# Use of Contour-Based DEMs for Deriving and Mapping Topographic Attributes 

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#### Abstract

Algorithms using contour-based DEMs to calculate slope gradient and aspect, and to classify and map slope profile and plan forms, were developed, which we call C-BATM (Contour-Based Automatic Terrain Mapping). These are important topographic attributes for various analyses and terrain-related hazard mapping. As a first step, a fall line, the line of the maximum gradients or a flow path, was generated from all data points of all contours. Then, using the fall line segment (between adjacent contours), slope gradient and aspect were calculated. The change in slope gradients of three consecutive contours are the basis for classifying slope profile form into concave, planar, and convex. Slope plan form was classified from the contour crenulation, using a point of inflection by examining the directional change of contour segments (line between two consecutive data points). In the process of classifying slope morphologies, the profile and plan curvatures were also calculated and recorded. Test results of these methods in mountainous areas indicate the advantage of using contour-based DEMS over the use of the grid-based DEM or TIN. These methods have a potential of much wider applications to terrain analyses and hydrological modeling.


## Introduction

In mountainous areas, disasters caused by mass movements such as landslides and debris flows are common, and where snowy in winter, snow avalanches are a serious threat. These phenomena are influenced by the pull of gravity, once they are set into motion, and their movement path is generally controlled by topography, i.e., slope gradient, aspect, and morphology (convexity).

In order to analyze, understand, and predict such phenomena, it is essential to make a terrain classification map using topographic attributes such as elevation, slope (gradient, aspect, and morphology), and break of slope. Such maps have traditionally been produced manually using a topographic (contour) map as the base, and contour-measured topographic attributes were subjected to statistical or model analysis in order to extract contributing attributes. Then, combined with other factors such as geology, surface material or soil, vegetation, and human activities, these maps may become a hazard map. For example, making a landslide susceptibility map, slope gradient, aspect, and morphologies (ridge or valley type) were found to be important topographic attributes (Aniya, 1985; Dikau, 1990). These attributes are also used for analysis of topographic characteristics of terrain (Speight, 1974). Slope
morphology can be classified into nine basic forms by combining profile and plan forms (Figure 1) (Dikau, 1990).

In recent years, the use of digital elevation models (DEMs) has become popular and common for topographic analyses and mapping of topographic attributes. Moore et al. (1991) discussed the characteristics of three DEM structures, grid-based DEM, triangulated irregular network (TIN) DEM, and vector or contour-based DEM, for deriving topographic attributes. They stated "the most efficient DEM structure for the estimation of these attributes is generally the grid-based method. The con-tour-based method requires an order of magnitude more data storage, and does not provide any computational advantage" (Moore et al., 1991, p. 5). However, Moore et al. (1993) pointed out the superiority of the digital contours over the grid-based DEM for hydrological analysis using drainage lines and areas. There is no data structure which is superior to all others with respect to all aspects of digital terrain modeling (Weibel and Brändli, 1995). Although the advantages of using contourbased DEMs or digital contours have been thus recognized for some type of geomorphological analysis, the difficulty of handling such data by computer has until now limited applications to terrain analyses.

Moore et al. (1988) pioneered using contour-based DEMs to calculate slope gradient and aspect among other geomorphic attributes in hydrological and ecological applications. They generated flow trajectories (flow lines) with TAPES-C (Topographic Analysis Programs for the Environmental SciencesContour) using contour data that were digitized in a consistent direction, with which they partitioned the catchment. Moore and Grayson (1991) used TAPES-C, after catchment partitioning, to model runoff producing mechanisms. Chou (1992) discussed comprehensively the problems associated with the use of gridbased DEMS when he developed a method to generate slope line, a line on a surface of steepest gradient through a point (Douglas, 1986), from contour-based DEMs. He emphasized the storage compactness of the digital contour data, and advocated comparative studies of the three structures of DEMS.

The contour-based calculation of slope gradient and aspect, and the classification and mapping of slope morphology, have many advantages over the use of a grid-based DEM, because topography is a continuous surface, which the contour represents as an analog visual model, and the gradient and aspect can be measured perpendicular to the contour line. As Mark (1979) emphasized, this is the phenomenon-based DEM structure. The recent advance of computer technology has alleviated problems of complicated computation with large

[^0]Photogrammetric Engineering \& Remote Sensing Vol. 68, No. 1, January 2002, pp. 83-93.

0099-1112/02/6800-083\$3.00/0
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Figure 1. Geometric forms of hillslopes (simplified after Dikau (1990)). L, linear; V, convex; C, concave. The thick lines divide these forms into three groups: (1) collinear (LL); (2) linear in one dimension and curved in the other; and (3) doubly curved.
amounts of data, opening up a way to handle digital contour data for geomorphometric computation.

The purpose of this study is to develop algorithms using contour-based DEMS for geomorphometric measures, and for classification and mapping of slope forms. We call this set of algorithms C-BATM (Contour-Based Automatic Terrain Mapping). First, we developed an algorithm with which to generate a fall line (a flow path, or a line of the maximum gradients) originating from every data point on all contours. Then, utilizing a fall line, we calculate slope gradient and aspect, and classify and map slope profile form. Slope plan form is classified and mapped, based on the contour crenulation. In the process of classifying the slope forms, the profile and plan curvatures are also calculated and stored. C-BATM, which is written in C language, was tested in the Shirakami Mountains in Japan.

## Background

Of the three structures of DEMs which Moore et al. (1993) discussed, grid-based DEMs have been extensively used for statistical and quantitative analyses of terrain, because they are suited for calculation and are easy to handle for raster overlay analysis, despite several disadvantages (Moore et al., 1991). The grid-based DEMs have been traditionally generated in two ways, direct photogrammetric measurements, or interpolation from digitized contours. Recently, other methods based on remote sensing such as interferrometry from SAR satellite data (Genz and Genderen, 1996) and laser scanner (Ackermann, 1996) have been developed for generating DEMs. However, contours are still widely available, and for many projects may be the only affordable source of elevation data from which to create DEMs (Wise, 2000). There are two errors in digitized contours; the one in the contour itself and the other caused in digitizing. In grid-based DEMs generated from contours, additional errors may be introduced by interpolation. The accuracy of grid-based DEMs generated from digitized contours cannot exceed that of the original contour.

1)-4: line number of contour data.
(1) - 8) : point number of a contour line.
$\leftarrow$ : the direction of contour data. The point number increases along this direction.

| (B)Line numberStarting point | $x y$ file | $z$ file |
| :---: | :---: | :---: |
|  |  | $1 z_{l}$ |
|  | $1, x \\|, y_{\\|}^{\prime \prime}$ | . |
|  | 2, $x_{12}, y_{12}$ |  |
|  | 5, x/5, y/s | . |
|  | END |  |
|  |  | L |
| Line number | $i$ | Line number |
| Starting point | $1, x_{n}, \quad y u$ |  |
|  | j, $x_{i j}, y_{i j}$ |  |
| Ending point | $\begin{aligned} & f, x_{i f}, y_{i f} \\ & \text { END } \end{aligned}$ |  |

$\left(j, x_{i j}, y_{i j}\right): j$ is a point number. $x_{i j}$ and $y_{i j}$ are $x y$ coordinates of $j$-th data point on the $i$-th contour data.
$z_{i}$ : elevation of the $i$-th contour data.
$f$ : the total number of data points of the $i$-th contour data.
Figure 2. Data structure and format of contours. (A) Data structure between adjacent contours: Contour 1; The left side of contour 4: Contour 2; The left side of contour 3 and the right side of contour 4: Contour 3; The right side of contour 2 and the right side of contour 4 : Contour 4 ; The left side of contour 1, the right side of contour 2 and the left side of contour 3. (B) Data format of contours.

Because the interpolation process is much more common, there is a lot of literature on the accuracy of the grid-based DEM derived from digital contour data, which in turn affects the outcome of geomorphic and hydrological analyses (e.g., Weibel and Heller, 1991; Lee et al., 1992; Moore et al., 1993; Robinson, 1994; Weibel and Brändli, 1995; Wise, 1998; Wise, 2000). In addition, the use of different algorithms to calculate geomorphometry, such as slope gradient and aspect using a window, results in different values (e.g., Skidmore, 1989; Guth, 1995; Wise, 2000).

There are some problems inherent in the use of gridbased DEMs. Depending upon the grid spacing, a window might straddle either the ridge or valley or both. In such a


Figure 3. Determination of a point $q_{j}$ and examples of errors in finding a point $q_{j}$. (A) $t_{1}$ is the closest point to $m$ in the selected data points, contour $T$ lies adjacent to contour $M$ and trial line $m t_{1}$ does not intersect with any contours. $t_{4}$ and $t_{5}$ are not selected data points. (B1) Trial line $m t_{1}$ intersects with contour $M$. This error often happens at a bending part of contour $M$. (B2) Trial line $m t_{1}$ intersects with contour $M^{\prime}$ (the same elevation as $M$ ). This error often happens at an isolated small mound. (B3) Trial line $m t_{1}$ intersects with contour $H$ (higher than $M$ ). This error often happens when the spacing of points on contour $T$ (lower than $M$ ) is wide. (B4) Trial line $m t_{1}$ intersects with contour $Q^{\prime}$ (the same elevation as $T$ ) and $L$ (lower than $T$ ). This type of error occurs when the spacing of points on $Q^{\prime}$ next to $M$ is wide and one point on $T$ is nearer to $m$ than all points on $Q^{\prime}$, which often happens at the valley bottom. (B5) Trial line $m t_{1}$ intersects with contour $T$ (lower than $M$ ). This error often happens at a bending part of contour $T$.
case, the computed geomorphometries do not represent the true surface, and slope characteristics classified based on this computation would be totally false. Reduction of the grid spacing, when generating data, alleviates this problem to some extent. Then the accuracy of a spot height relative to the grid spacing becomes crucial. With a given spot height accuracy of 2 m , for example, whether a DEM is sampled at a $50-\mathrm{m}$ interval or at a $25-\mathrm{m}$ interval has a profound influence on the resulting computation. Although the $25-\mathrm{m}$ spacing apparently reduces the number of windows astride the ridge or valley, the computed value itself contains larger errors than the $50-\mathrm{m}$ interval. The contour data may have a similar problem in that with a given scale and interval, contours may not accurately depict ridges and valleys. However, one advantage of contours is that their shape can provide extra information about morphology of the terrain surface (Mark, 1986; Robinson, 1994; Wise, 2000).

The generation of a drainage network from a grid-based DEM is greatly affected by the quality of the data, which usually have problems of pits or sinks, or spikes from interpolation. To remove these errors, a smoothing technique is usually employed, thereby altering other data as well. In determining the flow path, the earliest and simplest method (O'Callagan and Mark, 1984) has a limited number of flow directions (usually seven or less). Quinn et al. (1991) developed a multiple flow direction algorithm to compensate for this restriction. Tarboton (1997), after pointing out problems of these existing methods with which to determine flow directions, proposed a new method using eight triangular facets centered at each grid point in which flow direction could
take any value between $0^{\circ}$ and $359^{\circ}$. In this method, however, because a flow line is not necessarily from one grid point to another grid point, the flow line may be offset at a grid line, resulting in a zigzag flow path.

## Nature of Contour-Based DEMs Used

During the late 1990s, the Geographical Survey Institute (GSI) of Japan published grid-based DEMS with a $50-\mathrm{m}$ spacing covering all of Japan. This DEM was created using 1:25,000-scale topographic maps with a contour interval of 10 m . Contour lines were scanned and vectorized, and then used to generate data to form a $50-\mathrm{m}$ grid by interpolation. These vectorized contours were utilized in this study.

The vectorized data of contours carry information on the elevation and the number of data points for each contour without topological information. These data were imported into ARC/INFO after being converted to a compatible format, which we refer to as contour data hereafter. We assigned a line number to each contour and the sequential number to each point of the contour, and defined the direction of the contour data as the one along which the point number increases (Figure 2A). The right or left side of given contour data is taken as that when facing the direction of the contour data. This in-
formation is needed to construct topological relationships between neighboring contours. Then, the contour data are represented by two simple text files; one consisting of the line number and sets of $X Y$ coordinates of data points and the other listing $Z$ values for all contours (Figure 2B). In this way, each point can be identified by the line and point numbers, as well as xyz coordinates.

## Algorithms of C-BATM

## Generation of Fall Line (Program FL)

A fall line intersects contours at a right angle and descends in the direction of the maximum gradient; consequently, it never crosses a ridge or valley. Therefore, the generation of a fall line is the first step for the subsequent derivation of geomorphic attributes. A fall line is generated from all data points on every contour by repeating the following steps.

## Step 1. Initial Search

We pick up a contour with the smallest line number assigned in the study area, and start to generate a fall line from the first point of that contour. We generate a fall line from data point $m$ of contour $M$ (elevation $E_{M}$ ) in the following sequence.

## Step 2. Selection of Contours and Data Points

First, we identify all the contours whose elevation is lower than contour $M$ by one contour interval, and scan all data points of these contours, in which we flag data points located within a range $R$ of the reference data point (RDP) $m$. These points are referred to hereafter as selected data points (SDP). The range $R$ is chosen for a study area, depending upon the contour density by trial and error. In this study of a mountainous area, we chose $R=150 \mathrm{~m}$ (equivalent to 6 mm on a $1: 25,000-$ scale map). The choice of $R$ affects computing time. If the RDP $m$ is the end of a fall line, there is no SDP within the range $R$. In this case, we go back to Step 1 and pick up the next data point $m+1$ for Step 2 .

Step 3. Computation of the Distance between the RDP and the SDPs

We compute the distance between RDP $m$ and the SDPs in Step 2. We pick up an SDP, from which the distance to the RDP $m$ is the shortest. We denote it as data point $t_{1}$ (tentative), and the contour containing this point as $T$ (Tentative) (Figure 3A).

## Step 4. Picking up of the Point

First, we search contour segments (line connecting two consecutive points of the same contour), including data points located within the range $R$ of the RDP $m$. These contour segments are referred to hereafter as provisional contour segments (PCS). Using these PCSs, we check if contour $T$ lies adjacent to contour $M$. If $t_{1}$ is a data point of the contour adjacent to contour $M$, line $m t_{1}$ does not intersect with PCSs (Figure 3A). Upon confirming this relationship, we redesignate contour $T$ as contour $Q$, and data point $t_{1}$ as data point $q_{j}$, and proceed to Step 5.

If line $m t_{1}$ intersects with PCSs (Figure 3, B1-B5), we discard data point $t_{1}$, and go back to Step 3 where we pick up data point $t_{2}$ (the second shortest) for the subsequent check. If we cannot determine contour $Q$ after using all SDPs ( $t_{1}$ to $t_{n}$ ), data point $m$ is the end point of a fall line. Then, we go back to Step 1 and pick up the next data point $m+1$ for Step 2 .

## Step 5. Determination of a Fall Line

In this Step, we look for a shortest line $m w$; point $w$ lies on contour $Q$ and is to be determined in the following manner. The determined point $w$ becomes an RDP of a fall line generation (Figure 4). Data point $w$ is subsequently used for derivation of slope gradient, aspect, and profile.

We search candidates for point $w$ from data point $q_{i-5}$ to $q_{i+5}$ of contour $Q$. If $q_{i-5}$ is a candidate for $w$, line $m q_{j-5}$ does not intersect with PCSs. Upon confirming this relationship, we list data point $q_{i-5}$ as a candidate for point $w$. We repeat the same process for the rest of the data points ( $q_{i-4}, q_{i-3}, \ldots, q_{i+5}$ ).

Next, we draw a normal line from the RDP $m$ to a line pass-


Plate 1. An example of fall lines. Brown lines are contours and blue lines are fall lines that have the same ending point.
ing through data points $q_{j}$ and $q_{j+1}$, and check to see if intersection $p_{j}$ lies between data points $q_{j}$ and $q_{j+1}$. If it does, we examine further whether $p_{i}$ is a candidate for point $w$. If $p_{i}$ is a candidate for point $w$, line $m p_{j}$ does not intersect with PCSs and we list this point as a candidate for point $w$. This process is applied to all the data points from $q_{i-5}$ to $q_{i+5}$.

After listing all the candidate points, we pick up a point closest to the RDP $m$ (distance $m w$ is the shortest, in Figure 4, $\left.p_{i-1}\right)$. We go back to Step 2 to extend the fall line downward until we reach the end of the fall line, by redesignating point w of contour $Q$ as point $m$ of contour $M$. This program does not have to define starting and ending points of a fall line and a catchment boundary before generating a fall line, whereas TAPES-C (Moore et al., 1988) requires determination of these parameters before generating a stream path. The newly defined points in generating a fall line are stored in a separate file from the original contour data. Plate 1 shows an example of fall lines generated for a drainage basin.

## Construction of Contour Topology (Program TPGY)

For the classification of slope plan form, we have to identify whether a contour bends out toward higher contours or lower contours. This requires us to identify whether contour $Q$, which is the lower neighbor, lies on the right or left side of contour $M$. The Program TPGY utilizes the fall line for this purpose.

At a given RDP $m$ of a given reference contour $M$, we employ two ways to judge the height and positional relationships between contour $M$ and a contour lying next to it.

## Check 1

At the RDP $m_{j}$ of the reference contour $M$, we search a lower neighbor contour of contour $M$. We denote this contour $K$, and


Plate 2. Classification of slope gradient, the Shirakami mountains. The northeastern part of 1:25,000-scale map Quadrangle "Futatsumori." (A) Gradient derived from fall line data. (B) Gradient derived by tin which were generated from the contour data (contour interval 10 m ). (C) Gradient derived from gridded data which were generated from the contour data (contour interval $10 \mathrm{~m})$. (D), (E), and (F) are enlargement of the rectangle in (A), (B), and (C), respectively. Rectangles are the same as Plate 1.
check whether contour $K$ lies on the right or left side of contour M.

Using the Program FL, we draw a shortest line from the RDP $m_{j}$ to contour $K$, and denote the intersecting point $k$. If point $k$ does not exist, we cannot judge and use another data point $m_{j+1}$.

We designate vectors from the RDP $m_{j}$ to $m_{i+1}, m_{j-1}$, and $k$ as $\boldsymbol{\alpha}, \boldsymbol{\gamma}$, and $\boldsymbol{\beta}$, respectively (Figure 5), and calculate outer products $\boldsymbol{\gamma} \times \boldsymbol{\beta}$ and $\boldsymbol{\beta} \times \boldsymbol{\alpha}$ using only $x y$ values ( $z=0$ ). When $\boldsymbol{\gamma} \times \boldsymbol{\beta}$ $>0$ and $\boldsymbol{\beta} \times \alpha>0$, point $k$ lies on the right side of contour $M$, and the right side of contour $M$ is lower as shown in Figure 5. Or
when $\boldsymbol{\gamma} \times \boldsymbol{\beta}<0$ and $\boldsymbol{\beta} \times \boldsymbol{\alpha}<0$, point $k$ lies on the left side of contour $M$, and the left side of contour $M$ is lower. When $\boldsymbol{\gamma} \times \boldsymbol{\beta}$ $>0$ and $\boldsymbol{\beta} \times \boldsymbol{\alpha}<0$, or $\boldsymbol{\gamma} \times \boldsymbol{\beta}<0$ and $\boldsymbol{\beta} \times \boldsymbol{\alpha}>0$, or $\boldsymbol{\gamma} \times \boldsymbol{\beta}=0$ or $\boldsymbol{\beta} \times \boldsymbol{\alpha}=0$, point $k$ is not considered to be suitable for judgment.

## Check 2

The same procedure as Check 1, except for using a higher neighbor contour. We denote this contour $H$, and check whether contour $H$ lies on the right or left side of contour $M$.

$M, Q$ : contour data.
$m$ : reference data point (RDP) on $M$.
$q_{j}, q_{j+l}, q_{j-l}, p_{j-l}, p_{j}$ : candidates for $w$. Points from which a line to $m$ does not intersect with contours. $q_{j}, q_{i+l}$ and $q_{j-l}$ are original data points of $Q . p_{j-t}$ and $p_{j}$ are temporary points on $Q$, and $m p_{j-l} \perp q_{j-1} q_{j}$ and $m p_{j} \perp q_{j} q_{j+l}$.
$q_{j+2}, q_{i-2}, q_{i+3}$ : original data points from which a line to $m$ intersects with contours.

Figure 4. Searching procedure for a candidate point $w$.

$H, M, K$ : contour data. Elevation of $H, M$ and $K$ are $E_{H}$, $E_{M}$ and $E_{K} . E_{H}>E_{M}>E_{K}$.

- : original data points of contour data.

O : intersecting points.
○ : $j$-th data point $m_{j}$, and reference data point (RDP) on $M$.
Figure 5. Relationship between contour $M$ and $H$ (or $K$ ) next to $M$. See text for explanation.

We designate vectors from the RDP $m_{j}$ to $h$ as $\boldsymbol{\beta}^{\prime}$, and calculate outer products $\boldsymbol{\gamma} \times \boldsymbol{\beta}^{\prime}$ and $\boldsymbol{\beta}^{\prime} \times \boldsymbol{\alpha}$ using only xy values ( $z=$ 0 ) (Figure 5). When $\boldsymbol{\gamma} \times \boldsymbol{\beta}^{\prime}<0$ and $\boldsymbol{\beta}^{\prime} \times \boldsymbol{\alpha}<0$, point $h$ lies on the left side of contour $M$, and the left side of contour $M$ is higher as shown in Figure 5. Or when $\boldsymbol{\gamma} \times \boldsymbol{\beta}^{\prime}>0$ and $\boldsymbol{\beta}^{\prime} \times \boldsymbol{\alpha}>0$, point $h$ lies on the right side of contour $M$, and the right side of contour $M$ is higher. When $\boldsymbol{\gamma} \times \boldsymbol{\beta}^{\prime}>0$ and $\boldsymbol{\beta}^{\prime} \times \boldsymbol{\alpha}<0$, or $\boldsymbol{\gamma} \times \boldsymbol{\beta}^{\prime}<$ 0 and $\boldsymbol{\beta}^{\prime} \times \boldsymbol{\alpha}>0$, or $\boldsymbol{\gamma} \times \boldsymbol{\beta}^{\prime}=0$ or $\boldsymbol{\beta}^{\prime} \times \boldsymbol{\alpha}=0$, point $h$ is not considered to be suitable for judgment.

In order to ensure the topological relationship, which is crucial for the subsequent manipulation, we repeat the checks 1 and 2 a few times by changing the RDP ( $\left.m_{j}=m_{j+1}, m_{j+2}, \ldots\right)$. Program TPGY starts from a data point $j=2$ for each contour,
(A) Profile View

$W$ : fall line data.
$w_{j}: j$-th data point on $W$.
$v_{j}$ : middle point between data points $w_{j}$ and $w_{j+1}$.
$\delta_{j}$ : angle of line $w_{j-l} w_{j} w_{j+l}$ on the horizontal plane (B). $0^{\circ}-180^{\circ}$.
$\varepsilon_{j}$ : angle between line $w_{j} w_{j+1}$ and the horizontal plane (A).
$\omega_{j}$ : azimuth of line $w w_{j+1}(\mathrm{~B})$.
$\tau_{j}$ : angle of line $w_{j-1} w w_{j+1}$ on the vertical plane (A).

$$
\tau_{j}=180^{\circ}-\varepsilon_{j}+\varepsilon_{j-1}
$$

- : original data points of contour data.

0 : data points defined by fall line.
O: middle points between two consecutive data points on a fall line data.
Figure 6. Calculations of gradient and aspect, and classification of slope profile form.
and when the positional judgment is the same for three consecutive RDPs, we accept this judgment as final.

## Slope Gradient and Aspect

Referring to Figure 6, a unit for deriving slope gradient and aspect is a fall line segment $w_{j} w_{j+1}$ or $w_{j-1} w_{j}$. The gradient $\varepsilon_{j}$ is the angle between line $w_{j} W_{j+1}$ and the horizontal plane (Figure $6 \mathrm{~A})$, and the aspect $\omega_{j}$ is the angle between the north and line $w_{j} w_{j+1}$ (Figure 6B). Angles $\varepsilon_{j}$ and $\omega_{j}$ are attached to the fall line segment $w_{j} W_{j+1}$ as attributes.


Figure 7. The dividing point for classifying slope plan form.

## Slope Profile Form

A simple slope profile form can be classified by the change in slope gradients of two consecutive fall line segments $w_{j-1} w_{j}$ and $w_{j} w_{i+1}$ (Figure 6A). The angle $\delta_{j}$ is the angle on the horizontal plane at point $w_{j}\left(0^{\circ}<\delta_{j} \leq 180^{\circ}\right)$ between fall line segments $w_{j-1} w_{j}$ and $w_{j} w_{j+1}$ (Figure 6B). If angle $\delta_{j}$ is less than $90^{\circ}$ for line $w_{j-1} w_{j} w_{j+1}$, we do not use that line for obvious reasons. Point $v_{j}$ is the middle point between points $w_{j}$ and $w_{i+1}$, and line $V_{j-1} W_{j} v_{j}$ is one unit of slope profile form. Angles $\tau_{j}, \delta_{j}$, $\varepsilon_{j-1}$, and $\varepsilon_{j}$ are attached to line $v_{j-1} w_{j} V_{j}$ as attributes.

Slope profile form can be classified into three basic forms: $\tau_{j}=180^{\circ}$ (straight slope), $\tau_{j}>180^{\circ}$ (concave), and $\tau_{j}<$ $180^{\circ}$ (convex). However, in reality, there is virtually no slope of exactly $\tau_{j}=180^{\circ}$ and a range is allowed for $\tau_{j}$ of straight slope. Also, when considering the accuracy of contours, this is sensible. Using angles $\varepsilon_{i}$ and $\varepsilon_{i-1}$, the profile curvature can be computed, based on which slope profile form is classified.

## Slope Plan Form

Because slope plan form is classified by the shape of contours, a point of inflection of a curved line is the point at which to divide the plan form. Instead of fitting a curved line to data points to locate a point of inflection, we developed a simple method using the original contours.

At data point $m_{j}$ of contour $M$, let the vector from data point $m_{j}$ to data point $m_{j+1}$ be $\boldsymbol{\alpha}_{j}$, and then calculate outer product $\boldsymbol{\alpha}_{j-1} \times \boldsymbol{\alpha}_{i}$ at all data points of contour $M$ (Figure 7). If a sign of the outer product at point $m_{j+1}$ differs from that at point $m_{j}$, the middle point between points $m_{j}$ and $m_{j+1}$ is taken as the point of inflection, which is then added to contour $M$ as a new data point.

We judge slope plan form at all original data points of contour $M$. When contours $H$ and $K$ exist on both sides of contour $M$, we designate the elevation of contours $H, M$, and $K$ as $E_{H}, E_{M}$, and $E_{K}$, respectively, where $E_{H} \geq E_{M} \geq E_{K}$ (excluding $E_{H}=E_{M}=E_{K}$ ). If $\boldsymbol{\alpha}_{j-1} \times \boldsymbol{\alpha}_{j}<0$, line $m_{j-1} m_{j} m_{j+1}$ projects onto the left side of contour $M$ (Figure 8A). Or if $\boldsymbol{\alpha}_{j-1} \times \boldsymbol{\alpha}_{j}>0$, line $m_{j-1} m_{j} m_{j+1}$ projects onto the right side of contour $M$ (Figure $8 \mathrm{~B})$. If outer product $\boldsymbol{\alpha}_{j-1} \times \boldsymbol{\alpha}_{j}=0, m_{j-1} m_{j} m_{j+1}$ is a straight line, and angle $\theta_{j}$ between vector $\boldsymbol{\alpha}_{j-1}$ and vector $\boldsymbol{\alpha}_{j}$ is equal to $0^{\circ}\left(0^{\circ} \leq \theta_{j}<180^{\circ}\right)$. The program TPGY finds whether contour $H(K)$ lies on the left or right side of contour $M$. Slope plan form at point $m_{j}$ is classified in the following ways:

$M$ : contour data.
$m_{j}: j$-th original data point of $M$.
: point of inflection.
$\alpha_{j}$ : vector (from point $m_{j}$ to point $m_{j+1}$ ).
$\theta_{j}$ : angle between two consecutive vectors $\alpha_{j / l}$ and $\alpha_{k}$ $0^{\circ}-180^{\circ}$.
$\bigcirc$ : data point at which the outer product $\alpha_{j-1} \times \alpha_{j}<0$.
○: data point at which the outer product $\alpha_{j-1} \times \alpha_{i}>0$.
Figure 8. Slope plan form defined by the outer product of consecutive vectors.

Case 1. $\boldsymbol{\alpha}_{j-1} \times \boldsymbol{\alpha}_{j}=0\left(\theta_{j}=0^{\circ}\right)$ : Planar slope.
Case 2. $\boldsymbol{\alpha}_{j-1} \times \boldsymbol{\alpha}_{j}<0$ and contour $H$ (or $K$ ) is on the left (or right) side of contour $M$ : Convergent (Valley) slope (Figure 8A).
Case 3. $\boldsymbol{\alpha}_{j-1} \times \boldsymbol{\alpha}_{j}<0$ and contour $H$ (or $K$ ) is on the right (or left) side of contour $M$ : Divergent (Ridge) slope (Figure 8A).
Case 4. $\boldsymbol{\alpha}_{j-1} \times \boldsymbol{\alpha}_{j}>0$ and contour $H$ (or $K$ ) is on the left (or right) side of contour $M$ : Divergent slope (Figure 8B).
Case 5. $\boldsymbol{\alpha}_{j-1} \times \boldsymbol{\alpha}_{j}>0$ and contour $H$ (or $K$ ) is on the right (or left) side of contour $M$ : Convergent slope (Figure 8B).
Because it is extremely rare to have $\theta_{j}=0^{\circ}$ in the calculation, a range is allowed for $\theta_{j}$ to define the planar slope.

In Figure 9, points $s_{1}$ and $s_{2}$ are two consecutive points of inflection. Slope plan forms at data points between point $s_{1}$ and $s_{2}$ are the same, and a series of contour segments from point $s_{1}$ to point $s_{2}$ constitutes one unit of slope plan form. In addition to slope plan form, distances $D_{1}, D_{2}$, and $L$ are defined for each unit. Distance $D_{1}$ is the direct line from point $s_{1}$ to point $s_{2}$, while distance $D_{2}$ is the route (contour) length from point $s_{1}$ to point $s_{2}$. Distance $L$ is the longest line perpendicular to line $D_{1}$ from a data point ( $P$ in Figure 9) of the unit slope. The slope plan form can be further classified according to its degree of bend using a ratio $D_{1}: D_{2}$ or $D_{1}: L$. The curvature of the slope unit can be expressed by the cumulative value of $\theta_{j}\left(\Sigma \theta_{j}\right.$ from $\theta_{j-1}$ to $\theta_{j+2}$ in Figure 9), which may be attached to data point $m_{j}$.


Plate 3. Classification of the slope profile form. Three layers were combined: (1) main scarp and landslide block of the landslide map (Oyagi et al., 1985): (2) classification of the slope profile form: and (3) contours. In Plate 3A, straight slope, $175^{\circ} \leq \tau \leq 185^{\circ}$; convex slope, $\tau<175^{\circ}$; concave slope, $\tau>185^{\circ}$. In Plate 3B, straight slope, $170^{\circ} \leq \tau \leq 190^{\circ}$; convex slope, $\tau<170^{\circ}$; concave slope, $\tau>190^{\circ}$. The rectangles indicate the area of Plate 1 and (D), (E), and (F) of Plate 2.

## Application and Comparison

C-BATM was applied to the Shirakami Mountains in northern Honshu as a test. The Shirakami Moutains have a relief up to 1200 m with rugged as well as subdued topography, due to large-scale deep-seated landslides.

Plate 2A is a slope gradient map of the Shirakami Mountains using the fall line. For comparison, we also produced slope gradients from TIN (Plate 2B) and a $25-\mathrm{m}$ grid-based DEM (Plate 2C), using the same contour data, because the $50-\mathrm{m}$ gridbased DEM released by the GSI was found to be too coarse for this study area. Using algorithms available in ARC/INFO such as Topogrid, inverse distance weighting (IDW) functions (methods of nearest samples and within a radius), spline and krigings (methods of nearest samples and within a radius) (ESRI, 1999), we produced six $25-\mathrm{m}$ grid-based DEMs with which to map slope gradients. Except for those produced with Topogrid and IDW (within a radius), the four interpolation methods resulted in similar gradient maps. Plate 2 C is one of those four maps, which is based on the DEMS interpolated by the IDW function
using 12 nearest sample points. The difference in detailed information between Plates 2A and 2C is apparent and substantial. On a small scale, Plates 2A and 2B appear similar; however, by enlarging a part of these maps (Plates 2D, 2E, and 2 F) the advantage of using the fall line (Plate 2D) can be clearly recognized because, in addition to the gradient, we can perceive the terrain configuration depicted by contours. Figure 10 is slope aspect maps for the same area; Figure 10A using the fall line, Figure 10B using TIN, and Figure 10C using the $25-\mathrm{m}$ grid-based DEM (IDW with nearest samples). For Figure 10, a $30^{\circ}$ interval was employed in order to enhance the 3D perception, with shading by the northwest illumination. In terms of 3D perception, Figure 10B (based on TiN) appears best; however, Figure 10A (based on fall lines) conveys detailed surface configuration by contours in addition to 3D perception.

Plate 3 is an example of the slope profile-form classification, on which deep-seated landslide data (primarily interpreted on aerial photographs) were superimposed (Oyagi et al., 1985). Plate 3A was made with an allowance of $\pm 5^{\circ}$ for $\tau$ for


Plate 4. Classification of slope plan form. Slopes of $\theta<5^{\circ}$ are taken as planar slope. The rectangle indicates the area of Plate 1 and (D), (E), and (F) of Plate 2.


Figure 9. A unit of slope plan form; line from point $s_{1}$ to $s_{2}$. $s_{1}$ and $s_{2}$ are dividing points. $P$ is a point on the unit of slope plan form from which the perpendicular line to $D_{1}$ is the longest. The following attributes are given to the unit of slope plan form: (1) plan form of slope; divergent, convergent or planar: (2) elevation: (3) $D_{1}$; direct line length from $s_{1}$ to $s_{2}$ : (4) $D_{2}$; route length from $s_{1}$ to $s_{2}$ : and (5) $L$; the length of perpendicular line from $P$ to $D_{1}$.
straight slope ( $175^{\circ} \leq \tau \leq 185^{\circ}$ ), making concave slope defined by $\tau>185^{\circ}$ and convex slope by $\tau<175^{\circ}$. Plate 3A gives an impression of the banding pattern of slope forms, indicating that many slope profiles consist of alternating convex, concave, and straight segments. In reality, the slope profile is complex from the ridge top to the valley bottom, and the expression of complexity can be varied by changing the allowance for $\tau$ to define a straight slope. A large allowance for $\tau$ diminishes the banding pattern (Plate $3 \mathrm{~B}, \pm 10^{\circ}$ ), while a small allowance for $\tau$ depicts the subtle change in the profile (Plate $3 \mathrm{~A}, \pm 5^{\circ}$ ).

It can be recognized in Plate 3 that the edge of landslide
blocks generally coincides with a concave slope, suggesting that this slope classification may be utilized as one of the criteria for automatic identification and delineation of some types of landslide blocks. Similarly, the break of slope and escarpment may be delineated, with which to classify some geomorphological units.

The slope plan form classification was carried out for the same area (Plate 4). Again, a range of $5^{\circ}$ was allowed for $\theta$ to define planar slope $\left(\theta<5^{\circ}\right)\left(0^{\circ} \leq \theta<180^{\circ}\right.$ in Figure 8). It is apparent that the perception of slope form and topography is very easy because of the retained contours.

## Summary and Conclusions

We presented a set of algorithms, called C-BATM (ContourBased Automatic Terrain Mapping) to compute slope gradient and aspect, and to classify and map slope profile and plan forms using contour-based DEMs, by generating a fall line from each data point of all contours. Slope gradient and aspect were measured along a fall line. The slope profile and plan forms were classified by the change in the fall line gradient and using contour crenulation, respectively. Because the contour-based DEMs preserve the original topographic configuration, and the fall line never crosses a ridge or valley, all the measured and classified geomorphometries are truly representing the characteristics of the slope, which is unattainable by the more common grid-based DEM.

Because the maps produced by C-BATM retain the contour lines, they are much easier to overlay with other data such as landslides or avalanches, enabling detailed visual analysis of the relationship between topography and phenomena, than are those produced using a grid-based DEM. In particular, it is important to note that our products of profile and plan maps cannot be produced using a grid-based DEM. The accuracy and appropriateness of our measurements and classifications naturally depend upon the location and density of the original digitized contour data points.

C-BATM has a possibility of much wider applications. For example, the fall line can be used for construction of a drainage network and delineation of a drainage basin by grouping fall lines that have the same ending point (see Plate 1). Based on them, it is possible to carry out various statistical analyses


Figure 10. Slope aspect with an interval of $30^{\circ}$ of the Shirakami mountain. (A) Slope aspect derived from the fall line data. (B) Slope aspect derived by TIN which were generated from the contour data (contour interval 10 m ). (C) Slope aspect derived from gridded data which were generated from the contour data (contour interval 10 m ). Rectangles indicate the area of Plate 1 and (D), (E), and (F) of Plate 2.
of geomorphometries-such as area, gradient, and Horton's laws of streams-of a drainage basin.

C-BATM appears to work best for areas with dense contours (normally mountainous area) because, in a hilly area where contours are not dense with a $10-\mathrm{m}$ interval, we did not obtain as good visual results as those of this study in classifying slope morphologies.

For statistical analysis of geomorphometries, we may
employ a scheme of point sampling using our maps. There are many possibilities in assigning a value to a point. We just mention few possibilities here, because exploration and testing of these potential methods require another substantial effort. For example, a closest fall line segment to a specified point is located, to which the attributes of that fall line are assigned. In the case where two or more fall line segments are located at the same distance, we may take an average. Or we
may pick up fall line segments within a certain range from a specified point and take an average of them or calculate a value using an IDW function. In geographic information systems (GIS) analysis, overlaying different layers of topographic attributes and other factors is the most common, popular technique. For overlaying, it is common and much easier to use a raster format than a vector format; therefore, polygonization or rasterization of our map is necessary. For rasterization, we may employ systematic point sampling, in which a point is representative of a pixel or raster. Or we may take all fall line segments within a raster and take an average of them for a raster value. For morphological classification, we may adopt the classification category in which a sampling point falls. In order to make C-BATM also useful for statistical analyses of geomorphometries, we plan to carry out studies along these lines.

## Acknowledgments

Digitized landslide data of the Shirakami Mountains were made available by Mr. Yukihiro Izumita, a graduate student in the Graduate School of Environmental Sciences, University of Tsukuba. The first author would like to thank Mr. Hiroshi Masaharu, head of the Geographic Information Analysis Research Division, Geography and Crustal Dynamics Research Center, Geographical Survey Institute of Japan, who has patiently supported this research. We would like to thank Mr. Stephen Bird, an English teacher at the Meikei High School in Tsukuba, who read the manuscript. The authors would like to thank three anonymous referees for their useful comments and suggestions regarding the first draft of this manuscript.

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(Received 23 March 2001; accepted 21 June 2001; revised 07 September 2001)


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