Improving Accuracy in Earthwork Volume Estimation for Proposed Forest Roads Using a High-Resolution Digital Elevation Model

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Abstract – Nacrtak

Earthwork usually represents the largest cost component in the construction of low-volume forest roads. Accurate estimates of earthwork volume are essential to forecast construction costs and improve the financial control of road construction operations. Traditionally, earthwork volumes are estimated using methods that consider ground data obtained from survey stations along road grade lines. However, these methods may not provide accurate estimates when terrain variations between survey stations are ignored. In this study, we developed a computerized model to accurately estimate earthwork volumes for the proposed forest roads by using a high-resolution digital elevation model (DEM). We applied our model to three hypothetical forest road layouts with different ground slopes and terrain ruggedness conditions. We examined the effects of various cross-section spacings on the accuracy of earthwork volume estimation assuming that 1-meter spacing provides the »true« earthwork volume. We also compared our model results with those obtained from the traditional end-area method. The results indicate that as cross-section spacing increases the accuracy of earthwork volume estimation decreases due to lack of the ability to capture terrain variations. We quantified earthwork differences, which increased with terrain ruggedness ranging from 2 to 21%. As expected, short cross-section spacing should be applied to improve accuracy in earthwork volume estimation when roads are planned and located on hilly and rugged terrain.

Keywords: forest roads, earthwork volume, road design, LiDAR, digital elevation model

1. Introduction – *Uvod*

Earthwork usually represents the major cost component in the construction of low-volume forest roads, accounting for over 80 percent of the total construction cost on steep terrain (Stückelberger et al. 2006). It is essential to accurately estimate earthwork volumes to improve cost control and budgeting in forest road construction. Traditionally, ground information for the proposed roads is collected through a preliminary road centerline survey, where survey stations are placed usually at every 30 meters or at major gradient or direction changes to reduce expensive and labor-intensive field work. Ground slopes measured at each station is used to calculate cut and fill areas, which are then used to estimate earthwork volumes between consecutive cross-sections.

Earthwork volumes have been conventionally estimated using the average end-area or the prismoidal method (Hickerson 1964). Both methods require cross-section areas to be of the same type; either cut or fill. Epps and Corey (1990) developed procedures to estimate earthwork volumes differently for various configurations (cut and/or fill) of cross-section areas using the average end-area method. For linear ground profiles, the prismoidal method is known to provide more accurate estimates while the average end-area method generally overestimates earthwork (Epps and Corey 1990). Easa (1992a) developed a modified prismoidal method for estimating volumes on non-linear ground profiles. This method is based on the Pappus's theorem and estimates earthwork volumes approximately as the average of the volumes resulting from rotating both cross-section areas about an axis on their respective planes (see

Hickerson 1964 for more details). The Pappus-based method provides accurate estimates only when the two cross-sections are also of the same type (either cut or fill). Easa (1992b) also developed a mathematical method based on triple integration that can deal with transition road segments where one of two consecutive cross-sections has both cut and fill areas, while the other has only either one. This method is complicated and applicable only for road segments where the ground profile is linear (Aruga et al. 2005). These existing earthwork volume estimating methods assume that the ground slope at each road cross-section is constant, which is unlike for most hilly and mountainous terrains. Kim and Schonfeld (2001) developed two methods to estimate cross-section areas more precisely. These methods use an interpolation method (inverse distance-weighted) to obtain elevation data, and vector and parametric representation of cross-sections to account for irregular ground slopes.

The accuracy of all aforementioned methods seems to improve as the distance between consecutive cross-sections decreases (Kim and Schonfeld 2001). However, cross-sections can only be derived at survey stations, and an assumption about the homogeneity of ground slopes between consecutive cross-sections has to be made. High-resolution DEMs derived from the light detection and ranging (LiDAR) technology have recently been incorporated into forest road planning and design to increase accuracy in volume estimation by using the elevation data of each raster grid cell. LiDAR technology is known to provide accurate estimates of ground surface elevation even under a dense canopy cover (Reutebuch et al. 2003). Coulter et al. (2001) applied a 1-meter resolution LiDAR-derived DEM to estimate earthwork volumes for a proposed forest road. In this method, road elevation was assigned to each grid cell within the road template to estimate earthwork volume from the difference between road and ground surface elevations. However, this simplistic method is only applicable to straight road segments. Aruga et al. (2005) developed a computer program for forest road design that also uses a 1-meter resolution DEM. Their model precisely generates cross-sections and calculates areas, and accurately estimates earthwork volumes. As the actual ground profile can be represented more accurately when a shorter distance between cross-sections is applied (Aruga et al. 2005), earthwork volume estimations using a 1-meter resolution DEM were considered »exact« and comparable with other estimates obtained from different cross-section spacings and different estimation methods. The study was focused on the optimization of road design, and, however, limited emphasis was put on numerical procedures and the study does not provide a thorough analysis of the effects of cross-section spacing on earthwork volume estimation.

Although the accuracy of earthwork volume estimates is expected to increase with decreasing spacing between consecutive cross-sections, to our knowledge, there are no studies evaluating and quantifying the differences in earthwork volume estimates in various terrain conditions. In this study, we developed a computerized model to accurately estimate earthwork volumes for the proposed forest roads using a high-resolution LiDAR-derived DEM. We examined the effects of cross-section spacings on the accuracy of earthwork volume estimation by applying the model to the proposed roads in various areas under different terrain conditions and estimating earthwork volumes of the roads at different cross-section spacings. Similar to Aruga et al. (2005), we assumed that 1-meter cross-section spacing provided the »true« earthwork value in our study. Our computerized model was applied to three hypothetical forest roads laid out on low, moderate, and steep slope areas, and the earthwork volume estimates from the model were compared with those from the traditional end-area method, which considers only the cross-sections located at survey stations. Lastly, comparisons were also made on road sections with three levels of terrain ruggedness.

2. Computerized model – *Računalni model*

The computerized model developed in this study was designed to accurately estimate cut and fill volumes for a proposed forest road using a high-resolution DEM. The main input data for the model include: *i)* an ASCII text file representing the LiDAR-derived DEM for the area of interest, and *ii)* a text file representing the x- and y-coordinates of sequential survey station points along a proposed road. Based on the cell size (1 meter in our applications) and the x-and y-coordinates of the lower left corner of DEM, the model calculates x- and y-coordinates of each grid cell in the DEM. These coordinates are used to obtain the ground elevation of each survey station point along the proposed road gradeline.

2.1 Estimating ground elevation – *Procjena visine terena*

Starting from the beginning-of-project (BOP), ground elevations for each survey station point (SP) are obtained from the LiDAR-derived DEM. As DEM elevation values represent the elevation at the center of the grid cell and since a given SP might not co-

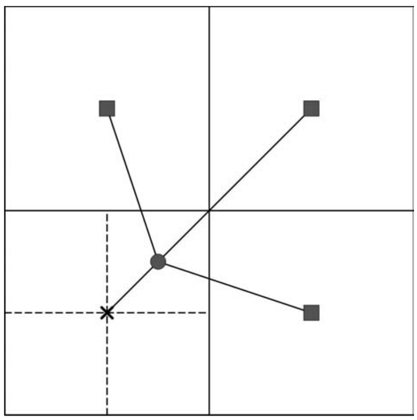

Fig. 1 Estimating ground elevation on a given point (dot) using the interpolation method based on four grid cells including the grid cell containing the point (grid cell with a cross) and three adjacent grid cells (grid cells with squares)

Slika 1. *Procjena visine terena određenoga položaja (točka) primjenom metode interpolacije zasnovane na četirima podacima pravilne mreže točaka (polje s križićem) i na trima susjednim poljima (polja s kvadratićem)*

incide with a grid cell center, an interpolation method is used to estimate the SP z-coordinate. The interpolation method uses inverse distance-weighted based on its four adjacent grid cells.

For a given SP, (dot in Fig. 1) the model identifies the grid cell containing it (grid cell with a cross in Fig. 1), and the other three adjacent cells (grid cells with a square in Fig. 1). The horizontal distances from the SP to the four grid cells are computed and their z-coordinates are obtained. The SP z-coordinate is then obtained based on the inverse distance to each adjacent grid cell and their respective elevation values (Eq. 1).

$$\mathrm{SP}_{Zi} = \sum_{j=1}^{N_i} (d_j^{-1} \cdot z_j) \Big/ \sum_{j=1}^{N_i} d_j^{-1} \qquad \forall j \in N_i \tag{1}$$

where, SP_{Zi} is the z-coordinate of the ith SP, d_j is the horizontal distance from the jth grid cell to SP, z_j is the z-coordinate of the jth grid cell, and N_i indicates the set of four closest grid cells to the ith SP. Once the three-dimensional coordinates of all SP are determined, the model locates a curve for each intersection point and identifies the position of the beginning and end of curve.

2.2 Locating horizontal curves – *Određivanje glavnih točaka horizontalnoga kružnoga luka*

We assumed all SP (n) along a proposed road except BOP and end-of-project (EOP) become intersection points (PI in Fig. 2), where curves are located to avoid sharp turns. Each horizontal curve location is determined based on the x- and y-coordinates of the SP_i, (same as the PI), SP_{i-1} and SP_{i+1}, and a user defined minimum allowable radius of the curve (R). In the United States, R ranges from 18 m to 40 m

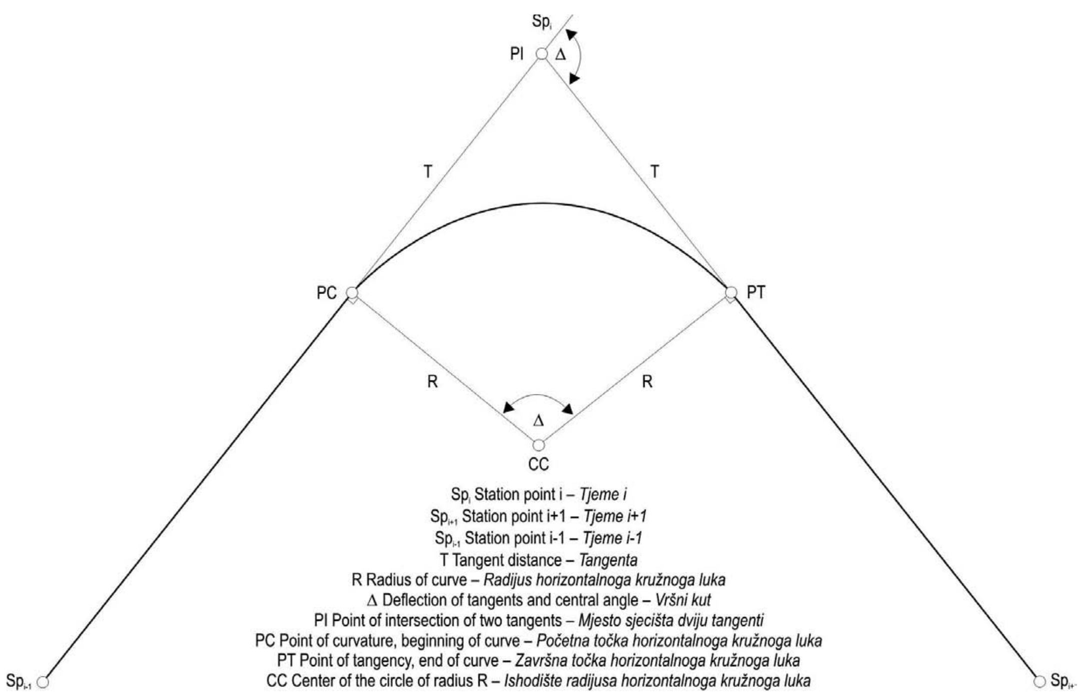

Fig. 2 An example of horizontal curve design and nomenclature
Slika 2. *Primjer oblikovanja i osnovne sastavnice horizontalnoga kružnoga luka*

depending on the road standard (Akay 2003). Fig. 2 shows the nomenclature used in the model to determine the location of the beginning and end of the curve (PC and PT, respectively), and the location of the curve center (CC in Fig. 2), whose arc passes through PC, and PT is also determined for posterior calculations of the curve design.

For each PI, represented by SP_i, the model calculates the direction of the two tangent lines in a two-dimensional (x, y) Cartesian coordinate system as follows:

$$m_1 = \frac{diff\_y_1}{diff\_x_1} = \frac{y_i - y_{i-1}}{x_i - x_{i-1}} \quad (2)$$

$$m_2 = \frac{diff\_y_2}{diff\_x_2} = \frac{y_{i+1} - y_i}{x_{i+1} - x_i} \quad (3)$$

where, m_1 and m_2 represent the direction of the two tangent lines (one arriving at SP_i and one leaving from SP_i), and x_i and y_i represent the x- and y-coordinates of the i^{th} SP, respectively.

The model converts tangent line directions into azimuths based on the sign of the numerator and denominator of the direction (Eq. 4).

$$\text{Azim} = \begin{cases} 90 - \tan^{-1}(m) & \text{if } diff\_y \geq 0 \wedge diff\_x > 0 \\ 270 + \tan^{-1}(m) & \text{if } diff\_y > 0 \wedge diff\_x \leq 0 \\ 270 - \tan^{-1}(m) & \text{if } diff\_y \leq 0 \wedge diff\_x < 0 \\ 90 + \tan^{-1}(m) & \text{if } diff\_y < 0 \wedge diff\_x \geq 0 \end{cases} \quad (4)$$

where, Azim and m are azimuth and direction of a tangent line, respectively. Then, the central angle (Δ in Fig. 2) is calculated as follows:

$$\Delta = \begin{cases} 360 - |Azim_2 - Azim_1| & \text{if} |Azim_2 - Azim_1| > 180 \\ |Azim_2 - Azim_1| & \text{otherwise} \end{cases} \quad (5)$$

Once the angle Δ is obtained, the model calculates the tangent distance (T in Fig. 2) from PI to PC and PT (Eq. 6).

$$\text{T} = \text{R} \cdot \tan(\Delta/2) \quad (6)$$

Using m_1, m_2, and T, the model calculates the two-dimensional coordinates of PC and PT (Eqs. 7–8 and 9–10, respectively) of the curve associated with SP_i by adding or subtracting a difference in the x- and y-coordinates from the coordinates of the PI (Eqs. 7–10).

$$\text{PC}_\text{Y} = \text{PI}_\text{Y} \pm \sqrt{(m_1^2 \cdot \text{T}^2)/(1+m_1^2)} \quad (7)$$

$$\text{PC}_\text{X} = \text{PI}_\text{X} \pm \frac{\sqrt{(m_1^2 \cdot \text{T}^2)/(1+m_1^2)}}{m_1} \quad (8)$$

$$\text{PT}_\text{Y} = \text{PI}_\text{Y} \pm \sqrt{(m_2^2 \cdot \text{T}^2)/(1+m_2^2)} \quad (9)$$

$$\text{PT}_\text{X} = \text{PI}_\text{X} \pm \frac{\sqrt{(m_2^2 \cdot \text{T}^2)/(1+m_2^2)}}{m_2} \quad (10)$$

These x- and y-coordinates and the slopes m_1 and m_2 are then used to determine the coordinates at the center of the circle (CC in Fig. 2) as follows:

$$\text{CC}_\text{X} = \frac{\text{PC}_\text{Y} - \text{PT}_\text{Y} + (\text{PC}_\text{X}/m_1) - (\text{PT}_\text{X}/m_2)}{m_1^{-1} - m_2^{-1}} \quad (11)$$

$$\text{CC}_\text{X} = \frac{\text{PC}_\text{Y} - \text{PT}_\text{Y} + (\text{PC}_\text{X}/m_1) - (\text{PT}_\text{X}/m_2)}{m_1^{-1} - m_2^{-1}} \quad (12)$$

Once the two-dimensional coordinates of PC, PT, and CC for each of the *n-2* curves have been determined, the model estimates the elevation (z-coordinate) of each of these points as described in the previous section.

2.3 Calculating road segment distance – *Izračun stacionaže*

The road layout has *n* station points and thus *n-1* straight road segments connecting consecutive station points. As one curved road segment is added for each of *n-2* intersection points, the total number of road segments (curved and straight segments) becomes *2n-3*. Starting from BOP and ending at EOP, these segments alternate between straight and curved segments.

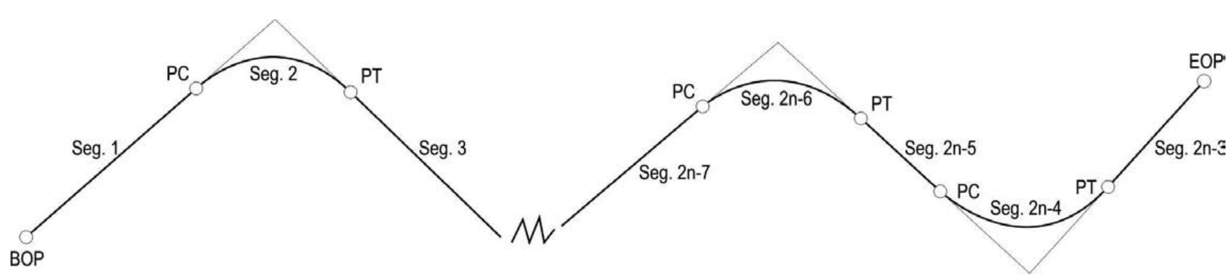

Fig. 3 Plan view of a proposed road including straight and curved road segments
Slika 3. *Položajni nacrt predložene šumske ceste s prikazom ravnih dionica i dionica u kružnim krivinama*

$$\mathrm{SD}_j = \begin{cases} \sqrt{(\mathrm{BOP_X} - \mathrm{PC}_{\mathrm{X}(j+1)})^2 + (\mathrm{BOP_Y} - \mathrm{PC}_{\mathrm{Y}(j+1)})^2} & \forall j \in Q = \{1\} \\ \sqrt{(\mathrm{PT}_{\mathrm{X}(j-1)} - \mathrm{PC}_{\mathrm{X}(j+1)})^2 + (\mathrm{PT}_{\mathrm{Y}(j-1)} - \mathrm{PC}_{\mathrm{Y}(j+1)})^2} & \forall j \in Q = \{3,5,7,\dots,(2n-5)\} \\ \sqrt{(\mathrm{PT}_{\mathrm{X}(j-1)} - \mathrm{EOP_X})^2 + (\mathrm{PT}_{\mathrm{Y}(j-1)} - \mathrm{EOP_Y})^2} & \forall j \in Q = \{2n-3\} \end{cases} \quad (13)$$

where, SD_j is the horizontal distance of the j^{th} road segment along the road centerline, and $\mathrm{PT}_{\mathrm{X}(j-1)}$, $\mathrm{PT}_{\mathrm{Y}(j-1)}$, $\mathrm{PT}_{\mathrm{X}(j+1)}$, and $\mathrm{PT}_{\mathrm{Y}(j+1)}$ are the x- and y-coordinates of the PT from the $(j-1)^{th}$ segment and the PC from the $(j+1)^{th}$ segment, respectively (Fig. 3).

For straight segments, the model calculates the horizontal distance using the x- and y-coordinates of the previous curve PT and the following curve PC (Eq. 13). For the case of the first segment, the distance is calculated from BOP until the first curve PC, and the distance of the last segment is calculated from the last curve PT to EOP (Eq. 13, Fig. 3).

For the case of curved segments, the model calculates the segment distance as follows:

$$\mathrm{SD}_j = 2 \cdot \pi \cdot \mathrm{R} \cdot \frac{\Delta_j}{360} \quad \forall j \in Q = \{2,4,6,\dots,(2n-4)\} \quad (14)$$

where, SD_j and Δ_j indicate the horizontal distance along the road centerline and the deflection of tangents in degrees associated with the j^{th} curved segment, respectively (Fig. 3).

2.4 Locating cross-sections for each road segment – *Određivanje poprečnoga presjeka u svakom profilu ceste*

The model determines the number of cross-sections (CSN) for a given road segment based on the segment distance and a user-defined cross-section spacing (CSS). CSN for the j^{th} road segment is then calculated by dividing SD_j by CSS (Eq. 15).

$$\mathrm{CSN}_j = \frac{\mathrm{SD}_j}{\mathrm{CSS}}, \quad \text{as a fractional notation}$$

$$\mathrm{CSN}_j = a\frac{b}{c} \ \text{if} \begin{cases} b > 0 \Rightarrow \mathrm{CSN}_j = a + 2 \\ b = 0 \Rightarrow \mathrm{CSN}_j = a + 1 \end{cases} \quad (15)$$

where, CSN_j is the number of cross-sections on the j^{th} road segment, a indicates the integer part of CSN_j, b and c represent the numerator and denominator of the fractional part, respectively. When the horizontal distance of a road segment is shorter than CSS ($\mathrm{SD}_j <$ CSS, thus $a = 0$), two cross-sections are located, one at the beginning and the other at the end of the road segment.

All cross-sections along a road segment are located perpendicular to the road centerline. For the given j^{th} road segment, the first cross-section is always located at the beginning of the road segment, the following cross-sections are spaced successively with an interval of CSS, and the last cross-section is always located at the end of the segment.

2.5 Designing cross-sections – *Kreiranje poprečnih presjeka*

For the purpose of comparing earthwork volumes estimated using different cross-section spacing, we simplified the cross-section design and made the following four assumptions: *i)* zero-line (balance point) is always located at half of the road width (RW), *ii*) road surface is flat, *iii*) road does not include a ditch, and *iv*) cut and fill slopes are constant. Fig. 4a presents the cross-section design considered in our model. For a given cross-section, horizontal distances from the road center (P1 in Fig. 4b) to its edges (P2 and P3 in Fig. 4b) are assumed to be fixed at RW/2. However, horizontal distances from P1 to the points where cut and fill slopes intersect with the ground profile (P4 and P5 in Fig. 4b) are variable because they depend on the ground slope.

To obtain the design points necessary to draw a cross-section, the model first identifies the x-and y-coordinates of points P2 and P3 using the road width, the coordinates of P1, and the direction of the road segment m_{rs} (Fig. 4b). The direction (m_{rs}) is calculated differently for straight and curved segments (Eq. 16 and 17, respectively).

$$m_{rs} = \begin{cases} \dfrac{\mathrm{PC}_{\mathrm{Y}(j+1)} - \mathrm{P1_Y}}{\mathrm{PC}_{\mathrm{X}(j+1)} - \mathrm{P1_X}} & \forall j \in Q = \{1,3,5,\dots,(2n-5)\} \\ \dfrac{\mathrm{EOP_Y} - \mathrm{P1_Y}}{\mathrm{EOP_X} - \mathrm{P1_X}} & \forall j \in Q = \{2n-3\} \end{cases} \quad (16)$$

$$m_{rs} = -\left(\frac{\mathrm{CC}_{\mathrm{Y}j} - \mathrm{P1_Y}}{\mathrm{CC}_{\mathrm{X}j} - \mathrm{P1_X}}\right)^{-1} \quad \forall j \in Q = \{2,4,6,\dots,(2n-4)\} \quad (17)$$

where, $\mathrm{CC}_{\mathrm{X}j}$ and $\mathrm{CC}_{\mathrm{Y}j}$ represent the x- and y-coordinates of CC associated with the j^{th} curved road segment. The location of P2 and P3 are then calculated by adding or subtracting a difference in the x- and y-coordinates from the coordinates of the P1 (Eqs. 18–19).

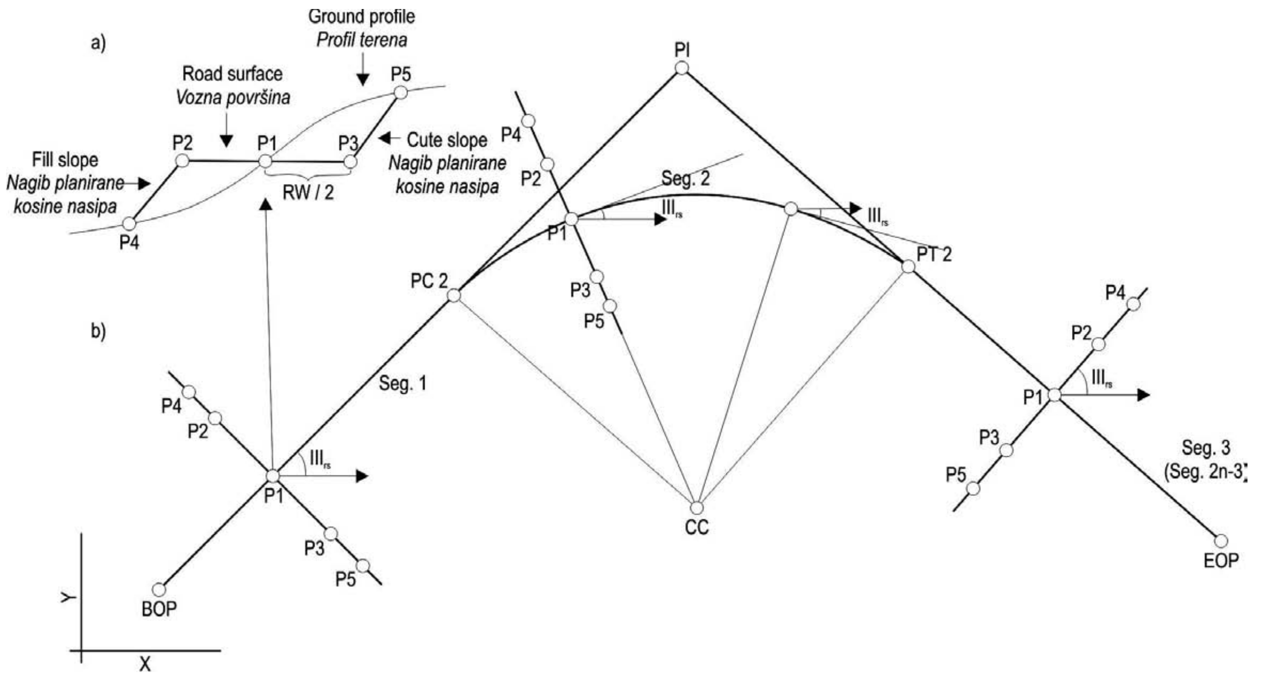

Fig. 4 Cross-section design considered by the model (a), and road segment slopes (m_{rs}) used to identify the location of cross-section design points on straight and curved road segments (b)

Slika 4. *Kreiranje poprečnog profila određenog modelom (a), te uzdužni nagib dionice šumske ceste (m_{rs}) korišten za određivanje osnovnih sastavnica poprečnog profila na ravnim dionicama te u horizontalnim kružnim krivinama (b)*

$$P_Y = P1_Y \pm \sqrt{\frac{(RW/2)^2}{m_{rs}^2 + 1}} \quad (18)$$

$$P_X = P1_X + m_{rs} \cdot (P1_Y - P_Y) \quad (19)$$

where, the two pairs of and represent the locations of P2 and P3.

To identify the locations of P4 and P5, the model iteratively places two points (Pt_1 and Pt_2 in Fig. 5) along the cross-section at a fixed distance interval, which is called span-distance (SpD) in our model. At iteration one, Pt_1 starts at the edge of the road (P2 or P3 for the left or right side of the road, respectively), and Pt_2 starts at meters away from Pt_1 (Fig. 5). Thereafter, both points Pt_1 and Pt_2 are moved farther away from the road edge by SpD meters at each successive iteration. At a given iteration, the model calculates the x-, y-, and z-coordinates of Pt_1 and Pt_2 using the horizontal distances of Pt_1 and Pt_2 from P1. The model then checks whether the line formed between Pt_1 and Pt_2 intersects with the fill or cut slope line. The iteration process stops when the two lines intersect. Once this intersection point is known, the model calculates the horizontal distances (X_dist) from the road edge to P4 and P5 (Fig. 5). The model then calculates the two-dimensional coordinates of points P4 and P5 using Equations 18 and 19 replacing (RW/2) with (RW/2 + X_dist).

2.6 Calculating cut and fill areas – *Izračun površine iskopa i nasipa*

To obtain ground elevations along a road cross-section, the model establishes ground points along the cross-section with an interval of SpD meters (Fig. 6a), and then estimates ground elevation on each point using the DEM and the interpolation method described in Section 2.1. The model then calculates cross-section areas (cut and fill) using a well-known

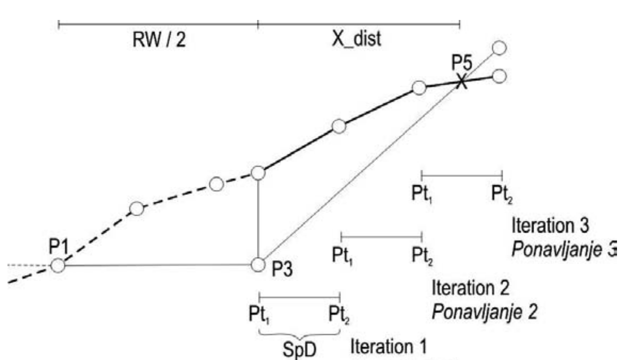

Fig. 5 Iterative process performed by the model to identify the intersection point (P5) between the cut slope and ground surface

Slika 5. *Postupak ponavljanja rada modela pri identificiranju točke sjecišta* (P5) *pokosa iskopa i terena*

$$\mathrm{CV_k} = \frac{\left(\dfrac{\mathrm{CSS}\cdot\mathrm{TCA_R}}{\mathrm{TCA_R}+\mathrm{TFA_R}}\right)\cdot\mathrm{TCA_R}}{2} + \frac{\left(\dfrac{\mathrm{CSS}\cdot\mathrm{TCA_L}}{\mathrm{TCA_L}+\mathrm{TFA_L}}\right)\cdot\mathrm{TCA_L}}{2} \tag{21}$$

$$\mathrm{FV_k} = \frac{\left(\mathrm{CSS}-\dfrac{\mathrm{CSS}\cdot\mathrm{TCA_R}}{\mathrm{TCA_R}+\mathrm{TFA_R}}\right)\cdot\mathrm{TFA_R}}{2} + \frac{\left(\mathrm{CSS}-\dfrac{\mathrm{CSS}\cdot\mathrm{TCA_L}}{\mathrm{TCA_L}+\mathrm{TFA_L}}\right)\cdot\mathrm{TFA_L}}{2} \tag{22}$$

where, $\mathrm{CV_k}$ and $\mathrm{FV_k}$ are the cut and fill volumes of the k^{th} road section defined by two consecutive cross-sections.

formula (Eq. 20), which provides the area of a polygon based on the coordinates of its vertices. This formula is derived from one half of the absolute value of the determinant of the matrix formed by the two-dimensional coordinates of the polygon vertices (Hush 1963).

$$\mathrm{A} = 0.5\cdot\sum_{p=1}^{\mathrm{TPN}}[(xx_p\cdot z_{p+1})-(xx_{p+1}\cdot z_p)] \tag{20}$$

where, xx_p is the horizontal distance from P1 to the p^{th} point in the cross-section, z_p is the elevation of the p^{th} point, and TPN is the total number of points representing one side of the road from P1 where the area is calculated. Equation 20 provides cut or fill areas depending on whether all ground elevation points are above or below the road surface. When both cut and fill areas are on one side of the road in the cross-section, where some ground elevation points are above the road surface and other points are below the road surface (Fig. 6b), the polygons representing either cut or fill are identified and their areas are calculated separately. Areas of the same type (cut or fill) are then added together to compute the total cut and fill areas for the right and left side of the road ($\mathrm{TCA_R}$, $\mathrm{TFA_R}$, $\mathrm{TCA_L}$, and $\mathrm{TFA_L}$ respectively).

2.7 Estimating cut and fill volumes – *Procjena obujma zemljanih radova*

Based on our assumption that road centerlines are located at the ground level, earthwork volumes

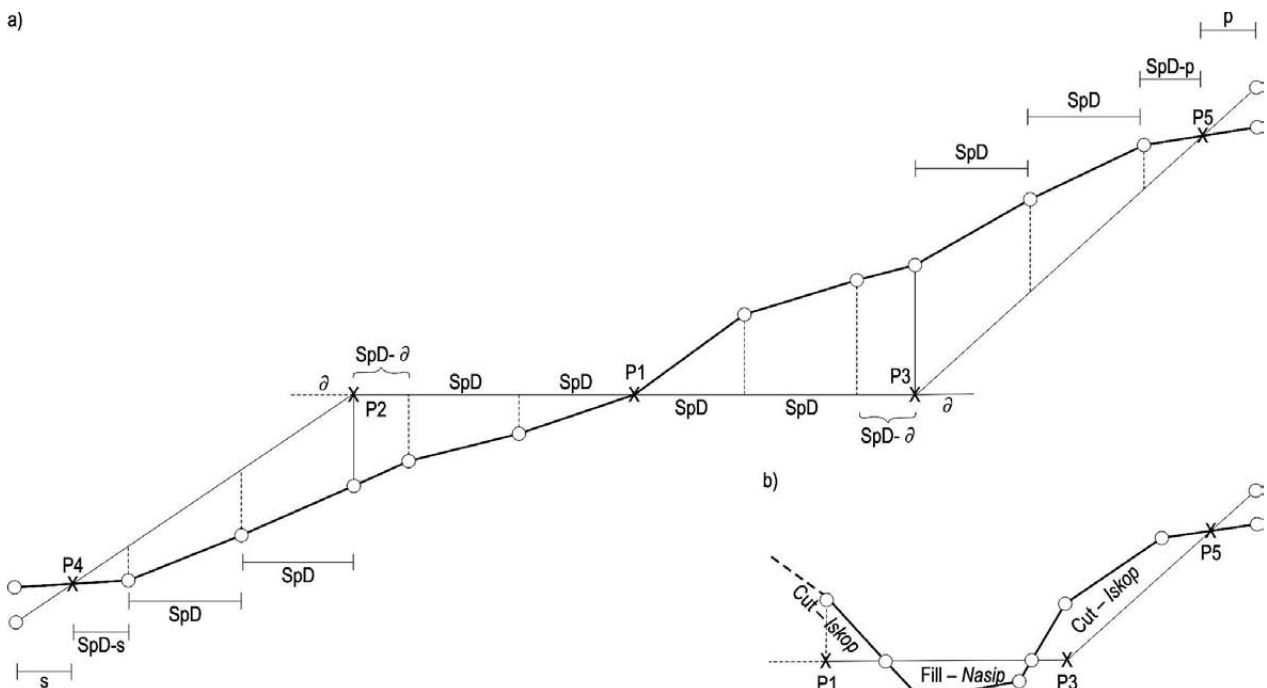

Fig. 6 Cross-section design points used to calculate cut and fill areas (a), and an example of a cross-section having both fill and cut areas on one side of the road center line (P1) (b)

Slika 6. *Osnovne točke poprečnoga profila korištene za izračun površina iskopa i nasipa (a) te primjer kada se s iste strane poprečnoga profila nalaze površine iskopa i nasipa* (P1) (b)

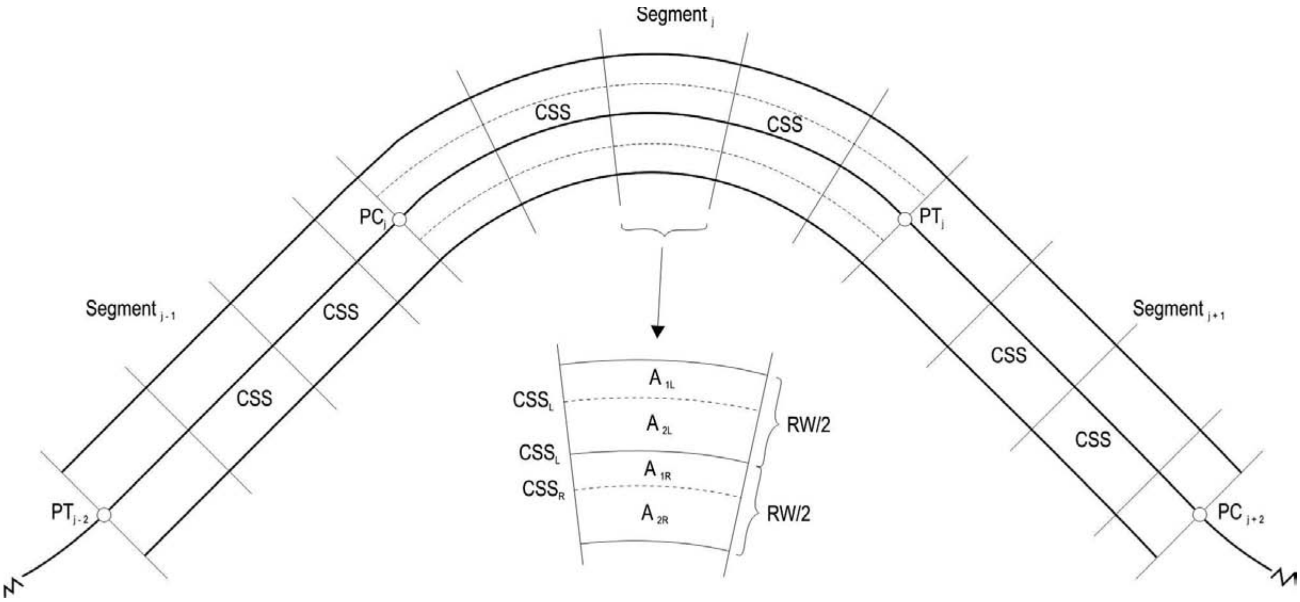

Fig. 7 Cross sections taken from straight and curved road segments for earthwork volume estimation
Slika 7. *Poprečni presjeci na ravnim dionicama te u horizontalnim kružnim lukovima ceste kao podloga za procjenu volumena zemljanih radova*

were estimated separately for each side of the road. For straight road segments we used the modified average end-area method developed by Epps and Corey (1990) to estimate earthwork volumes using the cut and fill areas of consecutive cross-sections (Eqs. 21–22)

The CSS is the same on both sides of the road center line for straight road segments, whereas this is not the case for curved road segments (Fig. 7). For curved road segments, the model computes the actual cross-section spacing for each side of the road center line (CSS_R and CSS_L) separately by calculating the arc length of a curve whose radius makes the areas on both sides of the curve equal ($A_{1R}= A_{2R}$ and $A_{1L}= A_{2L}$ in Fig. 7). The arc lengths can be calculated as follows:

$$D = \sqrt{\frac{R^2 + (R \pm RW/2)^2}{2}} \cdot \left(\frac{CSS \cdot 360^2}{R}\right)$$

$$\forall j \in Q = \{2,4,5,\dots,(2n-4)\} \tag{23}$$

where, the two values of D represent CSS_R and CSS_L.

Once cross-section spacings along a curved road segment are obtained for both sides of the road center line, Equations 21 and 22 are used to estimate cut and fill volumes between consecutive cross-sections for curved road segments after CSS in the equation is replaced with CSS_R and CSS_L. Then, the total cut and fill volumes are calculated for the jth road segment using the following equations:

$$CV_j = \sum_{k=1}^{CSN-1} CV_k \tag{24}$$

$$FV_j = \sum_{k=1}^{CSN-1} FV_k \tag{25}$$

Lastly, the total earthwork of the entire forest road is calculated by adding the total cut and fill volumes estimated for each road segment (Eqs. 26 and 27).

$$TCV = \sum_{j=1}^{2n-3} CV_j \tag{26}$$

$$TFV = \sum_{j=1}^{2n-3} FV_j \tag{27}$$

where, TCV and TFV represent the total cut and fill volumes of the entire road, respectively.

3. Model applications – *Primjena modela*

3.1 Verification – *Provjera*

We created a hypothetical forest road to verify the results of our model and analyze the effects of using a high resolution DEM on earthwork volume estimates. We compared these estimates with those from the traditional method, which considers ground information only from pre-defined station points. The hypothetical road has three station points (Fig. 8a), resulting in two straight and one curved road segments (Fig. 8b). The hypothetical road was laid out

Fig. 8 Hypothetical forest road layout; a) station point locations, and b) road segment locations
Slika 8. *Položajni nacrt hipotetske šumske ceste; a) položaj točaka terenske izmjere, b) položaj dionica šumske ceste*

in the southern portion of the Mica Creek watershed located about 67 km southeast of Coeur d'Alene, Idaho, United States, where a LiDAR-derived, 1-meter resolution DEM is available. The road was manually digitized »on-screen« in ArcMap 9.2 based on a 2-meter contour lines layer derived from the DEM of the area. The ground slope in the area was moderate, ranging between 30 and 60%. We considered the following cross-section design and spacing parameters; cut slope (CS) = 1:1, fill slope (FS) = 1.5:1, road width (RW) = 4 m, radius of curve (R) = 20 m, and SpD = 1 m.

3.2 Test case studies – *Testiranje studije slučaja*

To analyze the effects of various cross-section spacing on the accuracy of earthwork volume estimation, we created the layout of three hypothetical 1 km forest roads. These roads were located in areas with slopes between 0–30%, 30–60%, and 60–90% in the southern portion of the Mica Creek watershed to also examine the effects of ground steepness on earthwork volume estimation. We arbitrarily referred to these three areas with increasing slope as low, moderate, and steep terrain areas. The roads were manually digitized »on-screen« in ArcMap 9.2 based on 2-meter contour lines derived from the 1-meter resolution DEM of the area. The allowable road grade used the range from -15% to 15%. We assumed that 1-meter spacing provided the most accurate estimate, and used the earthwork volume obtained from 1-meter cross-section spacing as the true volume in comparison with other spacing. Fig. 9 illustrates the layout

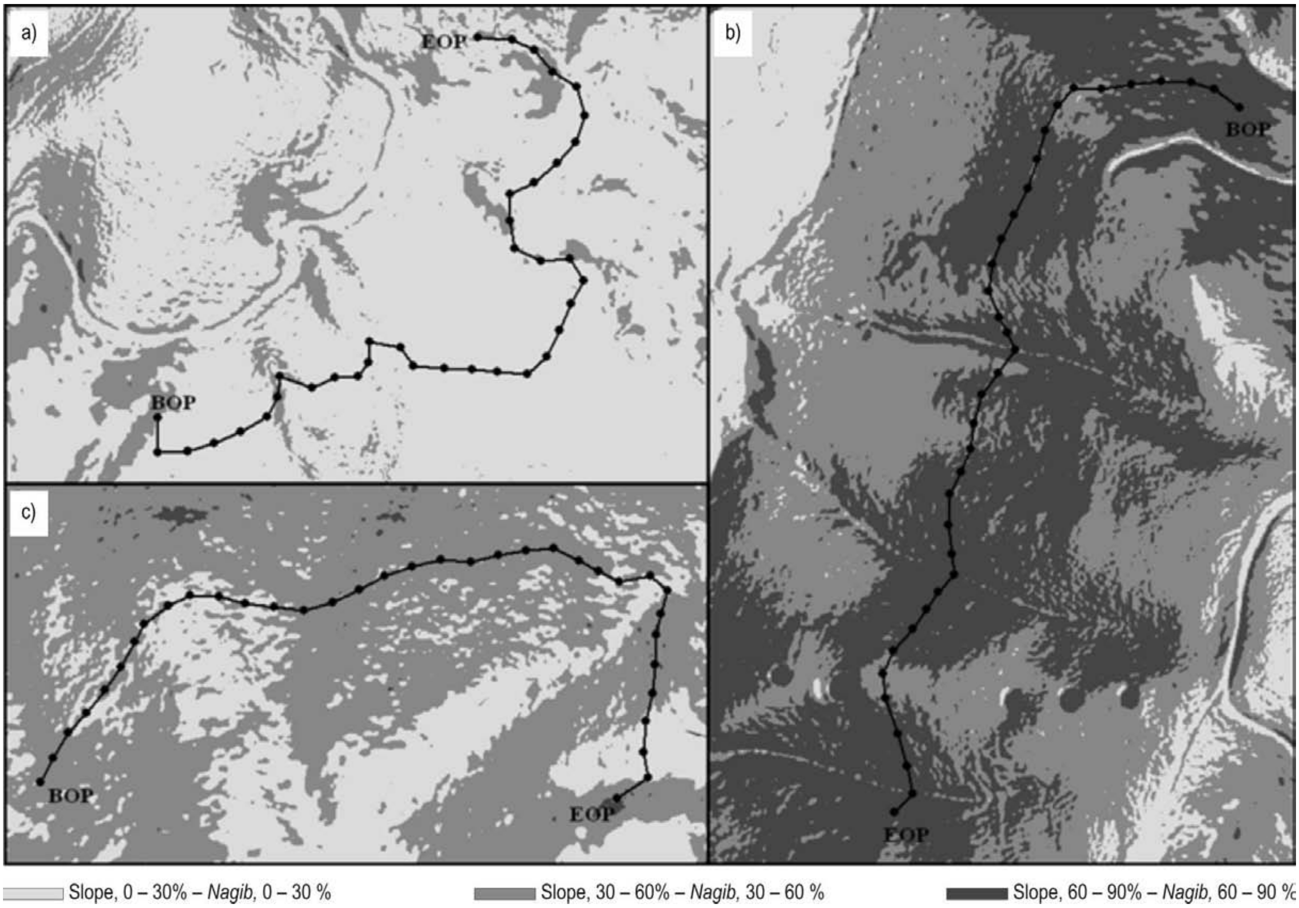

Fig. 9 Layout of the three hypothetical 1 km forest roads located in low (a), moderate (b), and steep (c) slope areas
Slika 9. *Prikaz tri hipotetske šumske ceste projektirane na različitim kategorijama nagiba terena (a – 0 do 30 %, b – 30 do 60 % i c – 60 do 90 %)*

of the low, moderate and steep slope forest roads, which have 37, 36, and 37 station points, respectively.

We also investigated the effect of terrain ruggedness on earthwork volume estimations. Most of the existing terrain ruggedness indexes calculated from ground elevation and aspect are designed to measure terrain heterogeneity for large areas using typically a 30 meter raster resolution (Riley et al. 1999, Sappington et al. 2007). When using a high-resolution 1-meter DEM, these indexes are not able to meaningfully capture terrain ruggedness for characterizing terrain variability along road segments. Therefore, we computed the coefficient of variation of the fill

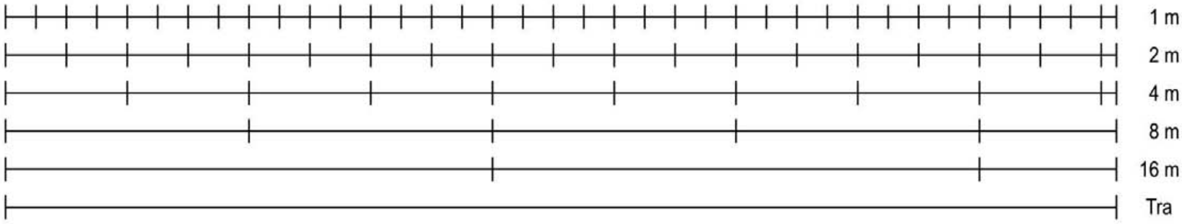

Fig. 10 Number and location of cross-sections along a given straight road segment for different cross-section spacings (1, 2, 4, 8, and 16 meters)
Slika 10. *Broj i položaj poprečnih profila uzduž ravne dionice šumske ceste za različite inačice razmaka između poprečnih profila (1, 2, 4, 8 i 16 metara)*

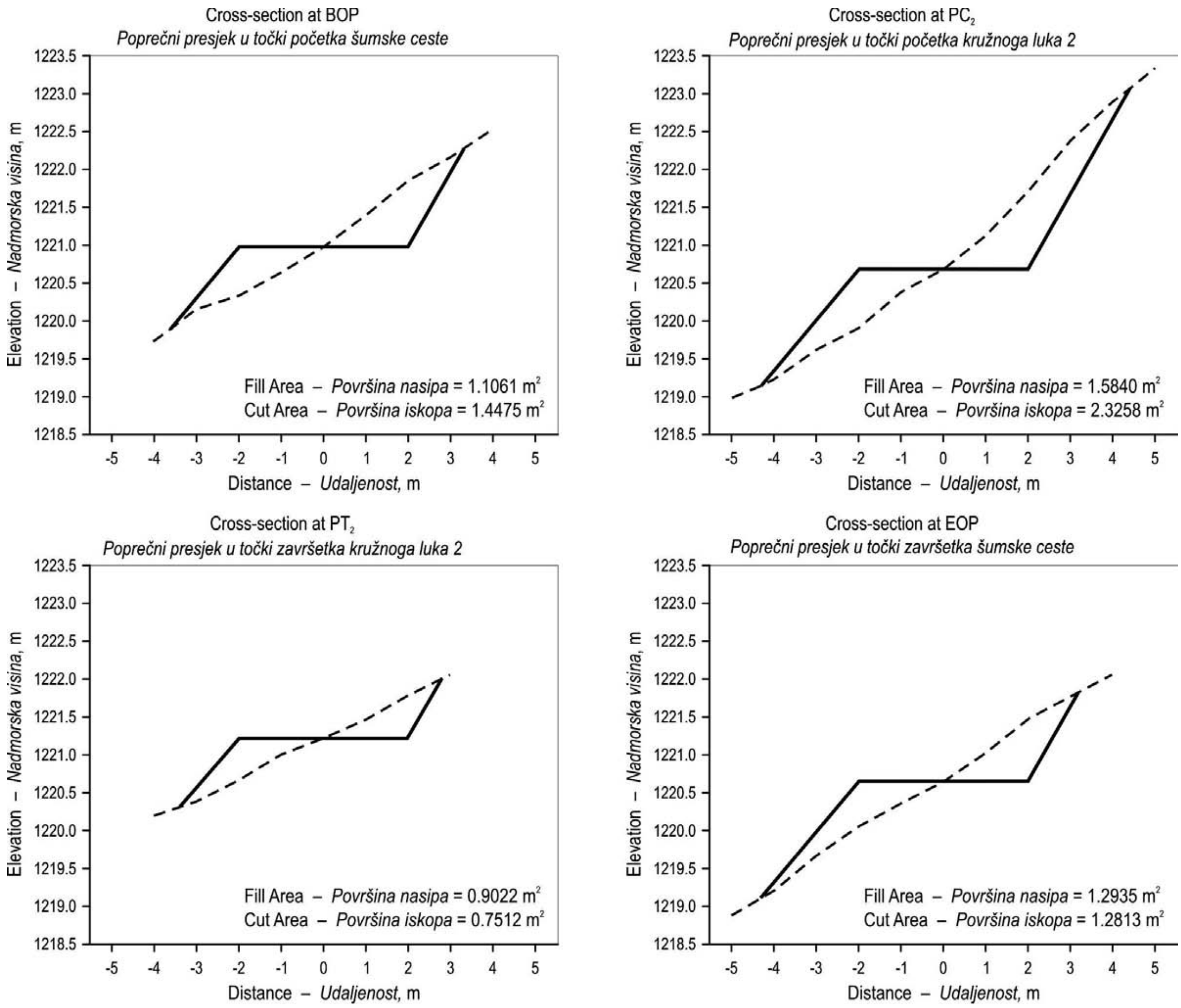

Fig. 11 Cross-section diagrams obtained for the 3-SP hypothetical forest road
Slika 11. *Crtani poprečni profil u točkama terenske izmjere na hipotetskim šumskim cestama*

and cut areas from all cross-sections in a given road segment, and used this coefficient of variation as a measure of terrain ruggedness in our study (e.g., the higher coefficient represents the more rugged terrain.) The coefficient was computed for all road segments included in the three hypothetical forest roads. Then, the road segments were grouped in three ranges of coefficient of variation: low (<20%), medium (20–40%), and high (≥40%).

The same parameter values used in the model verification regarding road design (RW and R), cross-section design (FS and CS), and spacing (SpD) were used for these applications. To make comparisons valid, specific cross-section spacings (e.g., 1, 2, 4, 8, 16 meters) were selected so that the same cross-sections can be used for smaller spacings analyzed (Fig. 10).

4. Results and Discussion – *Rezultati i rasprava*

4.1 Model verification – *Provjera modela*

Using the values of road design parameters specified above, we calculated cut and fill areas of each four cross-sections along the hypothetical forest road layout formed by two straight and one curve segment (see Fig. 8). Cut and fill areas for these cross-sections were also calculated manually to verify our model results (Fig. 11). Table 1 shows the coordinates of all cross-section design points as well as other points along the ground profile for each cross-section shown in Fig. 11. The results of area calculations from the model perfectly matched those calculated manually.

Table 1 X- and Z-coordinates calculated by the model to draw the cross-sections shown in Fig. 11
Tablica 1. *Modelom izračunate koordinate X i Z nacrtane na poprečnim profilima prikazanim na slici 11*

BOP coordinates *Koordinata početka ceste*		PC_2 coordinates *Koordinata početka kružnoga luka 2*		PT_2 coordinates *Koordinata završetka kružnoga luka 2*		EOP coordinates *Koordinata završetka ceste*	
X[1]	Z[2]	X[1]	Z[2]	X[1]	Z[2]	X[1]	Z[2]
–3.6234	1219.8796	–4.3041	1219.1348	–3.3858	1220.2944	–4.3221	1219.0900
–3.0000	1220.1448	–4.0000	1219.2062	–3.0000	1220.3676	–4.0000	1219.1963
–2.0000	1220.9619	–3.0000	1219.5960	–2.0000	1221.2183	–3.0000	1219.6519
–2.0000	1220.3194	–2.0000	1220.6709	–2.0000	1220.6660	–2.0000	1220.6380
–1.0000	1220.6205	–2.0000	1219.8930	–1.0000	1220.9959	–2.0000	1220.0318
0.0000	1220.9619	–1.0000	1220.3587	0.0000	1221.2183	–1.0000	1220.3419
1.0000	1221.3924	0.0000	1220.6709	1.0000	1221.4677	0.0000	1220.6380
2.0000	1220.9619	1.0000	1221.1097	2.0000	1221.2183	1.0000	1221.0162
2.0000	1221.8531	2.0000	1220.6709	2.0000	1221.7801	2.0000	1220.6380
3.0000	1222.1539	2.0000	1221.7045	2.7864	1222.0046	2.0000	1221.4700
3.3107	1222.2726	3.0000	1222.3679			3.0000	1221.7593
		4.0000	1222.8951			3.1738	1221.8119
		4.3946	1223.0655				

[1]X-coordinate represents the horizontal distance in meters from P1 located at the origin of x-axis – *koordinata X predstavlja horizontalnu udaljenost u metrima od središnje osi ceste (apscisa slike 11)*
[2]Z-coordinate represents elevation in meters – *koordinata Z predstavlja nadmorsku visinu u metrima*

Table 2 Comparisons of cut and fill volumes estimated by the traditional method and the model
Tablica 2. *Usporedba procijenjenoga obujma zemljanih radova standardnom metodom i modelom*

Segment Nº *Br. segmenta*	Distance *Udaljenost*	Road gradient *Nagib ceste*	Traditional method – *Stand. metoda*		Model – *Model*		Difference – *Razlika*	
			Cut Volume *Obujam iskopa*	Fill Volume *Obujam nasipa*	Cut Volume *Obujam iskopa*	Fill Volume *Obujam nasipa*	Cut Volume *Obujam iskopa*	Fill Volume *Obujam nasipa*
	m	%	m^3				%[1]	
1	21.84	–1.33	41.1984	29.3726	31.0145	28.4278	32.84	3.32
2	25.16	2.18	38.7107	31.2789	21.9750	25.0955	76.16	24.64
3	26.72	–2.17	27.1596	29.3404	28.8780	35.0607	–5.95	–16.32
Totals – *Ukupno*	73.72	-	107.0687	89.9919	81.8676	88.5840	30.78	1.59

[1][(Traditional method – Model) / Model] * 100

Cut and fill volumes were estimated by our model using cross-sections placed every 1 meter. For the traditional method, we only considered the cross-sections located at the beginning and end of each road segment. Volume estimates varied widely between both methods (our model and the traditional method) for the three road segments, ranging from –6% to 76%, but the circular road segment presented the largest differences (Table 2). Cut and fill volumes were overestimated by the traditional method for road segments 1 and 2 (from 3 to 76%), and underestimated for the last road segment (from 6 to 16%). All in all, the traditional method overestimated the total cut and fill volumes for the 3-segment hypothetical forest road by 30% and 2%, respectively, when compared with the results of the model.

Considerable variability in the cut and fill areas along the three road segments indicated that ground slopes along the road vary significantly (Fig. 12). This terrain variability caused the large differences in earthwork volume estimates between the two methods. While our model (by using 1-meter cross-section spacing) is able to capture details in terrain variations, these terrain details are ignored when only few cross-sections are considered in the traditional method. We also calculated the average value of the end areas resulted from the model and compared it with that from the traditional method (Fig. 12). The differences between the model average and the traditional method have a similar relationship as shown in the earthwork volume estimates presented in Table 2. This also suggests that the differences in earth-

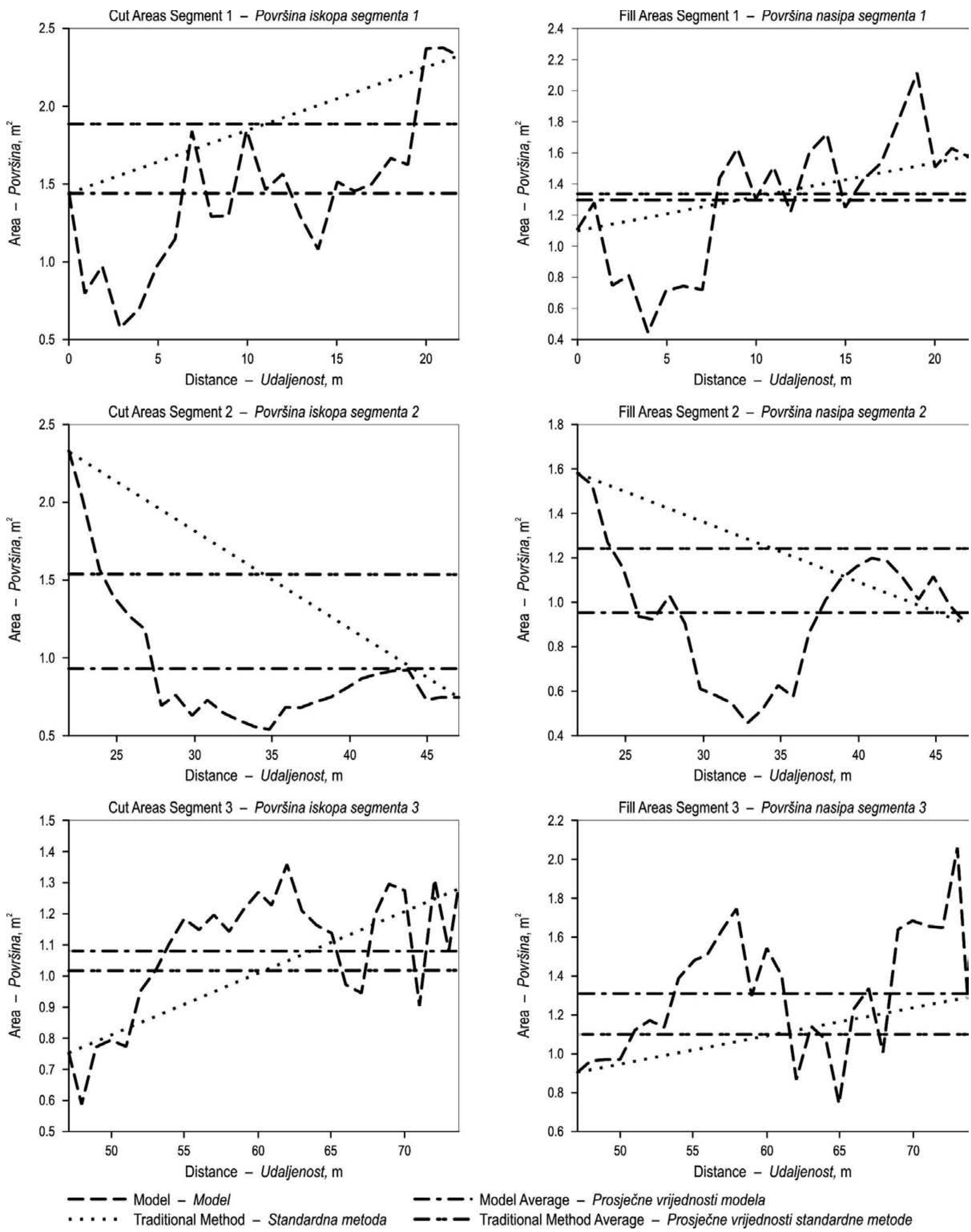

Fig. 12 Cut and fill areas for the 3-SP hypothetical forest road calculated by the model and the traditional method

Slika 12. *Površine iskopa i nasipa u točkama terenske izmjere na hipotetskim šumskim cestama izračunate modelom i standardnom metodom terenske izmjere*

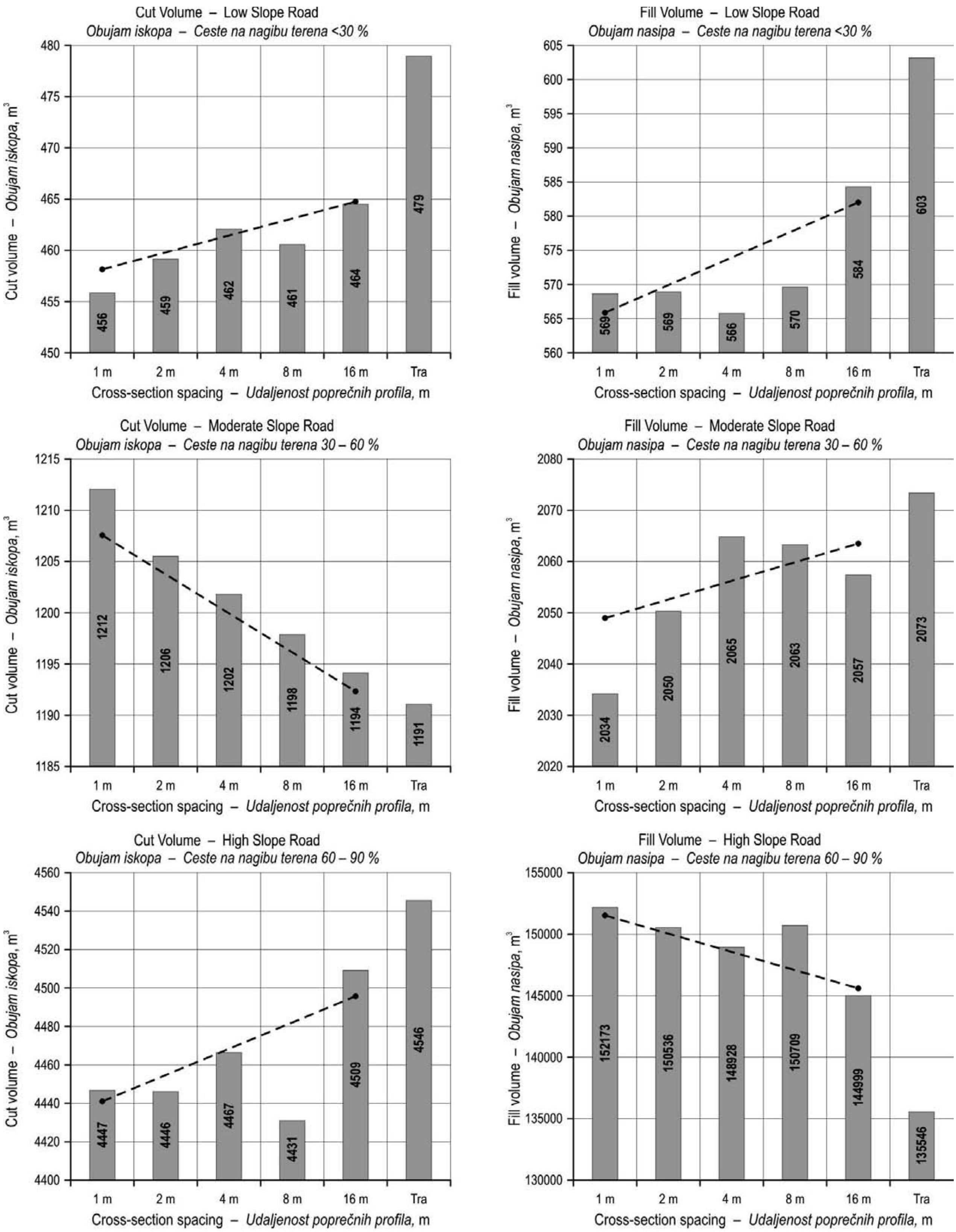

Fig. 13 Cut and fill volumes estimated by the model for the three hypothetical 1 km forest roads at different cross-section spacings

Slika 13. *Modelna procjena obujma iskopa i nasipa za tri hipotetske šumske ceste duljine po 1 km i za različite razmake između mjerenih poprečnih profila* work volumes between the two methods are caused by their different level of abilities to capture terrain variations. Due to the limitation in obtaining the »true« earthwork volume for a given road segment, it is impossible to properly verify our model for its earthwork volume estimation. However, our comparisons between the model results and the manual calculations of cut and fill area confirm that our model calculates correctly the earthwork volume and provides accurate estimates based on the assumption that the high resolution LiDAR-derived DEM provides an accurate representation of the ground surface.

4.2 Test case studies – *Testiranje studija slučaja*

The model results of earthwork estimation for different cross-section spacings on the three hypothetical 1000-meter roads are presented and compared with the traditional method in Figure 13. A trend line was added to the estimated earthwork volumes from our model to show the pattern of changes in volume across different cross-section spacings. For the low slope hypothetical road, the traditional method (labeled as »Tra« in Fig. 13) overestimated both cut and fill volumes by 5.0% and 5.9%, respectively, compared with the results of the model with 1-meter cross-section spacing. For the moderate slope road, the traditional method underestimated cut volume by 1.7% but overestimated fill volume by 1.9%. In contrast, the traditional method overestimated cut volume by 2.2% but underestimated fill volume by 12.3% for the road located on steep terrain. The model results from different spacings show a general pattern indicating that as cross-section spacing increases, the earthwork volume estimates become closer to the volumes estimated by the traditional method. This is likely explained by the fact that, as cross-section spacing increases, the ability to capture terrain variations that may exist between consecutive cross-sections decreases, making the volume estimates become closer to those of the traditional method. Although the trend lines may suggest a relationship between the results of our model and the traditional method, no evidence of consistency in over- or underestimation of earthwork volumes was found. Cut and fill volumes were either overestimated or underestimated depending on the specific terrain conditions of road segments.

Although Aruga et al. (2005) did not consider the same factors we did in this study, both studies realized that distance between cross-stations is important for accurately estimating earthwork volume. The shorter the distance, the larger ability we have in describing ground variability along the road lay out. Thus, it may be possible to estimate earthwork volume more accurately with short distances between cross-sections.

The results of earthwork estimation for the three ranges of terrain ruggedness are presented in Fig. 14. The number of road segments included in each terrain ruggedness class (coefficient of variation) is different. Therefore, to compare the three terrain ruggedness classes, we plotted the average cut and fill volume per linear meter of road for each cross-section spacing used by the model and the traditional method. As expected, the model results of cut and fill volume estimation were similar to the results of the traditional method on the road segments that have a low coefficient of variation. For road segments that are in the medium class of coefficient of variation, the difference in cut volume estimates between the model and the traditional method was minor, but fill volumes estimated by the traditional method were 13% lower than the model results with 1-meter cross section spacing. Lastly, for the road segments with high coefficient of variation (highly rugged terrain), the traditional method overestimated cut volumes by 10.4%, while it underestimated fill volumes by 20.9%. In general, it is noticed that the differences in earthwork volume estimates between our model and the traditional method become larger as terrain ruggedness increases.

Previous studies conducted by Aruga et al. (2005) and Akay (2003) also highlighted the importance of short distances between cross-sections in improving the accuracy of earthwork volume calculation, which is consistent with our findings in this study. The more rugged is the terrain where a forest road is laid out, the more important it would be to set out cross-sections in short distances in order to obtain an accurate estimation of earthwork volume. We recognize, however, that surveying a large number of cross-sections in the field might be a time-consuming task. We hope that the use of our model coupled with a high-resolution DEM can help improve the accuracy in earthwork volume estimation without much additional field work.

5. Conclusions – *Zaključci*

In this study, we developed a computerized model to accurately estimate earthwork volumes of low-volume forest roads using a high-resolution DEM, and analyzed the effects of cross-section spacing on the accuracy of earthwork volume estimates. Although the accuracy of earthwork is expected to increase as cross-section spacing is reduced, to our knowledge, our model is the first attempt to quantify the differences between methods using ground information only at station points (the average meth-

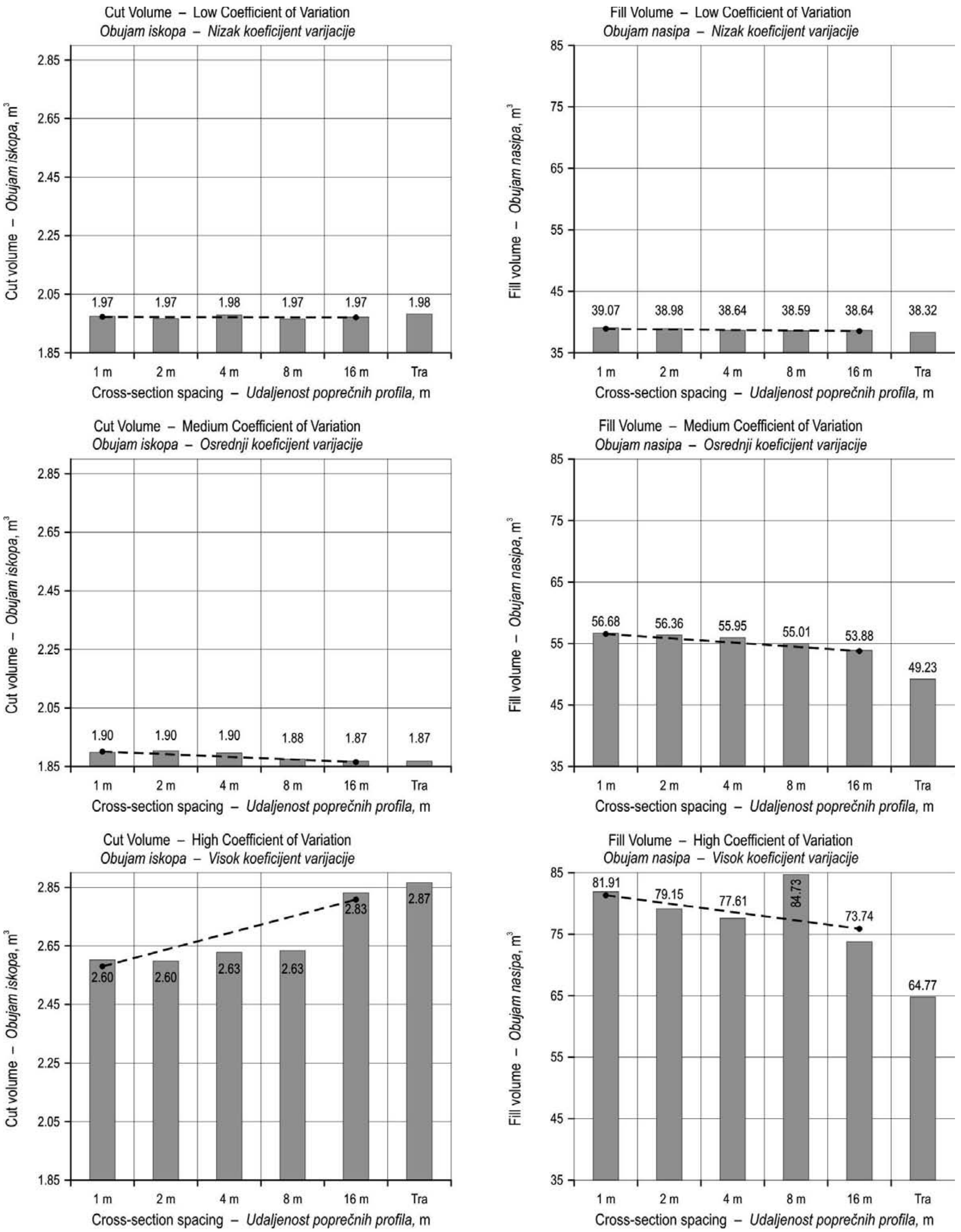

Fig. 14 Cut and fill volumes estimated by the model for the road segments classified into three terrain ruggedness classes across different cross-section spacings

Slika 14. *Modelna procjena obujma iskopa i nasipa dionica šumske ceste razdijeljenih u tri kategorije neujednačenosti terena za različite razmake između mjerenih (procijenjenih) poprečnih profila* od) and using high resolution DEM. When ignored, large terrain variations along road segments, as evidenced by the calculations of cut and fill areas from cross-sections spaced every 1meter, resulted in significant earthwork estimation errors. Our model offers a tool to help forest engineers to rapidly assess alternative forest road layouts and assist with planning activities to ensure the economic efficiency of forest road construction.

The model verification and application results correspond with previous studies (Kim and Schonfeld 2001, Aruga et al. 2005) in terms of the relationship between accuracy and cross-section spacing. Assuming that 1-meter cross-section spacing provides the »true« earthwork volumes, the accuracy of earthwork volume estimates decreases with the increase of cross-section spacing. Moreover, the discrepancies in earthwork volume estimates between our model and the traditional end-area method become larger in more rugged terrain. Consequently, short cross-section spacing should be used to capture terrain variations and estimate earthwork volume more accurately when forest roads are planned and located on mountainous and rugged terrain.

Several assumptions regarding cross-section design were made to simplify the estimation of areas and volumes as described in the method section. Although such assumptions may not seem practical, they do not affect our purpose of comparing earthwork volumes estimated at different cross-section spacings. In addition, the model can be further improved to consider real-world forest road survey and design practices.

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Sažetak

Poboljšanje točnosti procjene zemljanih radova za predložene šumske ceste primjenom digitalnoga modela terena visoke rezolucije

Zemljani su radovi (radovi na donjem ustroju) najveći trošak pri izgradnji šumskih cesta maloga prometnoga opterećenja i čine oko 80 posto ukupnih troškova izgradnje. Točnost procjene obujma zemljanih radova prijeko je potrebna pri procjeni troškova izgradnje šumskih cesta, racionalizaciji i kontroli troškovne sastavnice te pri *izgradnji i uspostavi ekonomski učinkovite primarne šumske prometne infrastrukture. Količina se zemljanih radova kod šumskih cesta uobičajeno temelji na procjeni podataka dobivenih terenskom izmjerom na trasi šumske ceste. Površina poprečnih profila procjenjuje se u svakoj točki izmjere, a zatim se klasične metode, kao što su metoda prosječnih površina ili metoda prizme, primjenjuju za izračun obujma zemljanih radova između susjednih poprečnih profila. Navedene metode pretpostavljaju jednoličan teren između poprečnih profila, što pri konačnoj procjeni rezultira nedovoljno točnim podacima u brdskim i planinskim područjima.*

U ovom je istraživanju razvijen računalni model poboljšane točnosti procjene zemljanih radova na šumskim cestama primjenom visoko razlučiva digitalnoga modela terena. Istraživan je utjecaj udaljenosti između profila na točnost procjene obujma zemljanih radova primjenom predloženoga računalnoga modela. Istraživane se šumske ceste nalaze u različitim reljefnim područjima, a prikazane su specifičnim terenskim čimbenicima te procjenom količine zemljanih radova za različite razmake između profila. Analiziran je utjecaj razmaka između poprečnih profila na točnost procjene količine zemljanih radova. Nadalje, utvrđena je varijabilnost površina poprečnih profila koja je korištena kao mjera nejednolikosti terena te su istraženi i učinci spomenute varijabilnosti na točnost procjene obujma zemljanih radova.

Izrađeni je računalni model primijenjen na trima hipotetskim šumskim cestama na terenima nagiba <30 %, 30–60 % i 60–90 %, a procjena obujma zemljanih radova dobivenih modelom uspoređena je sa standardnom metodom površina u točkama terenske izmjere. Općenito gledajući, rezultati pokazuju kako povećanje razmaka između poprečnih profila smanjuje točnost procjene obujma zemljanih radova zbog nemogućnosti uzimanja u obzir nejednolikosti terena. Utvrđene su razlike u procjeni obujma zemljanih radova između predloženoga modela i klasičnih metoda u rasponu od 2 do 12 % neovisno o nagibu terena. Jasniji je smjer primijećen kada se uspoređuju procjene obujma zemljanih radova predstavljenim računalnim modelom u odnosu na standardne metode. Povećanje nejednolikosti terena proporcionalno utječe na razliku uspoređenih metoda u rasponu od 2 % na jednolikim terenima (izraženo niskim koeficijentom varijacije površine profila) pa do 21 % na nejednolikim terenima (izraženo visokim koeficijentom varijacije površine profila).

Ključne riječi: šumske ceste, obujam zemljanih radova, projektiranje cesta, LiDAR, digitalni model terena

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