# Calculation of Slope Terrain Movement Rate from Tree Trunk Deformation

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**Abstract** Movement of terrain on slopes, unless intense, as in the case of landslides, is practically imperceptible and the deformed trunks of trees growing on slopes are detectors of these movements. The deformation of a tree trunk may therefore be considered as a continuous record of terrain movement for the period of tree vegetation life. The cause of trunk deformation is a slight change in the inclination of the terrain on slope that accompanies terrain movement, and to which the tree trunk adapts during its time growth development. Submitted article presents a proposal for a method that, based on the time dependence of the development of the curvature of a tree trunk, allows a calculation of the path length and rate of the slope terrain movement for either the whole or a particular time period respectively. The calculation of the path length of the terrain movement assumes that the horizontal position of the center of gravity of the tree trunk remains unchanged in time and space, and the horizontal component of the terrain movement path is given by the horizontal distance of the center of gravity of the tree trunk from the heel of the trunk. The rate of movement is calculated from the terrain movement path length and age of the tree, which is determined from the diameter of the trunk. The position of the trunk's center of gravity is calculated from the digitized shape of the trunk according to the principles of solid body mechanics.

**Keywords** slope, terrain, movement, rate, deformation, tree trunk

## 1 Introduction

Terrain movement is a phenomenon seen commonly on the Earth's surface. The innate incentive of terrain movement is gravity boosted by hydrodynamic forces of groundwater flowing through the terrain. In addition to these factors, movement is influenced by geomorphology, terrain slope, terrain profile and vegetation (Clague and Stead 2012). Human activity can contribute to terrain movement too and it can it initiate or make it more intensive. The terrain movement intensity in general can vary widely, ranging from barely noticeable creep to significant ground shifts like landslides. Terrain movement classifications are assessed through various methodologies (Selley et al., 2005; Rollins and Zekkos, 2012) and some are based on a rate of terrain movement. Unlike subjective descriptive verbal methods of assessing terrain movement, the rate of terrain movement is an objective parameter whose value can be precisely determined by appropriate measurements.

The rater of movement is generally given by the ratio of the length of the path of movement and the time duration of the movement. Both parameters can be determined by measurement. In the case of terrain movement, the length of the path of terrain movement can be determined geodetically by measuring the change in the position of a point located on the surface of the terrain, possibly by monitoring the movement of the ground using vertical inclinometers, or most recently by extraterrestrial methods from satellites (Scaioni 2016).

These direct measurements of terrain movement are not well suited for detecting and recording low-intensity terrain movement during long periods of time, taking several decades.

The presented article gives an unconventional original method for determining the rate of terrain movement from a tree trunk shape. The shape of a tree trunk is considered to be specific record of the development of terrain movement at the site of tree growth. From this record it can be derived for certain assumptions the rate of terrain movement.

## 2 Formation of tree trunk shape

Formation of tree trunk shape is associated with the kinematics of the terrain movement, in the area within the tree's root network reach. The tree trunk shape is a response to terrain movement if this terrain movement results into a change of terrain slope. Consequently, the trunk tilts and the upper part of tree turns back into vertical position in next tree's subsequent growth development (see Fig. 1).

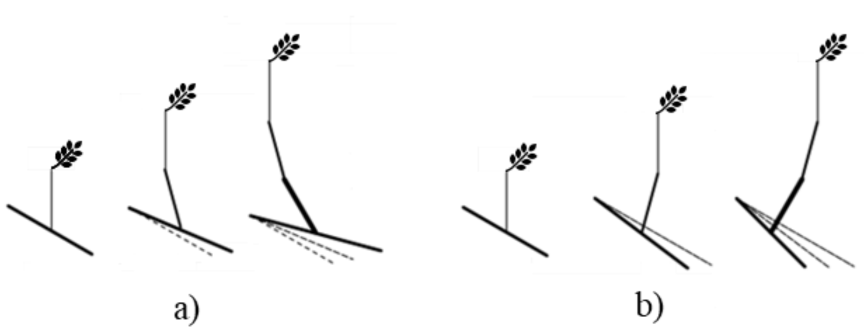


Figure 1: Formation of tree trunk deformation as a consequence of change of terrain inclination.

The change terrain slope arises from the terrain displacements that are could be described by vectors $u_A$ and $u_B$ at points A and B. The points are positioned at periphery of the root network on an intersection terrain and plane going through the trunk axis. The orientation of the plane should follow terrain slope gradient. The highest values of vectors $u_A$ and $u_B$ of terrain displacements and also the greatest tree trunk shape are expected in this direction (see Fig. 2).

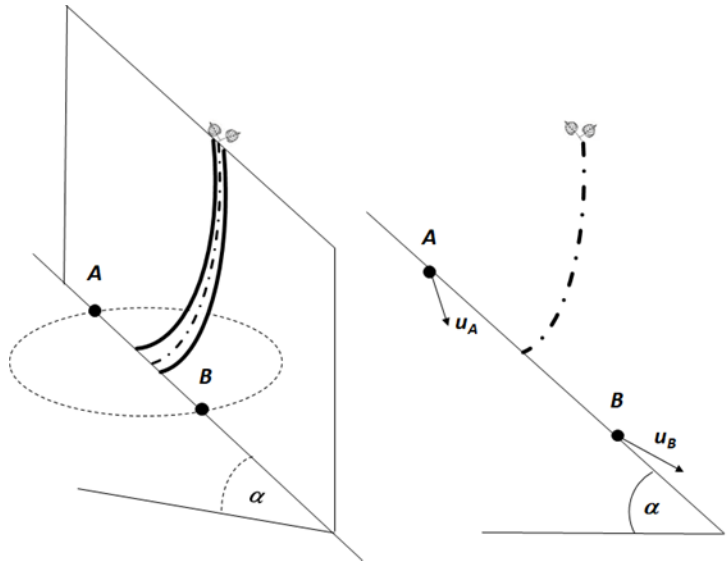


Figure 2: Kinematics of a root net movement.

If both vectors $u_A$ and $u_B$ are identical or parallel with the terrain, the slope doesn't change. In other cases the terrain slope undergoes alteration and either decreases or increases (see Fig. 3).

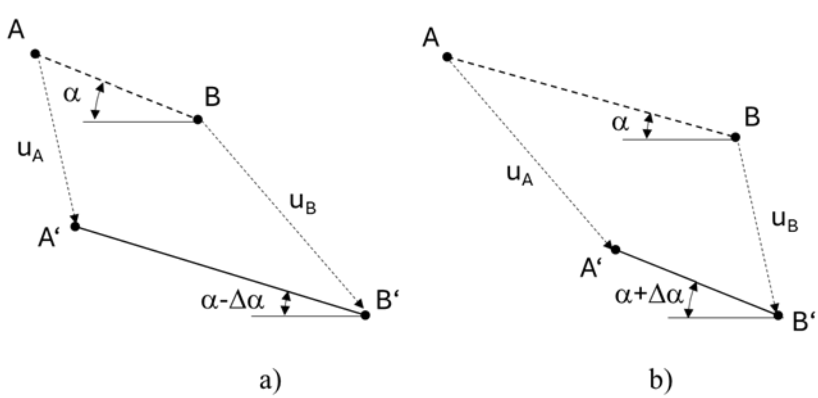


Figure 3: Vector diagrams of terrain movement.

The difference of the vectors $u_A$ and $u_B$ is a vector of terrain displacement ($l = u_A - u_B$) at section AB midpoint. Figure 4 shows both variations of terrain slope change and vector of terrain displacement (l). In situation a) terrain extends as inclination decreases and in b) terrain constricts as inclination increases.

## 3 Determination of terrain movement rate

The horizontal component of the vector $l_x$ is used to determine the terrain movement rate. The method assumes that the component $l_x$ is identical to the distance between the current gravity point (GP) of the tree trunk and midpoint between A and B. So $l_x$ is the horizontal terrain displacement.

The rate of terrain movement within a root terrain area *v* is given by

$$v = l_x/t, \tag{1}$$

where is *t* age of the tree and $l_x$ is given

$$l_x = u_{xA} - u_{xB}, \tag{2}$$

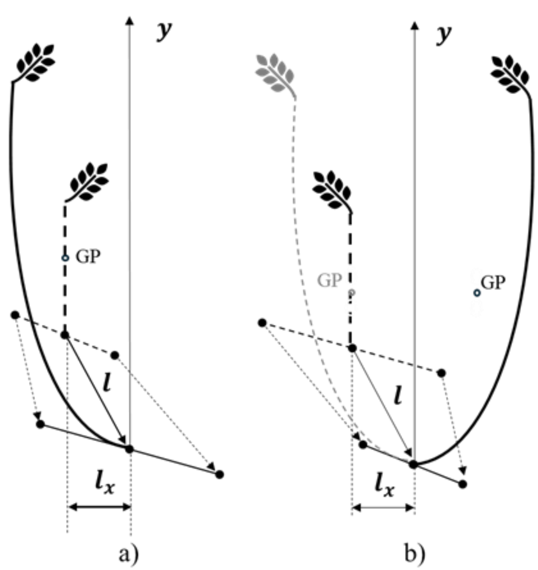


Figure 4: Vector diagrams of the movement of the base of the tree trunk.

The value of $l_x$ can be obtained from a static moment $M_y$ of the tree trunk (Fig. 5) given by formulae (3).

$$M_y = x_{\mathrm{GC}} \cdot W, \tag{3}$$

where $x_{\mathrm{GP}}$ is the x coordinate of the gravity point and $W$ the weight of tree trunk.

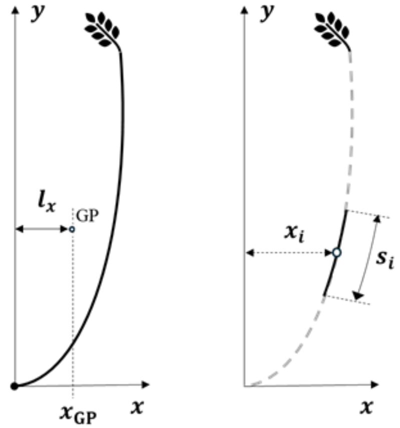


Figure 5: Scheme of a numerical calculation model of the position of tree trunk gravity point.

$$x_{\mathrm{GP}} = \frac{M_y}{W} = \frac{\sum M_{yi}}{\sum W_i} = \frac{\pi\gamma \sum s_i \frac{d_i^2}{4} x_i}{\pi\gamma \sum s_i \frac{d_i^2}{4}} = \frac{\sum s_i \frac{d_i^2}{4} x_i}{\sum s_i \frac{d_i^2}{4}}, \tag{4}$$

where $s_i$ is the length of a section of a tree trunk and $d_i$ is the diameter of section and $x_i$ is the length of a torque arm of $i$ section (see figure 5) and $\gamma$ is the tree trunk density that is truncated in relation (4).
The following example shows the application of the proposed method to determine the rate of terrain movement on the example of spruce.

## 4 Example

Figure 6. shows images of a scan of a spruce and figure 7 a digitalized spruce trunk.

Table 1 lists the coordinates of $x$, $y$ of the points on a trunk tree axis and corresponding trunk diameters $d$ read from the 2D image at these points. The 2D tree trunk axis is decomposed in sections characterized by geometrical parameters $d_i$ and $s_i$ implemented into the formulae (4) to calculate $M_{yi}$, $W_i$ with respective age (see Tab. 2). The age calculation of tree trunk is based on assumption that the annual increase in the diameter of the trunk of spruce growing in the Central Europe in a temperate climate zone at an altitude of 300 m above sea level is 0,0075 m.

The solution consists in a segmentation into calculation steps for separate age of tree growth and determination of the position of the gravity point $x_{\mathrm{GP}}^{*}$ for this age. Figure 8 shows the scheme of successive calculations of the positions of the gravity point $x_{\mathrm{GP}}^{*}$ of the tree trunk in the respective interval of tree growth.

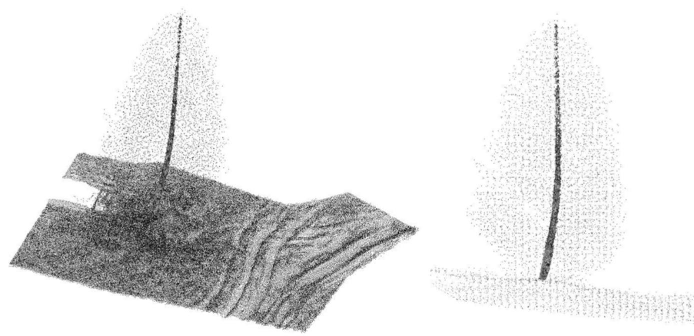

Figure 6: 3D scan of the spruce and a 2D projection to a plane with trunk greatest curvature.

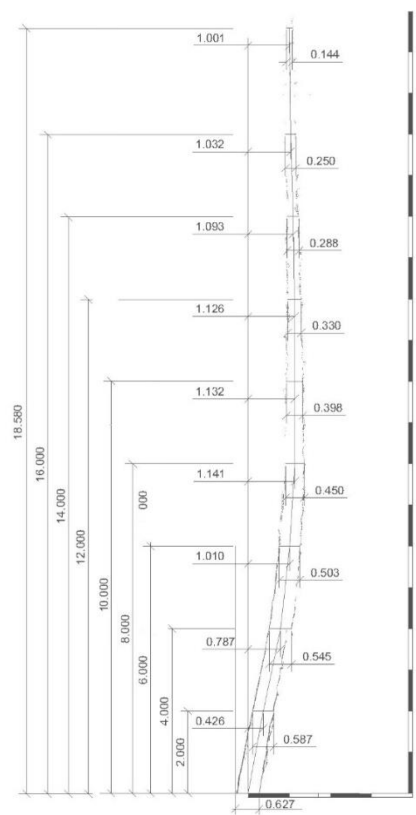


Figure 7: Digitization of the curve of the spruce trunk.

Table 1.

| $x$ [m] | $y$ [m] | $d$ [m] |
|---|---|---|
| 0 | 0 | 0,627 |
| 0,426 | 2 | 0,587 |
| 0,787 | 4 | 0,545 |
| 1,010 | 6 | 0,503 |
| 1,141 | 8 | 0,450 |
| 1,132 | 10 | 0,398 |
| 1,126 | 12 | 0,330 |
| 1,093 | 14 | 0,288 |
| 1,032 | 16 | 0,250 |
| 1,001 | 18,58 | 0,144 |

Table 2.

| $Age_i$ [years] | $d_i$ [m] | $s_i$ [m] |
|---|---|---|
| 80 | 0,607 | 2,045 |
| 75 | 0,566 | 2,032 |
| 69 | 0,524 | 2,012 |
| 63 | 0,477 | 2,004 |
| 56 | 0,424 | 2,000 |
| 48 | 0,364 | 2,000 |
| 41 | 0,309 | 2,000 |
| 35 | 0,269 | 2,001 |
| 26 | 0,197 | 2,580 |

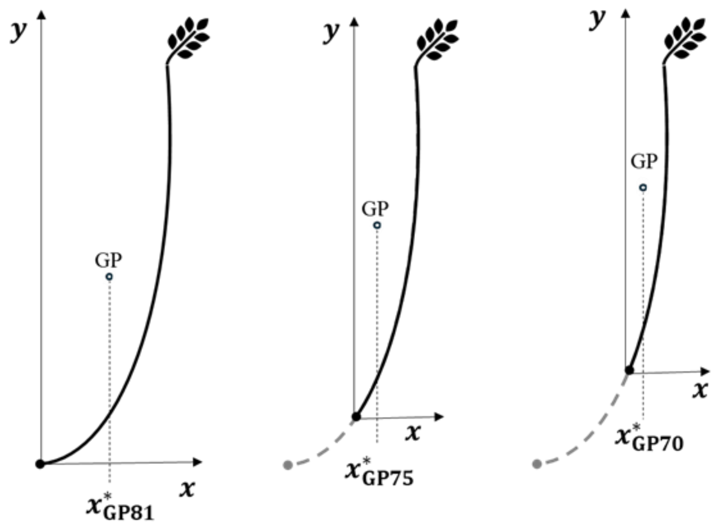


Figure 8: Segmentation distinct age intervals of tree.

Tables 3, 4 and 5 list values of $W_i$, $x_i$ and $M_{yi}$ to calculate coordinate of gravity point $x^*_{GP}$ for separate age of tree growth.

Table 3.

| $W$ [m³] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 80 | 75 | 69 | 63 | 56 | 48 | 41 | 35 | 26 |
| 0,5917 | | | | | | | | |
| 0,5113 | 0,5113 | | | | | | | |
| 0,4340 | 0,4340 | 0,4340 | | | | | | |
| 0,3574 | 0,3574 | 0,3574 | 0,3574 | | | | | |
| 0,2824 | 0,2824 | 0,2824 | 0,2824 | 0,2824 | | | | |
| 0,2081 | 0,2081 | 0,2081 | 0,2081 | 0,2081 | 0,2081 | | | |
| 0,1500 | 0,1500 | 0,1500 | 0,1500 | 0,1500 | 0,1500 | 0,1500 | | |
| 0,1137 | 0,1137 | 0,1137 | 0,1137 | 0,1137 | 0,1137 | 0,1137 | 0,1137 | |
| 0,0786 | 0,0786 | 0,0786 | 0,0786 | 0,0786 | 0,0786 | 0,0786 | 0,0786 | 0,0786 |

Table 4.

| $x_i$ [m] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 80 | 75 | 69 | 63 | 56 | 48 | 41 | 35 | 26 |
| 0,213 | | | | | | | | |
| 0,6065 | 0,181 | | | | | | | |
| 0,8985 | 0,473 | 0,112 | | | | | | |
| 1,0755 | 0,650 | 0,289 | 0,065 | | | | | |
| 1,1365 | 0,711 | 0,350 | 0,127 | 0,005 | | | | |
| 1,129 | 0,703 | 0,342 | 0,119 | 0,012 | 0,003 | | | |
| 1,1095 | 0,684 | 0,323 | 0,099 | 0,032 | 0,023 | 0,017 | | |
| 1,0625 | 0,637 | 0,276 | 0,053 | 0,079 | 0,069 | 0,063 | 0,031 | |
| 1,0165 | 0,591 | 0,230 | 0,006 | 0,125 | 0,116 | 0,110 | 0,077 | 0,016 |

Table 5.

| $M_{yi}$ [m$^4$] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 80 | 75 | 69 | 63 | 56 | 48 | 41 | 35 | 26 |
| 0,126 | | | | | | | | |
| 0,310 | 0,092 | | | | | | | |
| 0,390 | 0,205 | 0,048 | | | | | | |
| 0,384 | 0,232 | 0,103 | 0,023 | | | | | |
| 0,321 | 0,201 | 0,099 | 0,036 | 0,001 | | | | |
| 0,235 | 0,146 | 0,071 | 0,025 | 0,002 | 0,001 | | | |
| 0,166 | 0,103 | 0,048 | 0,015 | 0,005 | 0,003 | 0,002 | | |
| 0,121 | 0,072 | 0,031 | 0,006 | 0,009 | 0,008 | 0,007 | 0,003 | |
| 0,080 | 0,046 | 0,018 | 0,001 | 0,010 | 0,009 | 0,009 | 0,006 | 0,001 |

Table 6 lists the results of calculated positions of the gravity points $x^*_{\mathrm{GP}}$ and calculated average rate of the gravity point movement $v^*_{\mathrm{GP}}$ for the respective length of tree growth.

Table 6.

| Age [years] | 80 | 75 | 69 | 63 | 56 | 48 | 41 | 35 | 26 |
|---|---|---|---|---|---|---|---|---|---|
| $\sum W$ | 2,7274 | 2,1356 | 1,6243 | 1,1903 | 0,8329 | 0,5505 | 0,3424 | 0,1924 | 0,0786 |
| $\sum M_y$ | 2,1336 | 1,0978 | 0,4191 | 0,1053 | 0,0272 | 0,0210 | 0,0183 | 0,0095 | 0,0012 |
| $x^*_{\mathrm{GP\ Age}}$ | 0,7823 | 0,5140 | 0,2580 | 0,0885 | 0,0327 | 0,0381 | 0,0535 | 0,0493 | 0,0155 |

These calculated average rates do not represent the actual rates evolution, because these change as expanding root system of tree impedes terrain movement. However, these calculated average rate values are necessary to determine the actual rates values valid for the respective time interval of tree growth.

Table 7 shows the results of the calculation of rate of terrain movement v. It contains values of gravity points positions $x^*_{\mathrm{GP}}$ for the respective age of the tree calculated after the formulae (4) and $\Delta x_{\mathrm{GP}}$ that represents the increment of the change in the position of the gravity point for the respective growth interval.

$$\Delta x_{\mathrm{GP}\,(0-5)} = x^*_{\mathrm{GP80}} - x^*_{\mathrm{GP75}} - \cdots - x^*_{\mathrm{GP26}}$$

$$\Delta x_{GP\,(5-11)} = x^*_{GP75} - x^*_{GP69} - \cdots - x^*_{GP26}$$

……

$$\Delta x_{\mathrm{GP}\,(55-80)} = x^*_{\mathrm{GP26}}\ , \qquad (5)$$

and

$$\mathrm{v}_{int.} = \frac{\Delta x_{\mathrm{GP}\,int.}}{t_{int.}} \qquad (6)$$

Table 7.

| Grow Interval [years] | 0 - 5 | 5 - 11 | 11 - 17 | 17 - 24 | 24 - 32 | 32 - 39 | 39 - 45 | 45 - 54 | 54 - 80 |
|---|---|---|---|---|---|---|---|---|---|
| $\Delta x_{GP\,int.} = l_x$ [m] | 0,2683 | 0,2560 | 0,1696 | 0,0404 | 0,0099 | 0,0154 | 0,0042 | 0,0338 | 0,0155 |
| $t_{int.}$ [years] | 5 | 6 | 6 | 7 | 8 | 7 | 6 | 9 | 26 |
| $v_{int.}$ [m/year] | 0,0537 | 0,0427 | 0,0283 | 0,0058 | 0,0012 | 0,0022 | 0,0007 | 0,0038 | 0,0006 |

The tree movement rates v are presented in Figure 8.

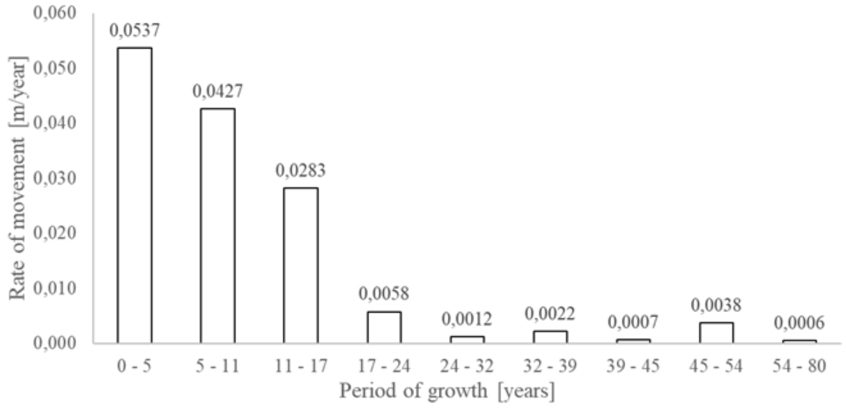


Figure 8: Diagram of terrain movement rates during tree growth.

## 5 Comment on the results

The rate of tree movement over time is not constant and changes in different intervals of tree growth. It decreases with growth and age of the tree, as the expanding root system of the tree mobilizes an ever-increasing volume of terrain mass reinforced by roots net, which acts as an effective stabilizing structure resisting the moving surrounding terrain masses especially from above a tree.

The course of a trunk axis (Fig. 9) demonstrates the change in rate movement of terrain by axis inclination that is not constant but at beginning it is steep later it becomes nearly vertical which signals quieting of terrain movement.

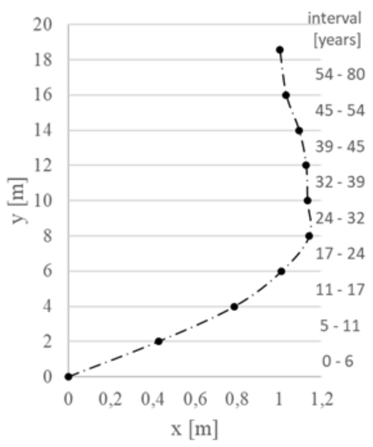

Figure 9: Graph of trunk axis.

Up to the age of 24 years, the terrain slope increases (see Fig. 1 b). After 24 years till the present time there is a barely noticeable change of the course of the trunk axis, but it generally points at negligible decrease of terrain slope (see Fig. 1 a).

The calculation of the tree rate movement in the intervals of tree growth, as well as the extent of this interval, depends on the value of the annual increment of the trunk diameter, which is taken constant, though in fact it could be affect by some other factors. Thus both the time intervals and respective calculated rates of terrain movement could be seen as only approximate. Improving the result would require individual determination of the age of individual sections of the trunk according to tree rings, which is theoretically possible, but in reality impractical.

The development of the rate of terrain movement demonstrates the general effect of trees in stabilizing slopes prone to sliding. With expanding of a root net the terrain is progressively reinforced. With increasing age of tree there in the terrain develops natural structure acting similarly like a gravitational wall.

In the example, a coniferous tree with a single trunk is analysed. This approach could also be used for deciduous trees with multiple trunk branches. In such a case, however, there is in the analysis need to create a fictitious stem that substitutes all trunk branches. This additional substitution makes the analysis difficult but does not disqualify it from determining the rate of terrain movement.

The shape of the tree trunk might result from many other factors beyond terrain movement, like irregular growth of the tree's canopy due to prevailing wind patterns, obstruction from nearby objects casting a shadow on it, and potentially human activities. Before applying this analysis it's advisable to account with them and eliminate them since they contribute to the shape of the tree trunk too. In these cases, it makes no sense to solve terrain movements using this method, because deformation of the tree trunk shape is not related to the terrain movement.

## 6 Conclusion

The article presents a method estimating the rate of terrain movement based on the shape of tree trunks. The shape reflects trees response to changes in terrain slope resulting from uneven terrain movement.

The method is suitable for sloping terrains, where there is a slow, smooth movement of the terrain and the inclination of the tree trunk, caused by the movement of the terrain, is rectified at the tree trunk top that grows vertically upwards.

Unique aspect of this method is its ability to capture the long-term progression of terrain movement that can't be determined with other monitoring equipment, which usually only cover short time periods.

The input parameters for this method are gained by a 3D scanning drone, the scanned 3D records are further processed by 3D image processing utilities. Compared to other methods, these circumstances give the method of determining the terrain rate movement from the tree trunk shape easy, fast, cheap and unlimited possibility of application in practice wherever there are trees in the field.

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