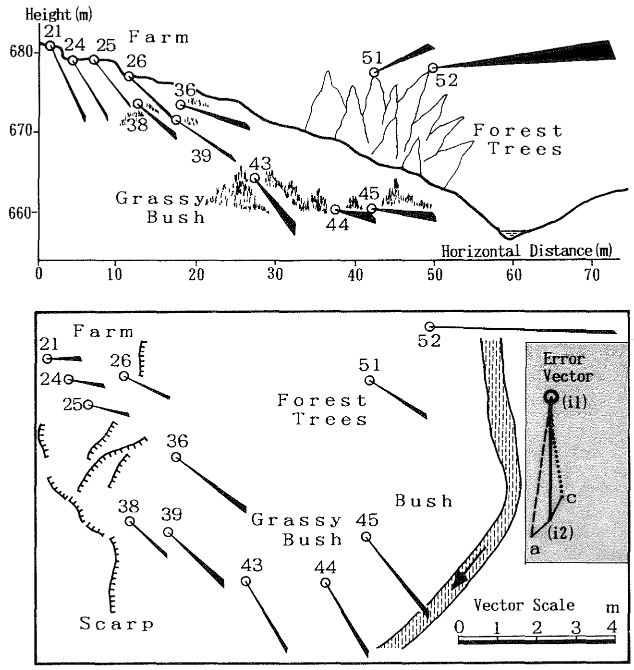


Fig.8 Error vector of tracking points (cf.Fig.1). Caption; Area of dark triangle or trapezoid shows the error of displacement vector. Error of height measurement is large in grassy bush and very large in forest trees. Thus the precision of vector is influenced by the measurement of coordinates.

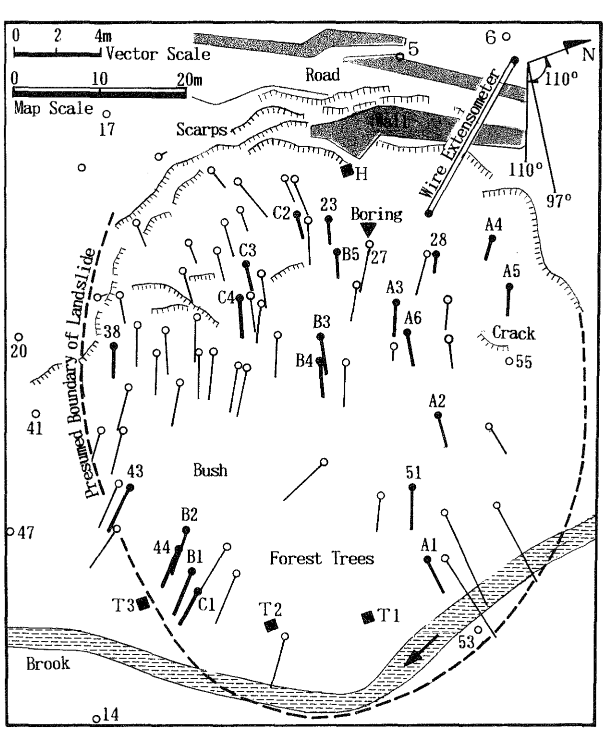


Fig.9 Horizontal displacement vector and boundary of landslide. Caption; Majority of displacement vectors detected by tracking points are illustrated. The vectors drawn by bold line are related to those shown in Figs.10,11 and 12. The broken line is the intersection of presumed three dimensional slide surface and the ground surface.

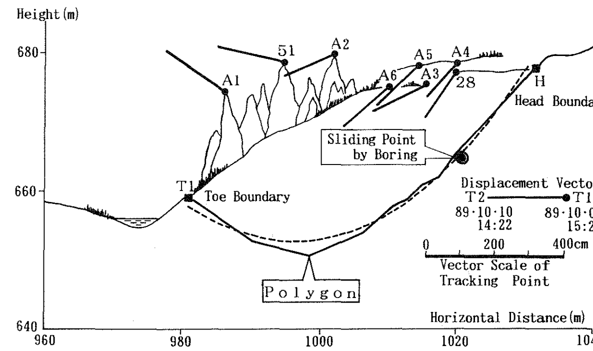


Fig.10 Pressumption of slide surface by polygon. Caption; Projection plane was taken 97° from the N(X) axis. Tracking points on the right side of the area in Fig.9 were used in this analysis. This polygon shows a good coincidence with the sliding point detected by field boring. The dashed curve is fitted to this polygon (Yoshizawa,et al.,1991).

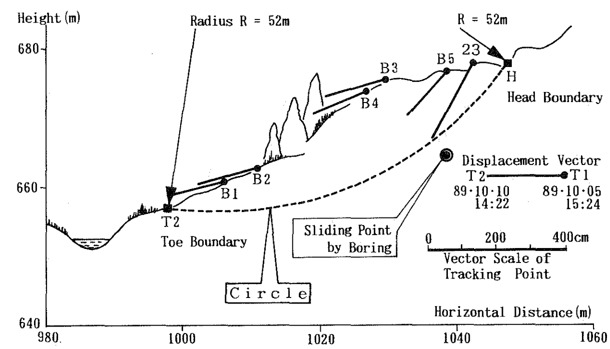


Fig.11 Pressumption of slide surface by circle. Caption; Projection plane was taken 98° from the N(X) axis. Tracking points on the center part of the area in Fig.9 were used in this analysis. This circle is shallow about 3m from the sliding point.

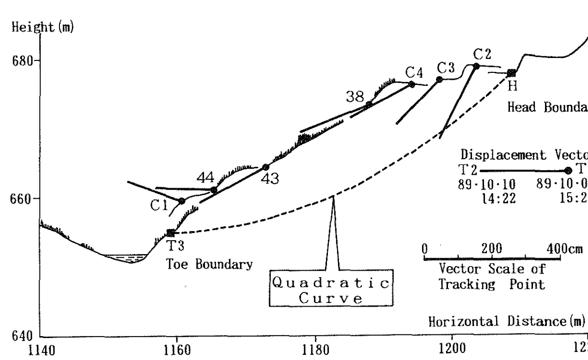


Fig.12 Slide surface presumption by polynomial. Caption; Projection plane was taken 110° from the N(X) axis. This is the main direction of movement of the mass on the left side of the area in Fig.9.

5. APPLICATION TO LANDSLIDE OF LARGE AREA

The photogrammetry is effectively applied to large area landslide. Fig.13 is the photograph on Narao landslide area,Nagano prefecture,Japan, taken Mar. 29,1977 (six months after the occurrence of landslide on Oct.6,1976). Extent of the landslide is 800m(length) and 200m(width) in this photograph.

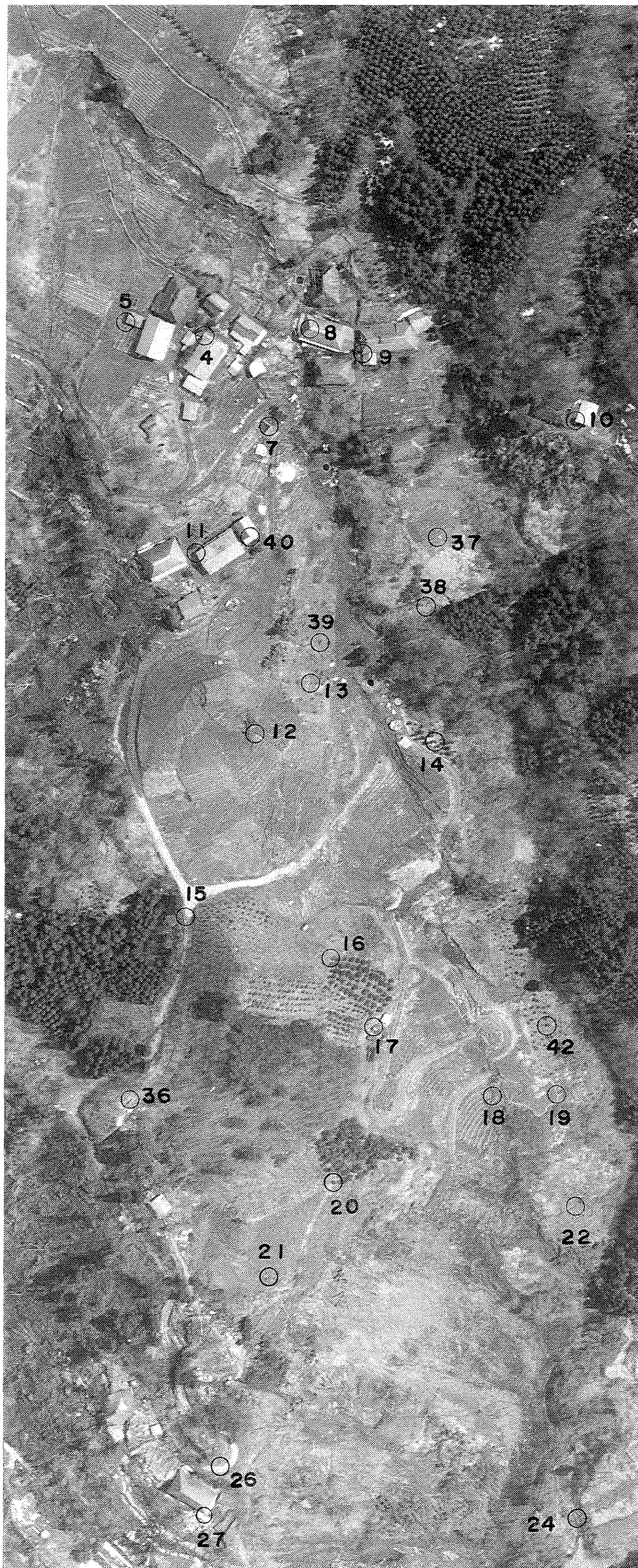


Fig.13 Photograph on landslide area (Narao,Nagano prefecture,Japan,Mar.29,1977). Caption; Near the point 18, the curved road is sheared by the slide.

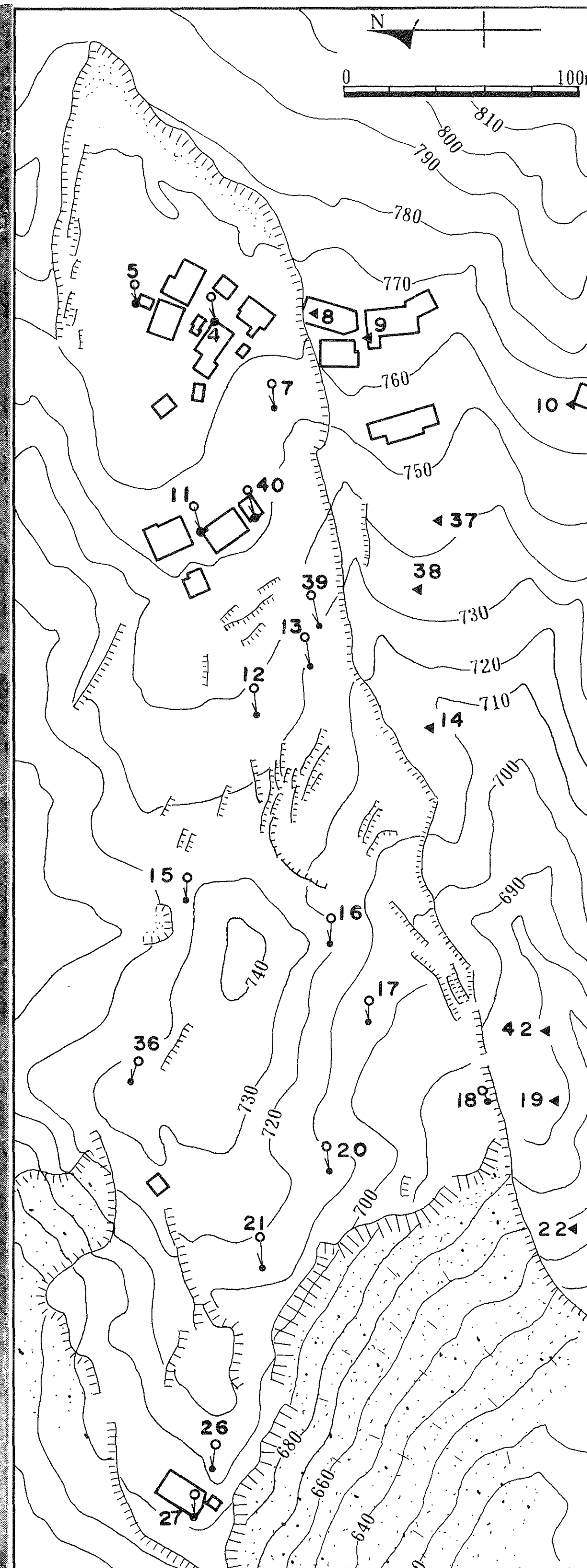


Fig.14 Displacement vector of tracking point on a topographic map corresponding to the photograph in the left. Note: (map scale) = (vector scale)

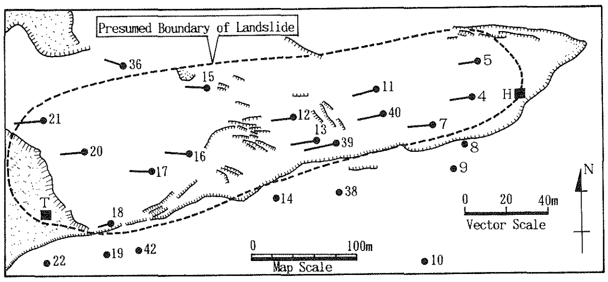


Fig.15 Presumption of landslide boundary line. Caption; Vectors shown in this figure (except 38) are used for three dimensional curved surface presumption. H is the head boundary point detected by boring. The point T is the toe boundary judged by bulge phenomena appeared on the outcrop.

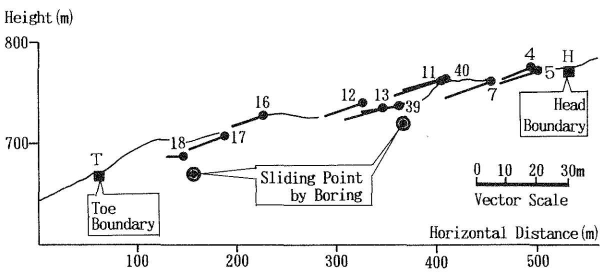


Fig.16 Displacement vectors on a Vertical Plane. Caption; Projection plane is taken 82^{0} from the N(X-axis).This is the main direction of horizontal movement of tracking points: 4,5,7,11,12,13,16,17, 18,39 and 40 shown in Fig.15.

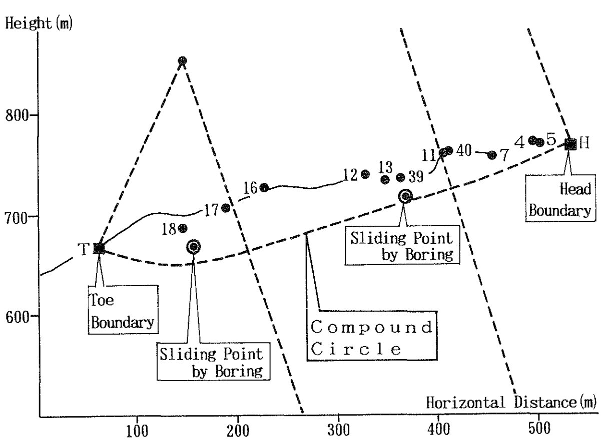


Fig.17 Shape of slide surface curve presumed by compound circles. Caption; Three arc elements whose rotational center is obtained by the method B are connected. Grouping of the tracking point is (16,1718),(11,12,13,39,40),(4,5,7,40).

The ground movement continued about three months. Consequently,many ground objects were destroyed or dislocated. Fig.14 shows the topographic map and displacement vector of the grpound objects. Many tracking points were selected on the roof corner of remaining hose, because the destruction was too hard and various objects have vanished away. Comparing with the photograph taken on Apr.26, 1975 (before the occurrence of landslide) we detected the displacement vector shown in this figure. The open circle is the position on Apr.26,1975,and the solid circle is on Mar.29,1977. No displacement was detected at the point shown by solid triangle.

In Fig.15, the curve of broken line is the intersection of the ground surface and slide surface presumed by the method F. A good compatiblity of this curve is observed with the cracks extending from the point 8 to 18 in the figure. But, at the head part of the landslide,they are nonconformity.

On the vertical projection plane parallel to the main direction of landslide movement, the method D is applied. Observing the displacement vectors in Fig.16, existence of partial rotational movement is examined. The vectors are grouped as stated in the caption of Fig.17. Rotational center of each group is obtained by the method B. Starting from the head boundary point (H),the compound circle is constructed. Unconformity error of this circle to the toe boundary point (T) is adjusted by graphic consideration.[5] Thus the shape of slide curve can be presumed as shown in Fig.17. Compared with the sliding point detected by field boring, this curve shows a little deeper presumption.

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