# Optimization of the Characteristic Straight Line Method by a "Best Estimate" of Observed, Normal Orthometric Elevation Differences

Mahmoud M. S. Albattah

*Abstract*—In this paper, to optimize the "Characteristic Straight Line Method" which is used in the soil displacement analysis, a "best estimate" of the geodetic leveling observations has been achieved by taking in account the concept of 'Height systems". This concept has been discussed in detail and consequently the concept of "height".

In landslides dynamic analysis, the soil is considered as a mosaic of rigid blocks. The soil displacement has been monitored and analyzed by using the "Characteristic Straight Line Method". Its characteristic components have been defined constructed from a "best estimate" of the topometric observations. In the measurement of elevation differences, we have used the most modern leveling equipment available. Observational procedures have also been designed to provide the most effective method to acquire data. In addition systematic errors which cannot be sufficiently controlled by instrumentation or observational techniques are minimized by applying appropriate corrections to the observed data: the level collimation correction minimizes the error caused by nonhorizontality of the leveling instrument's line of sight for unequal sight lengths, the refraction correction is modeled to minimize the refraction error caused by temperature (density) variation of air strata, the rod temperature correction accounts for variation in the length of the leveling rod's Invar/LO-VAR® strip which results from temperature changes, the rod scale correction ensures a uniform scale which conforms to the international length standard and the introduction of the concept of the 'Height systems" where all types of height (orthometric, dynamic, normal, gravity correction, and equipotential surface) have been investigated.

The "Characteristic Straight Line Method" is slightly more convenient than the "Characteristic Circle Method". It permits to evaluate a displacement of very small magnitude even when the displacement is of an infinitesimal quantity.

The inclination of the landslide is given by the inverse of the distance reference point O to the "Characteristic Straight Line". Its direction is given by the bearing of the normal directed from point O to the Characteristic Straight Line (Fig..6).

A "best estimate" of the topometric observations was used to measure the elevation of points carefully selected, before and after the deformation. Gross errors have been eliminated by statistical analyses and by comparing the heights within local neighborhoods.
The results of a test using an area where very interesting land surface deformation occurs are reported. Monitoring with different options and qualitative comparison of results based on a sufficient number of check points are presented.

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## I. INTRODUCTION

THE term "landslide" describes many types of downhill earth movements ranging from rapidly moving catastrophic rock avalanches and debris flows in mountainous regions to more slowly moving earth slides. Some landslides move slowly and cause damage gradually, whereas others move so rapidly that they can destroy property and take lives suddenly and unexpectedly. Gravity is generally the force driving landslide movement.

Factors that trigger landslide movement include heavy rainfall, erosion, poor construction practices, freezing and thawing, earthquake shaking, and volcanic eruptions. Landslides are typically associated with periods of heavy rainfall or rapid snowmelt and tend to worsen the effects of flooding. Areas burned by forest and brush fires are particularly susceptible to landslides.

Landslides exhibit vertical and horizontal movement down a slope, and most are triggered by heavy rain and snowmelt, earthquake shaking, volcanic eruptions, and gravity.
Although human activities may cause landslides on unstable slopes, most landslides are caused by natural forces or events, such as heavy rain and snowmelt, earthquake shaking, volcanic eruptions, and gravity.

The use of the "Characteristic Straight Line Method", (CSLM) developed here, can be considered as an innovation in topometric control process and gives to it additional extent as a monitoring tool of high accuracy.
The goals of the present paper are as follows:

1) Describe and illustrate the utility of the "Characteristic Straight Line Method" in improving the accuracy of the topometric control for landslides monitoring.
2) Evaluate what we can expect of vertical topometric observations in the field of any landslide monitoring program.
3) Achieving a "best estimate" of the geodetic leveling observations.

## II. LANDSLIDE BEHAVIOUR

The most general movement of the soil after a landslide looks like the movement of a mosaic of blocks. The dynamic

of each one can be fully described by: two rotations: the first, around a horizontal axis (inclination), and the second around a vertical axis (horizontal rotation), and two translations: the first is horizontal and the second is vertical.

The horizontal translations and rotations don't affect the altitudes. They, therefore, can't be predicted by leveling. In contrast, any inclination of the block modifies the relative altitudes of its points. So it can be detected by relative leveling interior to the block carried out before and after the movement.

It is clear that if one knows the inclination of a block and the variation in altitude of at least one of its points, it is possible to determine the variation in altitude of all its points so as the variation of the its mean altitude.

### III. BASIC CONCEPT OF TOPOMETRIC VERTICAL

Leveling is a process by which the geometric height difference along the vertical is transferred from a reference station to a forward station. Suppose a leveling line connects two stations $A$ and $B$. If the two stations are far enough apart, the leveling section will contain several turning points, the vertical geometric separation between which we denote as $\delta v_i$. Any two turning points are at two particular geopotential numbers, the difference of which is the potential gravity energy available to move water between them; hydraulic head. We also consider the vertical geometric separation of those two equipotential surfaces along the plumb line for $B$, $\delta H_{B,i}$.

We will now argue that differential leveling does not, in general, produce orthometric heights. Fig 1 depicts two stations $A$ and $B$, indicated by open circles, with geopotential numbers $C_A$ and $C_B$, and at orthometric heights $H_A$ and $H_B$, respectively.
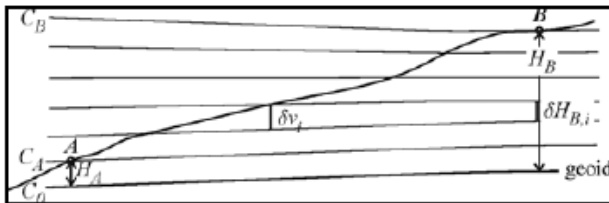


Fig. 1 A comparison of differential leveling height differences δvi with orthometric height differences δHBi.. The height determined by leveling is the sum of the δvi whereas the orthometric height is the sum of the δHB,i. These two are not the same due to the non-parallelism of the equipotential surfaces whose geopotential numbers are denoted by C.

The geopotential surfaces, shown in cross section as lines, are not parallel; they converge towards the right. Therefore, it follows that $\delta v_i \neq \delta H_{B,i}$. The height difference from $A$ to $B$ as determined by differential leveling is the sum of the $\delta v_i$. Therefore, because $\delta v_i \neq \delta H_{B,i}$ and the orthometric height at $B$ can be written as $H_B = \Sigma \delta H_{B,i}$, It follows that $\Sigma \delta v_i \neq H_B$.

We now formalize the difference between differential leveling and orthometric heights so as to clarify the role of gravity in heighting. In the bubble [2], we argued that the force moving the bubble was the result of a change in water pressure over a finite change in depth. By analogy, we claimed that gravity force is the result of a change in gravity potential over a finite separation:

$$g = -\frac{\delta W}{\delta H} \qquad (1)$$

where $g$ is gravity force, $W$ is geopotential and $H$ is orthometric height.

Simple calculus allows rearranging to give $-\delta W = g\ \delta H$. Recall that $\delta v_i$ and $\delta H_{B,i}$ are, by construction, across the same potential difference so $-\delta W = g\ _{\delta vi} = g'\ \delta H_{B,i}$ where $g'$ is gravity force at the plumb line. Now, $\delta v_i \neq \delta H_{B,i}$ due to the non-parallelism of the equipotential surfaces but $\delta W$ is the same for both, so gravity must be different on the surface where the leveling took place than at the plumb line. This leads us to:

$$\delta H_{B,i} = -\frac{g}{g'}\delta v \qquad (2)$$

*which* indicates that differential leveling height differences differ from orthometric height differences by the amount that surface gravity differs from gravity along the plumb line at that geopotential. An immediate consequence of this is that two different leveling lines starting and ending at the same station will, in general, provide different values for the height of final station. This is because the two lines will run through different topography and, consequently, geopotential surfaces with disparate separations. Uncorrected differential leveling heights are not single valued; meaning the result you get depends on the route you took to get there.

#### A. Orthometric heights

They are the natural 'heights above sea level,' that is, heights above the geoid. They thus have an unequalled geometrical and physical significance." National Geodetic Survey (1986) defines orthometric height as, "The distance between the geoid and a point measured along the plumb line and taken positive upward from the geoid", with plumb line defined as, "A line perpendicular to all equipotential surfaces of the Earth's gravity field that intersect with it".

In one sense, orthometric heights are purely geometric: they are the length of a particular curve (a plumb line). However, that curve depends on gravity in two ways. First, the curve begins at the geoid. Second, plumb lines remain everywhere perpendicular to equipotential surfaces through which they pass, so the shape of the curve is determined by the orientation of the equipotential surfaces. Therefore, orthometric heights are closely related to gravity in addition to being a geometric quantity.

How are orthometric heights related to geopotential equation gives that $g = -\delta W/\delta H$.

Taking differentials instead of finite differences and rearranging them leads to $dW = -g\ dH$. Recall that geopotential numbers are the difference in potential between the geoid $W_0$ and a point of interest $A$, $W_A$: $C_A = W_0 - W_A$, so:

$$\int_{V_0}^{W_B} dW = -{}^H\!\int_0^A g\,dH$$

$$W_A - W_0 = -{}^H\!\int_0^A g\,dH$$

$$W_0 - W_A = {}^H\!\int_0^A g\,dH$$

$$C_A = {}^H\!\int_0^A g\,dH$$

in which it is understood that $g$ is not a constant. The last equation can be used to derive the desired relationship:

$$C_A = \overline{g}H_A \qquad (3)$$

meaning that a geopotential number is equal to an orthometric height multiplied by the average acceleration of gravity along the plumb line. It was argued in the second paper that geopotential is single valued, meaning the potential of any particular place is independent of the path taken to arrive there.

Therefore, two points of equal orthometric height need not have the same gravity potential energy, meaning that they need not be on the same equipotential surface and, therefore, not at the same height from the perspective of geopotential numbers.

How are orthometric heights measured? Suppose an observed sequence of geometric height differences $\delta v_i$ has been summed together for the total change in geometric height along a section from station $A$ to $B$, $\Delta v_{AB} = \Sigma \delta vi$. Denote the change in orthometric height from $A$ to $B$ as $\Delta H_{AB}$.

Equation (3) requires knowing a geopotential number and the average acceleration of gravity along the plumb line but neither of these are measurable. Fortunately, there is a relationship between leveling differences $\Delta v$ and orthometric height differences $\Delta H$. A change in orthometric height equals a change in geometric height plus a correction factor known as the orthometric correction:

$$\Delta H_{AB} = \Delta v_{AB} + OC_{AB} \qquad (4)$$

where $OC_{AB}$ is the orthometric correction and has the form of:

$$OC_{AB} = \sum_A^B \left( \frac{g_i - \gamma_0}{\gamma_0} \delta v_i + \frac{\overline{g}_A - \gamma_0}{\gamma_0} H_A + \frac{\overline{g}_B - \gamma_0}{\gamma_0} H_B \right) \qquad (5)$$

where $g_i$ is the observed force of gravity at the observation stations, $\overline{g}_A, \overline{g}_B$ are the average values of gravity along the plumb lines at $A$ and $B$, respectively, and $\gamma_0$ is an arbitrary constant, which is often taken to be the value of normal gravity at 45º latitude.

Leveling is the procedure used when one is determining differences in elevation (vertical measurements) between points that are remote from each other.

Summing the relative height differences along a leveling line yields the elevation of those Bench Marks (BMs) with respect to the height of the first one. Repeated measurements of height enables measurement of deformation of the Earth's surface with time. Such deformation can occur gradually, such as by land subsidence due to groundwater or oil withdrawal, or by sudden geologic events such as earthquakes or landslides. The direction and tilt of the vertical deformation caused by an earthquake or any other natural or manmade event could be deduced from the elevation of points measured before and after the event.
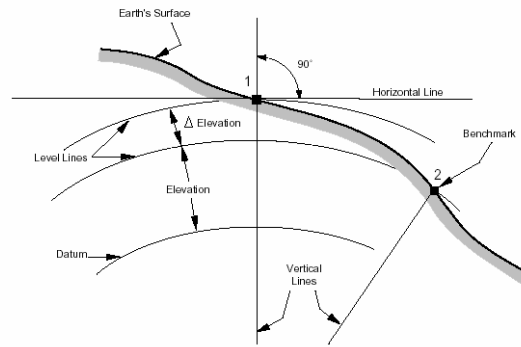


Fig. 2 Basic concept of topometric vertical control

Vertical measurements are made and referenced to datum, as elevations. The reference datum might be an arbitrary elevation chosen for convenience or a very precise value determined after lengthy studies.

The earth is an ellipsoid, not a sphere, flattened slightly at the poles and bulging somewhat at the equator. Datums are reference surfaces that consider the curvature of the earth for the mathematical reduction of geodetic and cartographic data.

1) The geoid: It is the equipotential surface within or around the earth where the plumb line is perpendicular to each point on the surface. The geoid is considered a MSL surface that is extended continuously through the continents. The geoidal surface is irregular due to mass excesses and deficiencies within the earth. The figure of the earth is considered as a sea level surface that extends continuously through the continents. The geoid (which is obtained from observed deflections of the vertical) is the reference surface for astronomical observations and geodetic leveling. The geoidal surface is the reference system for orthometric heights.

2) The ellipsoid: It is not referenced to a single datum point. It represents an mathematical ellipsoidal surface whose placement, orientation, and dimensions "best fit" the earth's equipotential surface that coincides with the geoid. The system was developed from a worldwide distribution of terrestrial gravity measurements and geodetic satellite observations. Several different ellipsoids have been used in conjunction with the World Geodetic System (WGS) ellipsoid. Several ellipsoids are used in the world for mapping purposes. The goal is to eventually refer all positions to the WGS, which has a specific set of defining

parameters, or to a WGS-compatible ellipsoid. Ellipsoids may be defined by a combination of algebraically related dimensions such as the semi-major and semi-minor axes or the semi-major axis and the flattening.

### B. Ellipsoid heights

They are the straight-line distances normal to a reference ellipsoid produced away from (or into) the ellipsoid to the point of interest. Before GPS it was practically impossible for anyone outside the geodetic community to determine an ellipsoid height. Now, GPS receivers produce three-dimensional baselines resulting in determinations of geodetic latitude, longitude, and ellipsoid height. As a result, ellipsoid heights are now commonplace.

Ellipsoid heights are almost never suitable surrogates for orthometric heights [1] because equipotential ellipsoids are not, in general, suitable surrogates for the geoid.

Confusing an ellipsoid height with an orthometric height could not result in a blunder less than two meters but would typically be far worse, even disastrous.

Ellipsoid heights have no relationship to gravity; they are purely geometric. It is remarkable, then, that ellipsoid heights have a simple (approximate) relationship to orthometric heights, namely:

$$H \approx H - N \tag{6}$$

where $H$ is orthometric height, h is ellipsoid height, and $N$ is the ellipsoid height of the geoid itself, a geoid height or geoid undulation.

This relationship is not exact because it ignores the deflection of the vertical. Nevertheless, it is close enough for most practical purposes.

According to (6), ellipsoid heights can be used to determine orthometric heights if the geoid height is known. Geoid models are used to estimate $N$.

### C. Geopotential numbers C

The geopotential number for any place is the potential of the geoid $W_0$ minus the potential of that place $W$ (recall the potential decreases with distance away from the Earth, so this difference is a positive number). Geopotential numbers are given in geopotential units (g.p.u.), where 1 g.p.u. = 1 kgal-meter = 1000 gal meter. If gravity is assumed to be a constant 0.98 kgal, a geopotential number is approximately equal to 0.98 H, so geopotential numbers in g.p.u. are nearly equal to orthometric heights in meters. However, geopotential numbers have units of energy, not length, and are therefore an "unnatural" measure of height [3].

It is possible to scale geopotential numbers by dividing by a gravity value, which will change their units from kgal-meter to meter. Doing so results in a dynamic height:

$$H^{dyn} = C / \gamma_0 \tag{7}$$

One reasonable choice for $\gamma_0$ is the value of normal gravity at some latitude, conventionally taken to be 45 degrees. Obviously, scaling geopotential numbers by a constant does

not change their fundamental properties, so dynamic heights, like geopotential numbers, are single valued, produce equipotential surfaces, and form closed leveling circuits. They are not, however, geometric like an orthometric height: two different places on the same equipotential surface have the same dynamic height but generally do not have the same orthometric height.

Thus, dynamics heights are not "distances from the geoid."

Measuring dynamic heights is accomplished in a manner similar to that for orthometric heights: geometric height differences observed by differential leveling are added to a correction term that accounts for gravity thus:

$$\Delta H_{AB}^{dyn} = \Delta v_{AB} + DC_{AB} \tag{8}$$

where $\Delta v_{AB}$ is the total measured geometric height difference derived by differential leveling and $DC_{AB}$ is the dynamic correction.

The dynamic correction $DC_{AB}$ from station $A$ to $B$ is given by:

$$DC_{AB} = \sum_A^B \frac{g_i - \gamma_0}{\gamma_0} \delta v_i \tag{9}$$

where $g_i$ is the (variable) force of gravity at each leveling observation station, $\gamma_0 = \gamma\ (45°)$ and the $\delta v_i$ are the observed changes in geometric height along each section of the leveling line.

### D. Normal Heights

Like orthometric and dynamic heights, normal heights can be determined from geometrical height differences observed by differential leveling and applying a correction. The correction term $NC_{AB}$ has the same structure as that for orthometric correction, namely [23]:

$$NC_{AB} = \sum_A^B (\frac{g_i - \gamma_0}{\gamma_0} \delta v_i + \frac{\overline{\gamma_A} - \gamma_0}{\gamma_0} H_A^* + \frac{\overline{\gamma_B} - \gamma_0}{\gamma_0} H_B^*) \tag{10}$$

with $\overline{\gamma}$ being the average normal gravity from $A$ to $B$

Normal corrections also depend upon gravity observations $g_i$ but do not require assumptions regarding average gravity within the Earth. Therefore, they are rigorous; all the necessarily quantities can be calculated or directly observed. Like orthometric heights, they do not form equipotential surfaces (because of normal gravity's dependence on latitude; recall that dynamic heights scale geopotential simply by a constant, whereas orthometric and normal heights' scale factors vary with location). Like orthometric heights, normal heights are single valued and give rise to closed leveling circuits.

### E. Earth Curvature

Due to the curvature of the Earth, the line of sight at the instrument will deviate from a horizontal line as one moves away from the level
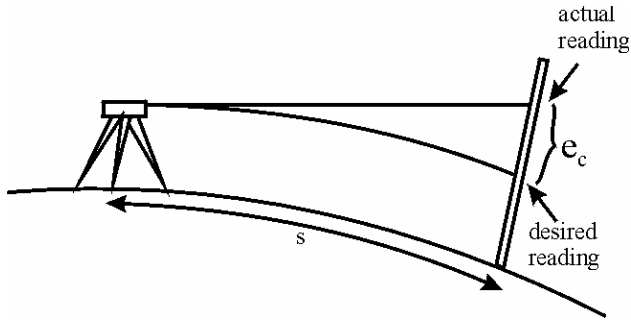
Fig. 3 Earth curvature effect: $s$ is the sight length and $R$ is the radius of curvature of the Earth considered as a sphere, $e_c$ is the error in rod reading due to the Earth curvature.

Ideally one would like the line of sight to be a curved line which is everywhere perpendicular to the direction of gravity. The error in staff reading due to Earth curvature is given by

$$e_c = \frac{s^2}{2R} \qquad (11)$$

where $s$ is the sight length and $R$ is the radius of curvature of the Earth. For a sight length of 100m the effect is only 1mm.

If the sight lengths are not equal with small difference $ds$, the resulting error is

$$de_c = \frac{s.ds}{R} \qquad (12)$$

If $s=100$m, $ds=3$m the value of $de_c$ is 1/20m

The propagation of this error over 20km of leveling gives a resulting error of 5mm. Its therefore far from negligible.

### F. Earth Curvature Variation

In the vertical plane sight the curvature of the level line is not constant because of the variation of Earth's curvature along the line of sight. Let R be the radius of the curvature of the meridian passing through the ground A (where the level is setup), R' be the radius of the curvature of the meridian passing through A' (at the rod) and η be the error due the variation of the curvature of the Earth along the line of sight (Fig. 4). The error η can be expressed by :

$$\left| \eta \right|_c \prec \frac{l^2}{2} \left| \delta\left(\frac{1}{R}\right) \right| = \frac{l^2}{2} \left| \left(\frac{1}{R'} - \frac{1}{R}\right) \right| \qquad (13)$$

The error $\eta$ is maximal in absolute value when the backsight and the foresight are both oriented parallel to the local meridian.
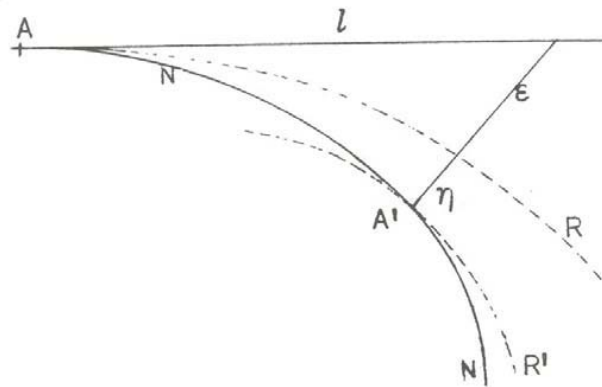


Fig. 4 Effect of Earth's curvature variation : $R$ is the radius of the local meridian passing through point A (where the level is setup), $R'$ is the radius of the local meridian passing through $A'$ (at the rod) and $\eta$ is the error due the variation of the curvature of the Earth along the line of sight

Taking the dimensions of the ellipsoid *Hayford* (semi-major axis $a=6378.38$ km, semi-minor axis $b=6356.909$km) and sight distances of 100m each, the error $\eta$ is limited by:

$$\left| \eta \right|_c \prec \frac{l^2}{2} \left| \delta\left(\frac{1}{R}\right) \right| = \frac{l^2}{2} \left| \left(\frac{1}{R'} - \frac{1}{R}\right) \right| = \frac{100^2}{2} \left| \left(\frac{6.4x10^4}{\left(6.4x10^4\right)^2}\right) \right| \prec \frac{1}{100} mm$$

### G. Atmospheric Refraction

A simplified version of the model is used to compute corrections to observed elevation differences of a section to minimize the effect of refraction:

$$R = -10^{-5} \gamma \left(\frac{s}{100n}\right)^2 \quad \delta dW \qquad (14)$$

where*:*
$R$ = refraction correction in millimeters for the section,
$\gamma = 70$
$s$ = section length in meters,
$n$ = number of setups,
$\delta$ = "predicted" temperature difference in degrees Celsius between temperatures at 2.5 m and 0.5 m above the ground (upper temperature minus lower temperature),
$d$ = difference of elevation for the section in units of half-cm, and
$W$ = weather factor (based on the recorded "sun code"). The weather factor W is as follows: 0.5 for 100 percent cloudy sky, 1 for 50 percent sunny sky, 1.5 for 100 percent sunny sky.
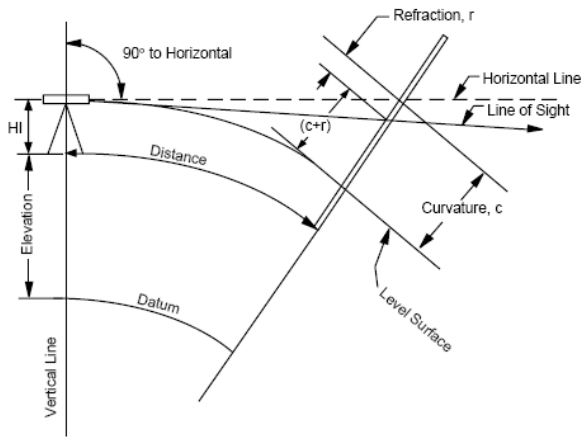
Fig. 5 Earth curvature and atmospheric refraction

## IV. THE CHARACTERISTIC STRAIGHT LINE METHOD

The method of the characteristic straight line is very easy to use. It improves the accuracy of the topometric vertical control in landslide monitoring. It can be described as follows:

Consider two points $A$ and $B$ of the rigid block. One assumes that the inclination of the rigid block is happened around a horizon axes passing through $A$. The bearing of the blocks inclination is $\theta_0$.

The difference in altitude between the two ground points $A$ and $B$ is as follows:

$$h = H_B - H_A \qquad (15)$$

Where $H_A$ is the altitude of point A and $H_B$ is the altitude of point B

By differentiation:

$$dh = S\, dI \leftrightarrow \frac{dh}{S} = dI \qquad (16)$$

*Where S is the horizontal distance AB, I is the inclination of the direction AB counted positive if B is above A, negative otherwise.*

So, the ratio $\dfrac{dh}{S}$ is the variation of the inclination of the direction $AB$ during the block movement.

The *dh* values can be obtained from leveling carried out before and after the Landslide.

On a convenient diagram, considered to be placed on a horizontal plane, one considers a point $O$, and a straight line $ON$ indicating the north direction. To each couple of ground points *(A,B),* one corresponds a point *(A,B)* of the diagram situated on a straight line oriented from $O$ to *(A,B)* which bearing is $\theta$ (Fig. 6) at a distance from $O$ equals in sign and magnitude the quantity $\dfrac{-S}{dh}$ .
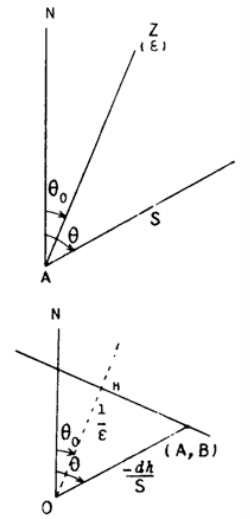


Fig. 6 The Characteristic Straight Line Method. The inclination of the block after the event is given by the inverse of the distance OH. The direction of the inclination $\theta_0$ is the bearing of the normal from $O$ to the Characteristic Straight Line.

On the diagram, previously defined, one considers the straight line oriented $OZ$ (Fig. 6) which bearing is $\theta_0$. In addition one considers H as the normal projection of the point *(A,B)* on this straight line.

So, in sign and magnitude we have:

$$OH = O(A,B)\cos(\theta - \theta_0) = \frac{-S}{dh}\cos(\theta - \theta_0) \qquad (17)$$

$$OH = +\frac{1}{\varepsilon} \qquad (18)$$

So, the point $H$ is the same for any couple of points *(A,B)* of the rigid block.

In this way, all the points *(A,B)* on the diagram related to a same rigid block are aligned on the same straight line which we call the "*Characteristic Straight Line*" which could be constructed easily by using the quantities $S$ and $\theta$ which one can obtain from a convenient map, and the altitude variation *dh* after the landslide's occurrence. This latest quantity is obtained by comparing the initial and the final vertical topometric observations.

The "*Characteristic Straight Line method*" seems to be more easy to use than the "*Characteristic Sinusoid Method*", but like it, this method provides immediately the characteristic parameters of the landslide dynamic: the direction and the tilt for each one the rigid blocks.

The dynamic of a rigid block is fully determined by using three ground points at least (non-aligned). The magnitude of the inclination $\varepsilon$ equals the inverse of the distance $OH$, while the direction of the tilt is given by the bearing of the direction defined by $OH$.

## V. PRACTICAL VALIDATION OF THE PROPOSED METHOD

The method proposed here was tested by studying the landslide dynamic in an area located along the Amman- Jarash highway (Fig. 7). The highway traverses an area of diverse geologic materials between Amman and Jarash. The rock units in the area have their characteristic weaknesses to weathering and erosion, ranging from chemical breakdown of some minerals in granite rocks to weak shear zones that lead to instability of mountain-scale masses of rock. The types and abundance of landslides can be related to these characteristic weaknesses in the geologic units. The area has been the site of recurrent landslides and soil movement for more than 11 years. More exactly after the construction of Amman-Jarash highway.

The deteriorating effects of landslides are well known. They usually cause soil damage and road blockage, resulting in major repair and maintenance costs. Economic losses can be significant to an entire region if a main route is closed for an extended period. Besides the costs associated with landslide damage, some types of landslides pose a risk to the safety of
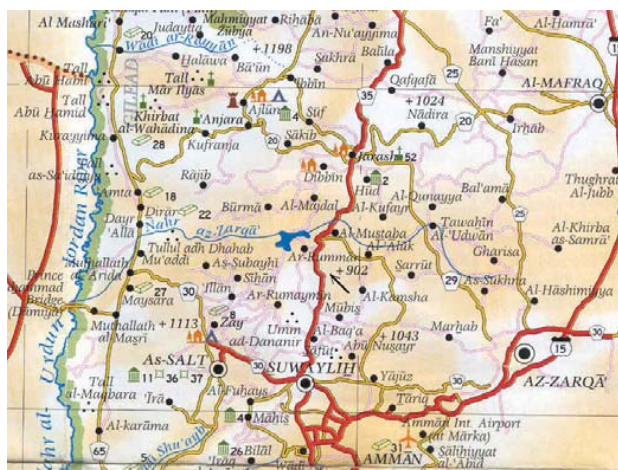

Fig. 7 The site of study (the arrow)

the traveling public. None of these risks can be eliminated. If roads are to pass through regions where landslides are common, the highway will be exposed to the risk of slide damage. The consequences of landslide movement are related to the size and location of a landslide, and the amount and velocity of soil movement. Larger slides may displace part of a roadway, resulting in greater repair costs. Larger displacements also translate to greater repair costs. If large movements accumulate slowly, over years or decades, they may be a continuing maintenance problem where cracks are filled and the pavement re-leveled frequently. Large, rapid displacements of even small volumes of material may undermine the road or deposit material on the road sufficient to close (or partially close) the roadway.

These smaller rapidly moving volume, slides are the most likely to pose a safety risk to the traveling public. Large and deep landslides are less likely to move rapidly or have significant displacement in any one episode of movement, but the rare rapid, large displacement of large landslides can have

particularly severe consequences. Significant displacements of large and deep landslides may result in the roadway being closed for repair or, in the worst case, closed for long periods for reconstruction or rerouting. For the reasons mentioned above, it is primordial to study thoroughly this event and to determine with great precision their nature, types, sizes and the magnitudes of their displacements

In order to study the soil movement in the area of study, all the rigid blocks (rocks) have been equipped with sufficient number of well defined ground points (at least 10 points per block). Complete leveling of the region occurred each summer and winter from 1997 to January 2008. The leveling surveys have been run to standards equal to those required for first-order, class 1 as set out by USA-based Federal Geodetic Control Committee (FGCC). The standard error for each elevation difference can be taken to be 0.5 mm. Leveling observations were corrected for rod scale and temperature, level collimation, and for atmospheric refraction and magnetic effects. Leveling surveys were not referenced to the national datum because we were only interested in monitoring relative elevation changes within the landslide region.

The "characteristic straight line method" has been used for each one of the rigid blocks by reporting on a diagram the points $(A,B)$ defined by the values $\frac{-S}{dh}$ and the bearings $\theta$ previously defined.

Table I illustrates the soil deformation in the area of study during the investigation's period from 1997 to January 2008. Looking through the values shown in Table 1, it is possible to estimate the dynamic of the landslide. The major part of l the blocks are moving slightly in the same direction. Some blocks show more dynamic in the movement than others depending on their mass and on the neighboring trough. For certain blocks, the height changes were not big enough; it can be concluded that the proposed "*Characteristic Straight Line Method*" gives the same results as the "*Characteristic Circle Method*". Both they could improve the accuracy of the precise vertical topometric control. It is clear that precise leveling based-on this method could be used for the study of the landslide dynamic of very small magnitude even when other means are insufficient for these purposes.

TABLE I
VALUES OF THE MAGNITUDE AND DIRECTION OF THE TILT OF EACH RIGID BLOCK. THIS ILLUSTRATES THE LANDSLIDE DYNAMIC IN THE REGION OF ALJUAIDIEH (AMMAN-JARASH HIGHWAY) WITHIN THE PERIOD FEBRUARY 1997 – JANUARY 2008

| Bloc number | Bearing of the direction of tilt (in degrees) | Tilt magnitude (in degrees) |
|---|---|---|
| 24 | 130° 30′ 55″ | 01° 12′ 34″ |
| 25 | 132° 54′ 52″ | 02° 31′ 00″ |
| 34 | 143° 10′ 12″ | 02° 01′ 32″ |
| 35 | 179° 35′ 16″ | 01° 52′ 21″ |
| 36 | 176° 22′ 45″ | 03° 21′ 43″ |
| 44 | 115° 55′ 14″ | 04° 50′ 52″ |
| 45 | 170° 44′ 47″ | 01° 40′ 41″ |
| 46 | 173° 14′ 23″ | 00° 53′ 23″ |
| 47 | 155° 00′ 51″ | 00° 31′ 21″ |
| 54 | 156° 37′ 54″ | 01° 11′ 55″ |
| 55 | 160° 11′ 01″ | 01° 50′ 12″ |
| 56 | 158° 36′ 11″ | 02° 32′ 16″ |
| 57 | 215° 26′ 56″ | 01° 00′ 02″ |

Table II illustrates the soil deformation in the area of study during the investigation's period from 1997 to January 2008 using the "best estimate" of the geodetic leveling observations Looking through the values shown in Table 2, we notice a better estimate of the landslide dynamic.

TABLE II

VALUES OF THE MAGNITUDE AND DIRECTION OF THE TILT OF EACH RIGID BLOCK. THIS ILLUSTRATES THE LANDSLIDE DYNAMIC IN THE REGION OF ALJUAIDIEH (AMMAN-JARASH HIGHWAY) WITHIN THE PERIOD FEBRUARY 1997 – JANUARY 2008 WHEN USING THE "BEST ESTIMATE" OF THE GEODETIC LEVELING OBSERVATIONS

| Bloc number | Bearing of the direction of tilt (in degrees) | Tilt magnitude (in degrees) |
|---|---|---|
| 24 | 130° 30′ 56.4″ | 01° 12′ 35.4″ |
| 25 | 132° 54′ 52.3″ | 02° 31′ 00.6″ |
| 34 | 143° 10′ 17.6″ | 02° 01′ 32.8″ |
| 35 | 179° 35′ 18.5″ | 01° 52′ 21.8″ |
| 36 | 176° 22′ 42.8″ | 03° 21′ 43.2″ |
| 44 | 115° 55′ 11.8″ | 04° 50′ 52.5″ |
| 45 | 170° 44′ 42.4″ | 01° 40′ 41.2″ |
| 46 | 173° 14′ 23.9″ | 00° 53′ 23.9″ |
| 47 | 155° 00′ 55.3″ | 00° 31′ 21.4″ |
| 54 | 156° 37′ 53.4″ | 01° 11′ 55.2″ |
| 55 | 160° 11′ 00.0″ | 01° 50′ 12.8″ |
| 56 | 158° 36′ 13.3″ | 02° 32′ 16.3″ |
| 57 | 215° 26′ 56.4″ | 01° 00′ 02.6″ |

Fig. 8 shows the dynamic of the landslide in the area of study during the investigation period. By using topometric measurements elaborated before and after the events, and using field measurement of the bearings of the used ground points, a characteristic straight line has been constructed for each one of the moving blocks. The constructed diagram provides the blocks dynamics parameters: magnitude and orientation. From results illustrated in Fig. 8 one can easily notice that very small soil movement could be precisely determined by using very simple techniques such as the geodetic precise leveling.

## VI. CONCLUSION

The most general movement of the soil after a landslide looks like the movement of a mosaic of blocks. The dynamic of each one can be fully described by: two rotations: the first, around a horizontal axis (inclination), and the second around a vertical axis (horizontal rotation), and two translations: the first is horizontal and the second is vertical. The horizontal translations and rotations don't affect the altitudes. They, therefore, can't be predicted by leveling. In contrast, any inclination of the block modifies the relative altitudes of its points. So it can be detected by relative leveling interior to the block carried out before and after the movement. It is clear that if one knows the inclination of a block and the variation in altitude of at least one of its points, it is possible to determine the variation in altitude of all its points so as the variation of the its mean altitude. The *"Characteristic Straight Line Method"*, developed here, can be considered as an innovation of the precise topometric monitoring in the field of landslide dynamics study.

In order to optimize the "Characteristic Straight Line Method" , a "best estimate" of the geodetic leveling observations has been achieved by taking in account the concept of 'Height systems" and by minimizing systematic errors.

"Height systems" concept has been discussed in detail and consequently the concept of "height"
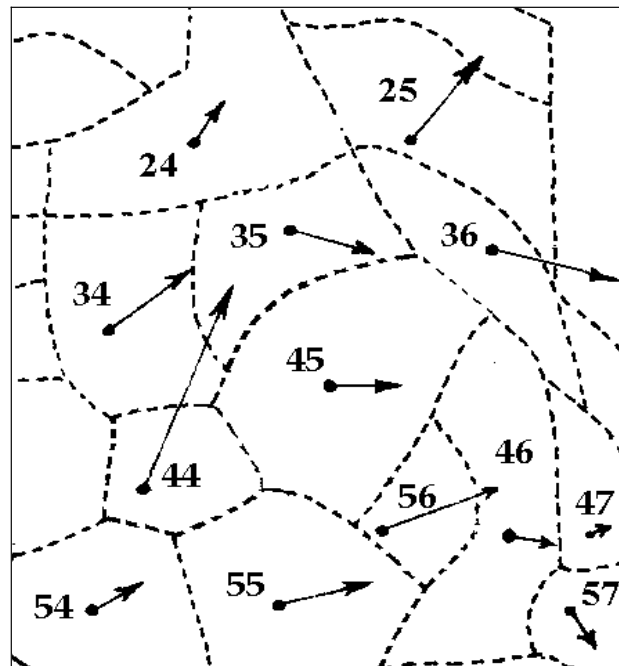


Fig. 8 Terrain deformation. Magnitude and direction of the tilt of the rigid blocs forming the moving terrain. Scale factor of the tilt magnitude is: 1cm = 1°. The planimetric scale factor is 1cm: 50m. The Directions of tilts are calculated with respect to the north direction (Table I)

The "Characteristic Circle Method" could give the topometry a considerable extent to become a monitoring tool of very high accuracy. It permits the exploration and the accuracy improvement of these techniques. It permits to evaluate a soil deformation of very small magnitude even when the dynamic is of an infinitesimal quantity. The results of a test using a very interesting area where an important landslide land occurs show the advantages of the proposed method in terrain deformation control and monitoring. The results obtained here are very close to these obtained by using the "Characteristic Circle Method" knowing that this method is more easy to use and the "Characteristic Straight Line Method" permits to construct the diagram without any difficulties.

## REFERENCES

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