

Determination of Excavation Boundaries and Construction of the Profile of a Construction Site [†]

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Abstract

This article presents an in-depth theoretical analysis and a systematized methodology for the digital design of general site plans in construction engineering, based on the precise processing of digital topographic data. The focus of the research is the development of a complex engineering structure comprising a horizontal construction platform and two specific ramps—straight and curved—whose implementation is grounded in the fundamental principles of descriptive geometry and vertical planning. Through the application of the method of projections with numerical marks in an automated environment, the study demonstrates how geometric relationships can be transformed into an applied algorithm for defining complex spatial interrelations between design elevations. On this basis, not only the geometric configuration and dimensions of the structure are determined, but also its gradients, excavation volumes, and the flow directions of floodwater and stormwater runoff. The scientific novelty of the study lies in the systematization of a methodology for transitioning from theoretical geometric principles to the digitalized design of vertical planning within the environment of AutoCAD. The main contribution consists of the implementation of an algorithmic approach for generating an unambiguously defined and reversible model that integrates, within a unified process, the calculation of design contours, earthwork volumes, and hydrological runoff parameters. The study further demonstrates the operational interoperability of the generated data with highly specialized software modules, thereby providing a precise foundation for subsequent engineering-geological and linear infrastructure design.

Keywords: earth construction; excavations; embankment; design; construction site; numerical signs



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1. Introduction

The behavior of earth structures involving excavation works is highly complex, as their actual performance frequently differs from the assumptions established during the initial design stages. The construction process of earth structures comprises a wide range of procedures and operations. One of the most significant, costly, and technically demanding components is earthwork excavation. This encompasses a comprehensive set of activities carried out during construction, including trench and pit excavation, soil removal, transportation, and placement.

Earthworks constitute an essential part of every construction process, regardless of its purpose—residential, industrial, hydraulic, or transportation infrastructure. During these operations, embankments and excavated pits are formed, serving as the foundation for buildings, roads, and other engineering structures. In addition to conventional construction applications, such activities are also required for the implementation of landscape design concepts and vertical planning projects.

In engineering practice, there are structures whose horizontal dimensions significantly exceed their vertical dimensions. Typical examples include terrain surfaces with associated structures, roads, platforms, embankments, and similar facilities. For the design of such objects, the application of conventional orthogonal projection methods is often impractical. In these cases, the use of a specialized method—projections with numerical marks—is more appropriate. These represent a particular form of orthogonal projection characterized by the absence of a second projection plane, while still preserving the reversibility of the drawing.

The missing projection is compensated for through numerical marks indicating the distances of points and other elements of the designed object from a reference plane, which is usually identical to the projection plane itself. This method has been developed in particularly great detail within the fields of cartography and photogrammetry. Projections with numerical marks provide a means for representing spatial objects within a two-dimensional or three-dimensional environment, where numerical values are used to denote elevations, dimensions, distances, and other essential parameters. This approach is widely applied in engineering graphics, architecture, and geodesy. In engineering drawings, projections of specific components are frequently supplemented with numerical marks in order to represent particular construction details with greater precision.

Previous studies have primarily focused on optimizing the calculation of excavation volumes using the example of arbitrary topographic surfaces [1]. Some authors [2] examine methods for performing excavation works in foundation pits intended for foundation construction, as well as techniques for stabilizing and securing the excavation site. Their studies determine the bearing capacity of soils and evaluate the degree of its reduction based on physico-mechanical characteristics. Other studies [3,4] focus on the principal indicators of construction process efficiency, such as productivity, construction duration, labor costs, and overall production expenditures. In order to improve the efficiency of the construction process, these studies demonstrate the importance of clear process organization and the competent selection of construction equipment. They further establish that minimizing operational costs requires the optimization of earthmoving machinery utilization during construction activities.

Some authors, such as [5], present numerical and analytical methods for the rapid assessment of the impact of excavation pit development on the displacement of the surrounding soil mass while taking into account the stiffness of the retaining structure. Their approach is based on solving the problem through numerical modeling using the Design of Experiments (DOE) method. According to these researchers, it is necessary, even at the preliminary design stage of excavation development, to perform calculations for multiple design alternatives in order to evaluate the impact of the construction process on adjacent buildings and surrounding structures.

The authors in [6,7] define the types and volumes of work required for the organization of temporary construction infrastructure facilities and elements, including the possibility of subsequent financial settlement for completed construction and installation works. Other studies, such as those presented in [8], compare the Monge projection method with projections using numerical annotations and conclude that it is easier to construct point projections and mentally visualize their spatial positions when projections with numerical markings are applied.

Thus, although previous studies have focused on the development of methods for determining earthworks using projections with numerical marks, there is still a lack of a proposed model based on computer-aided design (CAD) environments.

Therefore, the aim of this study was to design a structure according to a given site plan, consisting of a horizontal construction platform, using an automated system for generation based on two-dimensional CAD design in AutoCAD 2025. As a result of the reviewed and analyzed sources related to the design of construction sites with numerical marks, the focus is directed not only toward the geometry and dimensions of the structure, but also toward slopes, excavation volumes, and the direction of stormwater and flood runoff. Based on the adopted methodology and preliminary data, a computational-graphical study was carried out to determine the slope intervals of embankments and cuttings within the AutoCAD environment, which are of critical importance for the accurate definition of excavation boundaries.

An integral part of the architectural design documentation consists of drawings that provide information on site layout and landscaping around the building, the relationship between the designed structure and the terrain, the arrangement of pathways, sidewalks, and the organization of surface water flow. All this information is contained in a dedicated section of the project, which, in addition to the general site plan and other supporting materials, includes drawings and diagrams of the vertical planning of the built-up area.

Vertical planning objects are areas of the earth's surface with various structures located on them, such as construction sites, pits, embankments, excavations, drainage basins, and similar elements. A distinguishing feature of these objects, in addition to their geometric form, is the significant predominance of horizontal dimensions over vertical ones; therefore, the method of orthogonal projection onto two or three mutually perpendicular projection planes is not suitable in such cases [9,10]. In architectural design and construction practice, a specialized method for representing the earth's surface is used, known as the method of projections with numerical marks.

The essence of this projection method is that the represented object is orthogonally projected onto a single horizontal projection plane only. The resulting image is referred to as a plan [11,12] (Figure 1).

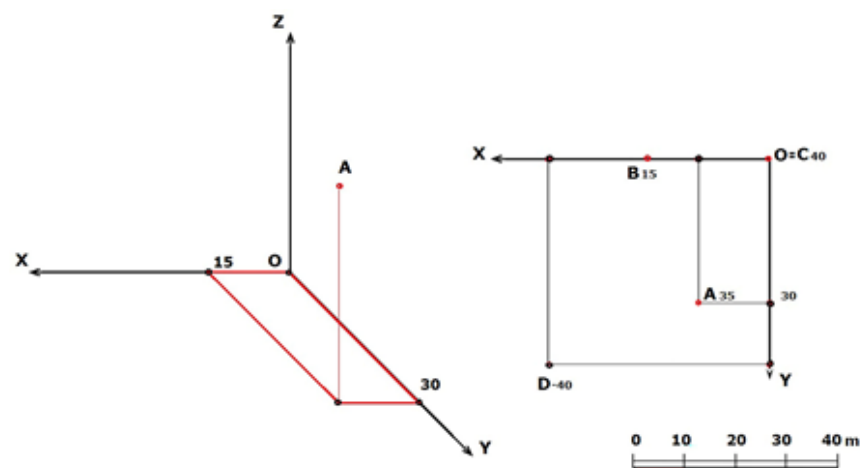


Figure 1. Site plan.

The plan shows only two dimensions of the object: its length and width on a single horizontal projection plane [13]. The third dimension—the vertical projection—representing the elevations of the object's points, is expressed numerically through annotations (numerical symbols). These values define the distances of the characteristic points of the object from the reference projection plane, taken as zero and denoted as P_0 . A minus sign is placed before

the numerical value if a point is located below the zero reference plane. The projections of points are designated either by letters with numerical indices or by numbers alone. The absolute elevation values are given in meters (Figure 1).

It should be noted that, in order to fully determine the spatial position of the object represented in the plan, it is necessary to specify the drawing scale as well as the linear unit in which the numerical marks are expressed. The interval between contour or grading intervals is typically 1 m.

2. Exposition

A common problem is the determination of excavation boundaries during construction site organization, which involves defining the lines of cutting and filling as well as designing slopes according to the given project requirements.

The determination of excavation boundaries is a critical process in construction site organization. It includes precise geodetic identification of the area where excavation activities will be carried out, while ensuring safety, efficiency, and compliance with the design documentation [14]. The use of the graphical CAD system AutoCAD enables a relatively simple, fast, and accurate determination of the structural geometry and its dimensions.

If the platform level is higher than the existing ground surface, the construction area is formed as an embankment; if it is lower, it is formed as an excavation. Figure 2 presents a schematic cross-section of a road body transitioning from a cut zone to a fill zone, illustrating how slopes and the subgrade of a conceptual platform are formed. From the profile, it can be seen that point O must first be defined for the embankment, with the ground surface marked to the left of this point. Point O represents the zero-work point, indicating the transition between cut and fill, where the design elevation coincides with the natural terrain level. The lines EF and CD represent the intersection lines between the excavation and the topographic surface and are referred to as earthwork boundaries. In order to determine these boundaries, it is necessary to calculate their corresponding volumes. The slope angles φ and φ' of the excavations depend on the specified design requirements for slope inclination.

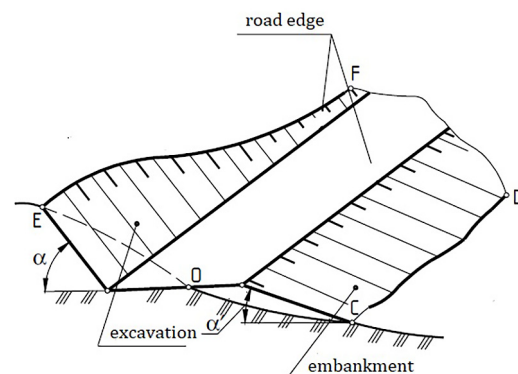


Figure 2. Image of an embankment, excavation, and cross-sectional profile of a conceptual construction platform.

It should be clarified that embankments are earth structures in which soil is added and compacted in order to create an artificially elevated ground level. They are commonly used in the construction of roads, railway lines, hydraulic structures, platforms, and other civil engineering projects. Excavations are an essential part of construction activities in which soil masses are removed to create space for foundations, infrastructure, underground utilities, or other structural elements. The planes and surfaces that define the construction site on all sides and connect it to the natural terrain are referred to as slopes [15]. The inclination of slopes is selected depending on the type of soil and is defined during the design stage of construction projects.

The work involved in constructing the slopes of excavations and embankments, as well as the intersection lines between slopes and the topographic surface, depends on a number of parameters. Based on a given site plan, a structure has been designed consisting of a horizontal construction platform and two ramps. The terrain horizontal platform is defined at an elevation of +20.0 m. A ramp is a section of a road characterized by a longitudinal slope. The construction of the building platform has been carried out on the basis of the specified parameters of the design elements and earthworks (slopes) presented in Tables 1 and 2, as well as the defined criteria for boundary determination listed in Table 3.

Table 1. Parameters of project elements (Scale 1:200).

Object Element	Project Kota/Slope (<i>i</i>)	Interval (<i>l</i>) [m]	Drawing Step (<i>d</i>) [mm]	Characteristics
Venue	+20.00 m	0.00	0.00	Horizontal surface
Ramp Rights	1:6 (16.7%)	6.00 m	30.0 mm	Constant longitudinal slope
Twisted ramp	1:4 (25.0%)	4.00 m	20.0 mm	Radial contours
Field Lines	in the 1.00 m	-	5.0 mm	Main relief

Table 2. Parameters of the terrestrial body (Slopes).

Type of Earthwork	Condition (<i>H_t</i> vs. <i>H_p</i>)	Slope (<i>i</i>)	Drawing Step (<i>d</i>) [mm]	Graphic Indication
Excavation	$H_{terrain} > 20.0$	1:1	5.00 mm	Short/long line to the subject
Embankment	$H_{terrain} < 20.0$	1:1.5	7.5 mm	Short/long line to the pitch

Table 3. Criteria for setting boundaries.

Stage	Action	Criterion	Purpose
Zero Line	Crossing the loop at elevation 20	$H_{terrain} = H_{project}$	Separates the excavation from the embankment
Designed contour	Intersecting named contours	$H_t(n) \cap H_p(n)$	Defines the scope of an excavation/embankment
Vertical Cut	Projection on a cutting plane	$\Delta H = H_t - H_p$	Visualization of profile A-A
Volumetric masses	Cross-sectional area x length	$V = \sum (F_{avg} \cdot L)$	Quantity Bill

Based on the provided technical parameters, the procedure for the precise determination of excavation and embankment boundaries is carried out using the following algorithm:

- Definition of the “Zero Line” (Intersection Line);
- Determination of the elevation at an arbitrary point on the ramp (H_x).

$$H_x = H_{basic} \pm (i \cdot L) \quad (1)$$

where *i* is the longitudinal slope of the ramp, and *L* is the distance from the starting point. Plan width of the slope (*S*):

$$S = (H_{terrain} - H_{project}) \cdot m \quad (2)$$

where *m* is the slope coefficient (e.g., 1:1 or 1:1.5).

- Calculation of design intervals (*l*)

For the graphical construction of slopes (batters), grading intervals are used, calculated by the formula:

$$l = \frac{1}{i} \quad (3)$$

where

for excavation ($i = 1:1$): $l_{\text{exc}} = 1.00$ m horizontal distance for each 1 m of vertical height
for embankment ($i = 1:1.5$): $l_{\text{emb}} = 1.50$ m horizontal distance for each 1 m of vertical height

- Grading of the design surfaces;
- Determination of boundary points (Intersection method);
- Finalization of the design contour;
- Verification through a vertical section (profile);

3. Results and Discussion

3.1. Determination of Excavation and Embankment Boundaries

The intersection lines between the slopes of cuts and embankments and the ground surface are known as slope boundaries. These boundaries on the drawing define the lines of soil removal or addition, enabling the calculation of the earthwork balance (i.e., the agreed volumes of excavation and fill). The construction of slope grids is shown in Figure 3a. The diagram illustrates the lines of the specified slopes and their corresponding intervals. Embankment values are plotted on the vertical scale, while excavation values are plotted on the horizontal scale. These define the zones where either cutting or filling is performed. The zero point defines the location where the excavation and embankment lines intersect the natural ground surface, meaning that no earthworks are required at that location. The drawing scale is 1:200, the grid spacing is 5 mm, and the grid interval is 10 mm.

[–]Top[2D Wireframe]

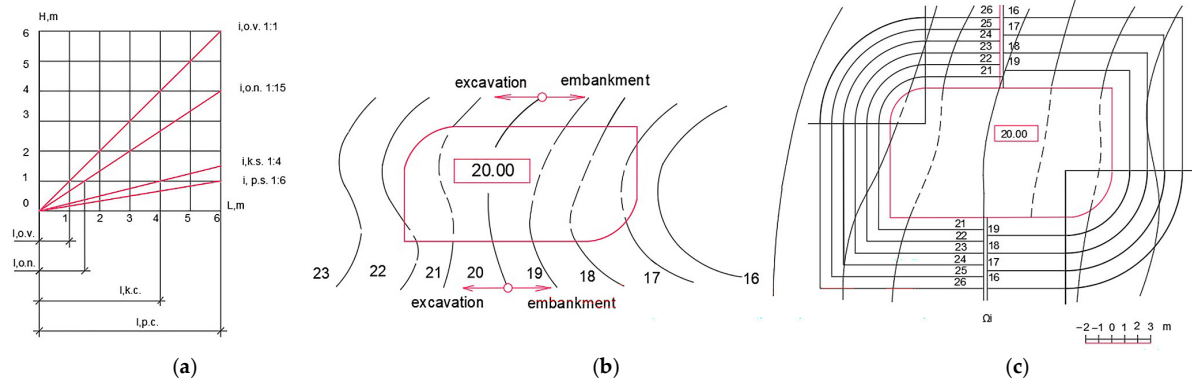


Figure 3. Site data: Slope scale (a); terrain horizon (b); markings of the project contours (c).

Figure 3b presents a horizontal plan with contour lines used for the design of earthworks, including both cut and fill zones. The method employs numerical annotation of spot elevations to define vertical dimensions. The curved numbered lines (16 to 23) represent the contour lines of the existing terrain, where the numbers indicate the absolute elevation (height in meters).

The central design area represents a horizontal construction platform with a constant design elevation of 20.00 m. In zones where the natural terrain has a higher elevation than 20.00 m (e.g., 21, 22, 23), earth excavation is required, and these areas are defined as cut zones. In zones where the natural terrain has a lower elevation than 20.00 m (e.g., 19, 18, 17, 16), embankment is performed in order to reach the design level. The intersection line marks the boundary of the construction platform, where the slopes of either cut or fill begin.

The dashed lines indicate the slope gradients, which connect the designed platform to the existing terrain surface.

3.2. Construction of Design Contours

The construction of design contours (Figure 3c) is carried out based on two parameters: direction and interval. In the construction drawing, the intervals are indicated along the slope scale line, which is drawn through the points defining the boundaries of the embankment and excavation.

From Figure 3c, it can be observed that, on embankment slopes, the markings of the design contours of the platform decrease, whereas on excavation slopes they increase. Initially, the design horizontal lines of the ramps are drawn perpendicular to the reference axis at appropriate intervals, as shown in Figure 4a. In the case of a curved alignment, the interval length is measured along the axis of the alignment, while the direction of the horizontal lines is radial. For ramp slopes, the design contours are not parallel to the ramp outline but are instead positioned tangentially to the horizontal sections of auxiliary cones, with their apex located at the intersection point between the alignment contour line and the object boundary. The slope of these generating cones is equal to the slope of the ramp surfaces. The horizontal sections of the auxiliary cones are circles with radii equal to multiples of the interval value. An auxiliary construction is used for their graphical representation (Figure 4b).

[-][Top][2D Wireframe]

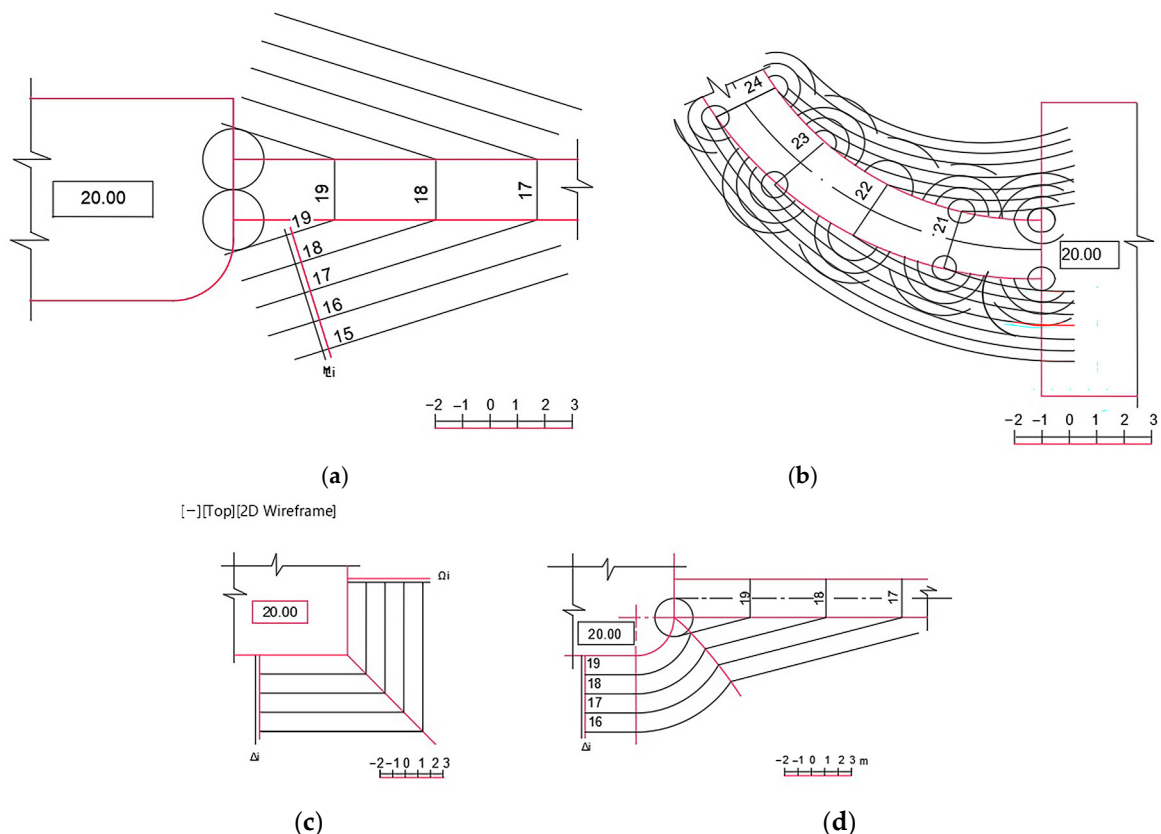


Figure 4. Construction of the intersection line of the ramp: perpendicular to the initial axis (a); with auxiliary axis (b); with transition points for straight lines (c); with curved line (d).

At the intersection point of the alignment contour lines with the object boundary, a circle is drawn with a radius equal to the interval value, corresponding respectively to the

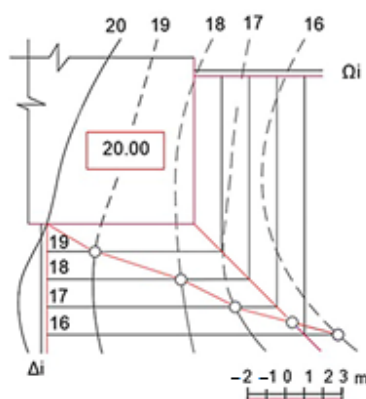
slopes of the embankment or excavation. The horizontal slope line of the ramp marked 21 (Figure 4b) is constructed as a tangent to this circle.

The intersection lines of adjacent slopes are constructed using transition points, i.e., segments of the same design slope contours (Figure 4). If both adjacent slopes are planar, the line of intersection between them is a straight line (Figure 4c). If at least one of the slopes is curved, the resulting intersection line between the slopes may become a curved line (Figure 4d).

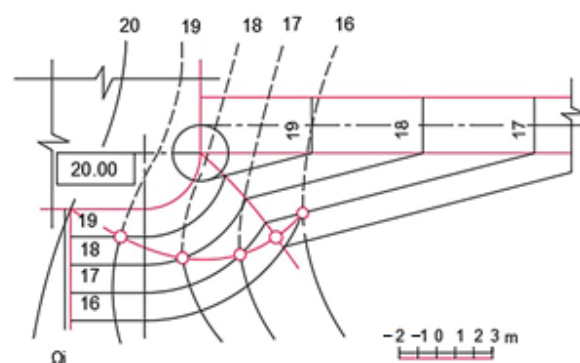
3.3. Construction of Intersection Lines Between the Structure Slopes and the Ground Surface

The intersection line between the slopes of the structure and the ground surface is constructed through the intersection points of identical design slope contours and terrain contours (Figure 5). For a straight slope, adjacent points are connected by straight-line segments (Figure 5a), while for a curved slope, they are connected by a smooth curved line (Figure 5b).

[–][Top][2D Wireframe]

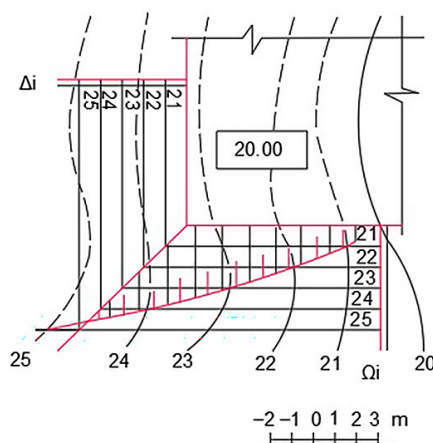


(a)

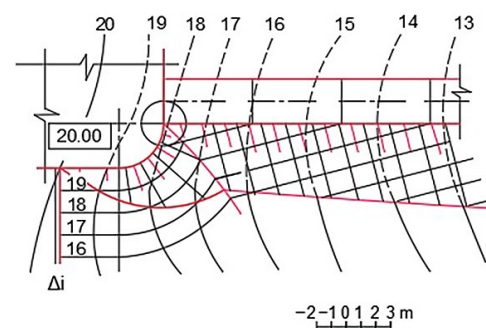


(b)

[–][Top][2D Wireframe]



(c)



(d)

Figure 5. Construction of the lines of intersection of the slopes of the structure with the ground surface: for a straight slope (a); curved slope (b); direction of water flow for straight slopes (c); for curved slopes (d).

In this case, it is necessary to construct the corner (vertex) points of all slope intersection lines. To construct them, the intersection line between the structure slope and the ground surface is extended up to point 16, which lies on the side of the adjacent slope. It is sufficient to construct each corner point from the side of one slope only. The corresponding line from the adjacent slope is then extended to crossing it.

3.4. Design of Slope Hatching and Profile Construction

Slope hatching are symbols used in technical documentation for earth structures and are widely applied in construction drawings. They indicate the direction of surface water flow along the slopes of the structure.

They provide a quick and clear visual representation of slope orientation, especially in more complex geometries such as conical slopes. Their direction is perpendicular to the design contour lines of the slopes (Figure 5c). In the case of a conical slope, this corresponds to the direction along the formations of the cone (Figure 5d).

The position of the profile is determined by the distance from the intersection points of a given cutting plane with the horizontal contours of the area outside the boundary of the structure. Figure 6a shows the distance between points with elevations 18 and 23. In the profile, the horizontal position is plotted along the horizontal axis, while the elevations of the points are plotted along the vertical axis according to the specified scale. On the base line, all intermediate points are marked: 19, 20, 21, 22, 23, and 24. Each point of the profile is projected vertically to its corresponding elevation level. Adjacent points are connected by straight-line segments. The resulting profile line of the topographic surface is marked with a conventional symbol consisting of alternating triple hatch marks drawn at a 45° angle to the drawing frame line.

For constructing the structural profile on the base, the following key points are defined: start of earthworks, start of platform, end of platform, and end of earthworks. The start and end points of excavation are placed on the profile line of the topographic surface, while the start and end points of the platform are placed at elevations corresponding to the horizontal design level. The constructed points are then connected by straight segments. The embankment section in the structural profile is represented using the conventional symbol for fill material (Figure 6b).

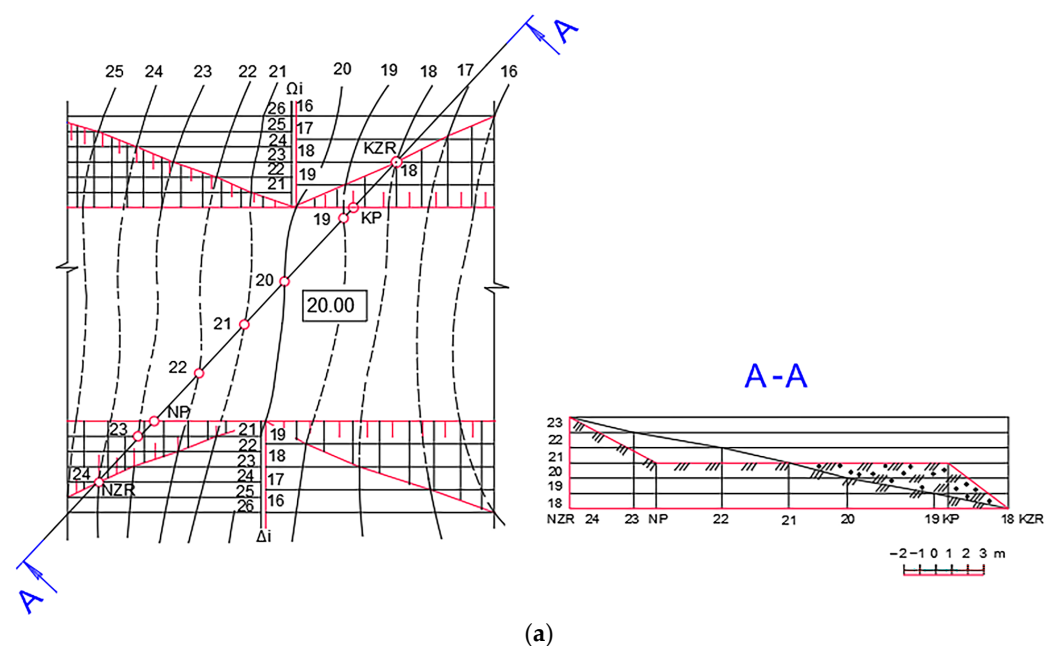


Figure 6. Cont.

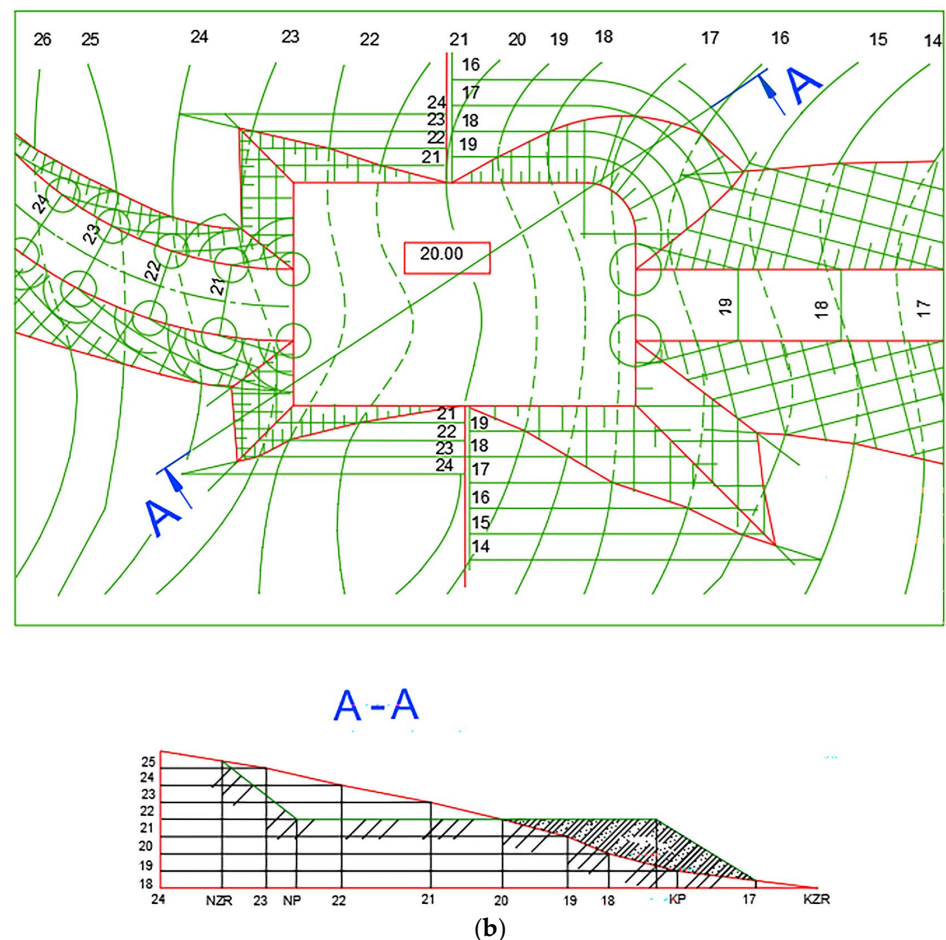


Figure 6. Distance between the points with elevations 18 and 23 (a) and construction of the structural profile on the base (b).

4. Conclusions

The conducted study successfully demonstrates that the synthesis between classical methods of descriptive geometry and modern computer-aided design systems (AutoCAD) provides a highly efficient methodology for modeling earthworks. The results of the work are expressed in the precise graphical and numerical definition of complex geometric structures—horizontal platforms and ramps with variable slopes—integrated into a real topographic environment.

The main outcome of the research is the development of an intelligent algorithm that establishes interaction between the theoretical method of projections with numerical annotations and digital drafting tools. By applying specific automation functions, the study transforms static topographic data into a dynamic model that enables the simultaneous generation of plans, sections, and quantitative parameters.

The significance of the developed approach is further strengthened by the fact that it optimizes the transition to the next level of design—the integration of prepared data into AutoCAD Civil 3D. In this way, the obtained results are used not only for the execution of the initial construction phase (the so-called “zero cycle”), but also for long-term analysis of infrastructure sustainability, including drainage management and erosion control.

From an economic perspective, the precise balancing of cut and fill volumes in a digital environment leads to a significant reduction in transportation costs and construction time. Ultimately, the presented methodology establishes AutoCAD not merely as a

drafting tool, but as an essential engineering system for managing the full lifecycle of a construction project.

The proposed methodology is highly valuable not only in education but also in professional practice, as it can be applied in specific geodetic and engineering algorithms.

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