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Mathematical model prototype to optimise engineering management of the construction site

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ABSTRACT
Modern construction technologies strongly affect the environment. Therefore, design and building construction should also follow the sustainable development principle. In this case, design and construction work based on the sustainable development principle should aim at creating a safe and healthy living environment, the economical use of natural resources, and the stimulation of economic development to create the welfare for humans and favourable natural conditions. The article proposes a mathematical algorithm as a comprehensive solution for engineering management of the planning construction site, from the calculation of the earthworks to the automated creation of the engineering geological cross-sections. The paper integrates engineering management, mathematical modelling, and BIM technology. The application of the building information model is undoubtedly one of the most advanced technologies used in the engineering management field, whose advantages have been shown by researchers. In the preliminary stage of construction and production management, decisions should be made regarding material and human resources, schedules, and estimates. The main purpose of this article is the optimisation of the excavation. Other issues important to the organisation and management of the construction are the planning of safe work on the construction site, depending on the soil type. Geotechnical sections allow ascertaining the need for additional fortifications and the depth of the fortifications for safe work. The paper describes the principal mathematical model developed by the authors to design a construction site using BIM technologies. It presents the main formulas of a mathematical algorithm aimed at selecting the objects used on the building site and the need for them. It also gives the main principles of engineering management and methods for selecting the mechanisms used on the construction site. Understandably, a specialist's visit to the construction site will not be avoided, and it is difficult to present the entire current situation only with a review report or photographs. Using a photogrammetric model, the expert has the opportunity not only to visually evaluate the current condition but also to perform measurements (length, width, and volume) directly in the photogrammetric model. Important and new information about the construction site indicates all relevant obstacles, i.e., plants, surrounding constructions, and other objects.

KEY WORDS
BIM, building information modelling, engineering management, building site planning, building site management

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Introduction

A construction project is a complex process that requires not only specific knowledge but also managerial skills. Therefore, engineering management and technology management are especially important factors for proper planning and management of a construction project. One of the main problems in the organisation of construction activities is the inefficient planning of construction execution, which increases the cost of construction, prolongs construc-

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tion work execution time, and irrational use of construction machinery and building materials. Construction is one of the first conscious activities of humankind, born from the original human security needs. In its first manifestations, construction was a rather primitive integral process that united three components: thought, means, and action. From today's perspective, these are different components that can already be seen as the beginning of individual stages: the idea, planning, design, measures and actions — construction works. Later, as humanity evolved, construction processes became more complex, forming aesthetics and style. The need for specific knowledge and qualifications separated the individual activities, giving rise to such concepts as "architect", "engineer", etc. The most impressive transformation occurred when simple activities became science and art. As a result of this process, construction (in the general sense) was broken down into a sequence of independent processes with different actors. Today, this sequence is known as an extended concept of the life cycle of a building (project) that begins with the idea of the building and ends with its demolition.

When engineering management is performed, and the construction site is planned, all the factors and risks that may arise in construction management must be considered. It is well known that using the BIM methodology, a building is built twice: first, virtually, and then physically. An analysis of foreign scientific literature revealed that in German-speaking countries, the preparation for construction is separated into an individual stage of construction project management, while in English-speaking countries, it is decided just before the construction or during the construction stage. Of course, the stage selected for addressing the issues of preparation for construction depends on the model implemented by the construction project. Therefore, the earlier the relevant decisions are made, the less costly will be the changes in the future, both in terms of time and money.

Next, in a brief discussion, the authors consider the structure of information system prototyping. It is assumed that the current situation is captured by virtual reality technologies. Tools are currently being developed to capture the current situation using photogrammetry and laser scanning. Using the scanned model further, it is necessary to convert the resulting model to a parametric model. At this stage, no effective solution has been found to automate it. Manual conversion of point cloud to the BIM model is currently available. To effectively plan a construction site, it is necessary to know vacant sites, locations unavailable for machinery installation, the building of temporary roads or designing temporary infrastructure. Currently, this can only be achieved manually, i.e., simply rendered in 3D space, considering the competence of the draftsperson.

One of the most important problems at this point is that current software solutions cannot fully resolve the question of planning construction sites. As shown in Fig. 1, there are still plenty of manual steps to complete the construction-site design process.

Digital technology can have a significant impact on construction management processes. The advantages of BIM technologies for designers are optimised design solutions using the variant design method, improving the quality of the projects and reducing

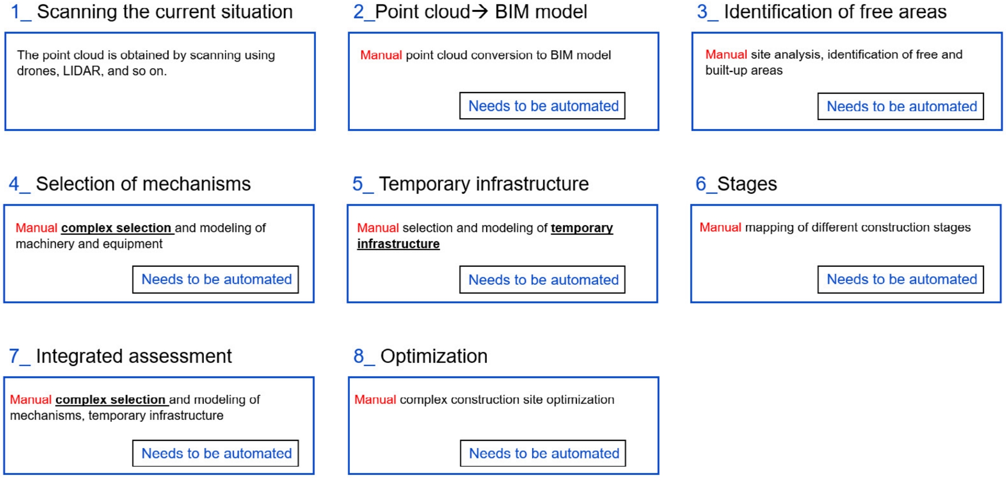

Fig. 1. Information system prototyping structure

labour costs. In engineering production, BIM technologies made it possible to introduce a unique industrial construction, whereas previously, industrial housing construction was associated only with type series and catalogues of standardised products. During the construction management phase, BIM technologies affect the following activities: work planning and management; supply of materials, equipment, and components; performance construction and installation works; carrying out acceptance events; and documentation of works. However, before planning any construction work, it is necessary to carry out the earthworks. The earthworks analysis is useful not only for the design of a building and the calculation of structures, but the results of the earthworks analysis are also extremely beneficial for planning the organisation of construction works.

1. Brief review of the literature and software

Many BIM-related scientific articles and conferences discuss a common data environment, cooperation between project participants, and building modelling. As known, the greatest impact on the investment can be made at its earlier stage. Therefore, the design of a building begins with an analysis of the existing situation, which is very important not only for foundation design but also for construction management planning. Therefore, when analysing the topic of the present article, all articles that somehow analyse BIM and geotechnics were considered. The extensive analysis showed currently no available suggestions for a comprehensive solution for visualisation, design, and optimisation of soil calculation. With a certain solution, engineering management is less risky. Thus, the balance is between three topics of scientific articles that analyse BIM integrity and geotechnics, visualisation, case study, and optimisation. The ways of visualising the land vary depending on the designer's software tools. It is possible with Autodesk Products to successfully visualise soil layers, for example, as indicated in several articles. The efficient three-dimensional visual expression of survey data can not only weigh the scheme scientifically but also make decision-making convenient, simple and efficient. The 3D virtual terrain environment is modelled based on Autodesk Civil 3D and used to assist the geotechnical engineering survey and design. Engineers can view the geological structure data more accurately and intuitively in the real 3D environment, making the design scheme more effective and reasonable (Bai et al., 2021; Berner et al., 2016; Fadoul et al., 2018). There are also solutions in the literature to optimise not only the relevant work related to soil design but also representing a construction site with pairs of simple polygons — demand and supply areas — fully contained in it. The tasks in the articles are different, from the selection and the location of cranes on-site in a cost-minimal way to the systematic exploration of capabilities of virtual prototyping to assist designers in focusing on detailed elements of design optimisation, such as connections, geometry, weight, etc. The assessment also incorporates the importance of part minimisation, standardisation, waste reduction, efficiency improvement, and reduction of on-site operations, machines, and workers (Briskorn et al., 2019; Gbadamosi et al., 2019; Jing et al., 2021; Mahmoudi et al., 2021; Xu et al., 2020). However, no solution was found that would include, for example, calculation, visualisation, and optimisation. Another topic that appears more and more frequently in scientific articles is a case study. The preload analysis process model created by Civil3D can consider uneven settlement during the stacking period in a large-scale site to obtain accurate stacking and unloading engineering quantities (Jian, 2021). BIM has become an important tool for creating a detailed process of building the geotechnical database and the informative geotechnical model, and the geotechnical data. The result of the analysed article (Zhang, 2018) shows that the geotechnical data archived with the proposed strategy can be integrated into the BIM model to form a complete BIM model, which can make decisions and maximise the past investment in geotechnical data. Others present (Wei et al., 2021) the support of BIM software at home and abroad for the scope of application of the BIM model calculation method in the field of landslide control and risk as not enough to completely restore the complicated field situation, but not fully checked in the field of geology. In addition, the focus now is on the combination of geological 3D modelling and BIM with the intention to display BIM projects in the geological surroundings, which is used similarly to a traditional site investigation. Geotechnical data gathered as construction proceeds can be implemented, so the geological and geotechnical situation can be displayed in context. Geotechnical 3D models, which are parallel and based on the geological model, are also used. In them, geotechnical units (rock mass types) are modelled as volume blocks and linked with geotechnical parameter sets (Cudrigh et al., 2018).

In contrast to BIM technologies, which are used to create digital terrain models and building structures in the field of engineering and geological surveys, up to now, the collection and processing of research data have been carried out manually with a presentation in the form of reports on paper or, at best, in digital form in ASCII and XLS formats. Simultaneously, the results of soil stratigraphy determination are presented in JPEG, BMP, etc., in the form of lithological columns and two- or three-dimensional cuts. Among the programs most used by geotechnical engineers are GEO5, PLAXIS, STIMAN, etc. Note that in programs for graphical construction of a two- or three-dimensional geological model, AutoCAD, MicroStation, and NanoCAD are used. All these and other known programs focus on storing data from engineering-geological and geotechnical studies and their processing. An analysis of the programs for geologists noted above shows that they all have the following disadvantages: (1) field and laboratory test data are entered into test data interpretation programs manually into the appropriate tables or via Excel, (2) the absence of a procedure for automatically determining the soils characteristics from geological and geotechnical studies necessary for calculation of bases using analytical decisions, (3) the lack of procedure for determining parameters for soil models from geological and geotechnical research required to calculate the stress–strain state of foundations using numerical methods, (4) the lack of connection between geological and geotechnical studies and programs for calculating foundations for limit states, (5) the lack of assessment of the heterogeneity of a natural soil massif and its influence on the behavior of construction objects, (6) traditional representation of a three-dimensional model in the form of soil layers, and not in the form of a digital field of soil characteristics, and (7) the presentation of research data in the form of a paper report in docx or pdf formats. However, a more significant drawback is the impossibility of transferring data from geotechnical surveys in digital form from the geological programs noted above into geotechnical programs. Geotechnical level programs, e.g., Flac, Z-soil, MidasGTS, etc., perform the calculation using the data from engineering, geological, and geotechnical studies. Usually, solving various engineering problems in geotechnical programs is associated with manual input of soil characteristics directly into programs or using the appropriate procedure of a specific finite element program.

2. Main purpose and methodology

The main task of geological and geotechnical engineering research is to create a computational geomechanical model that will help in engineering management. Traditionally, a geomechanical model is a three-dimensional soil mass consisting of various engineering geological elements and a set of normative and design geological models. It is necessary to carry out the following work: (1) an analysis of engineering and geological surveys of previous years, (2) the determination of the name of soils according to static sounding data and building a lithological column, (3) a complex of laboratory and field studies of soil properties, and (4) 2D or 3D digital imaging of soil characteristics. One of the existing problems is the definition of the boundaries of engineering–geological elements, which are often subjectively found by a geotechnical engineer, especially in the presence of lenses or wedging of soil layers.

To increase the accuracy of the geological layers and boundaries, a digital model of soil characteristics should be developed. Then, the available completed information allows a broad and accurate analysis of

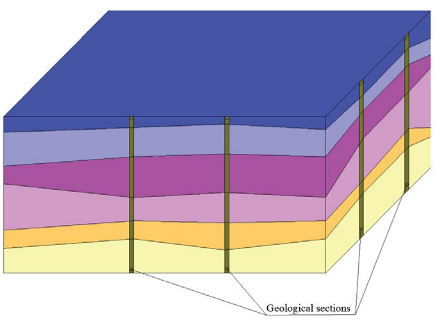

Fig. 2. Geological sections

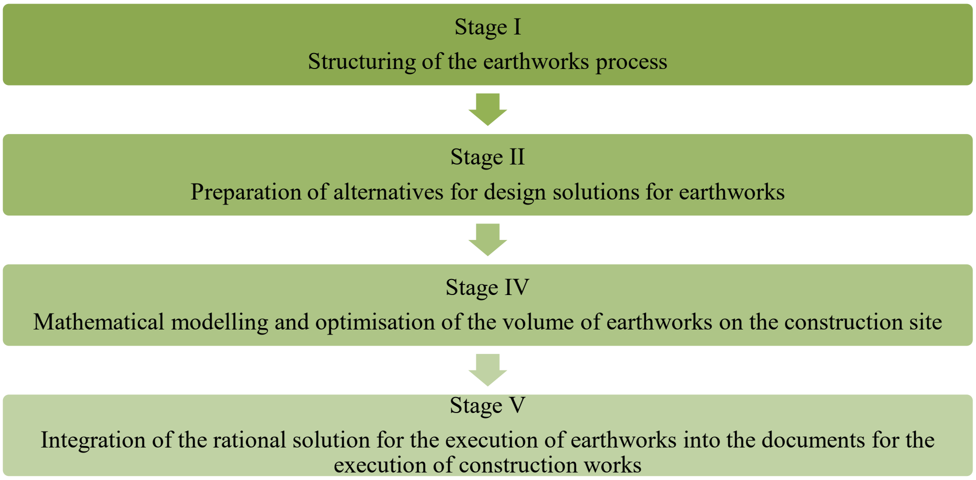

Fig. 3. Rational design solutions for the performance of earthworks

the soil. In the construction engineering preparation system, rational design solutions for the performance of the earthworks are prepared in the following stages.

3. Mathematical modelling and optimisation of earthworks on the construction site

A project made with BIM technology is built twice, once virtually and then physically. BIM technology and principles apply not only to buildings but also to all construction-related processes, including the calculation of earthworks. Therefore, it is vital to fully analyse the current situation in advance and perform a simulation of the planned works. When planning construction work, one of the most important advantages of BIM technology is the calculation of earthworks. This section presents mathematical modelling and optimisation of the volume of earthworks, which are necessary for the designer to develop a construction organisation project, during which engineering and production management are planned. The average range of ground movement is determined by the designers to calculate the labour costs for the execution of earthworks according to the vertical layout, choose a set of earth-moving vehicles and estimate their costs. An analysis of the works allowed concluding that no relationship has been established between the volume of soil and the range of its movement from the slopes of the projected site. Therefore, the study focuses on the influence of the slopes of the construction site on the volume of the soil and the range of its movement. Converting the natural terrain into an easy-to-build view is carried out vertically on the site layout. Experience has shown that when planning work, due attention is often unpaid to the preservation of the vegetation layer, which must be cut off and saved for reclamation of disturbed relief areas before starting site planning work.

Construction site planning can be carried out at a given planning level or with a zero balance of the earth masses. To drain the atmospheric water, slopes are attached to the construction site. When developing documentation for the vertical layout of the site slopes, they are set intuitively, based on the designer's experience. To study the effect of construction slopes on the volumes of earth masses and their distance, the movement was taken on a platform measuring 120 by 160 m, which is divided into squares with a side of 40 m. In the study, 46 options for various slopes were considered. A site without slopes (horizontal) was taken as an assessment option. The calculated results obtained as volumes of earthen masses (V_i,m^3) and distances of soil movement (L_i, m) are expressed in relative values, i.e., the percentage of the volume of earth masses (P_v) and the range of their displacement (P_L) on a horizontal platform. The conducted studies of changes in the volume of earth masses and the distance of their movement from the slope construction sites showed that the slope of the site, the volume of earth masses, and the range of movement of the soil were in a functional relation-

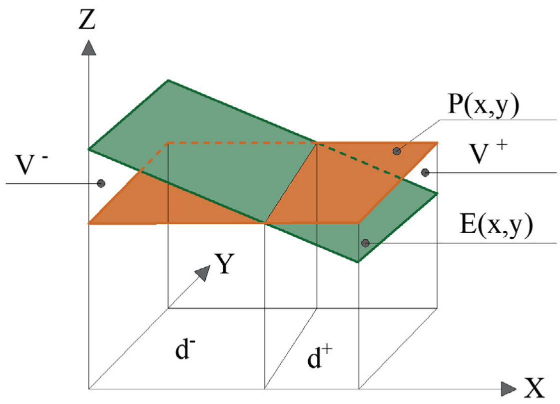

Fig. 4. Layout scheme for an elementary site

ship. For example, when the slope along the Y-axis changes from plus 4 % to negative, the difference in the volumes of earth masses reaches 52 % and the distance of ground movement changes by 26.3 %. The method of determining the volume of earth masses is based on finding the volume of an elementary site, the planned site, enclosed between the surface of the relief and the planned plane. Fig. 4 shows the layout diagram of the elementary section.

The construction site can be tied to an arbitrary coordinate system and divided into elementary sections, at the vertices of which you can define the z_1 and z marks. The boundary of the relief surface in each elementary section is sufficiently smooth and is described by a polynomial of the second order: $z_{1i} = ax^2(y^2) + bx(y) + c, i = \overline{1,4}$, then the existing surface can be represented as $E(x, y)$. The projected surface in each elementary section is a plane whose boundaries of which are straight lines $z_i = kx(y) + b, i = \overline{1,4}$, and it can be written as $P(x, y)$. The task is then to determine the volume bounded between the projected surface $P(x, y)$ and the existing surface $E(x, y)$. The following cases are possible:

1. if $z > z_1$ at any point in the elementary section, i.e., $P(x, y) - E(x, y) > 0$, then the volume will be "+" (filling).
2. if $z < z_1$ at any point in the elementary section, i.e., $P(x, y) - E(x, y) < 0$, then the volume will be "–" (cutting).
3. if $z > z_1$ in some domain of the elementary section, and in the other $z < z_1$, then there is a transition boundary where $z = z_1$, i.e., $P(x, y) - E(x, y) = 0$.

Surfaces E and P can be defined as the following equations:

$$E = A1x + B1y + C1xy + D1 \quad (1)$$

$$P = Ax + By + Cxy + D \quad (2)$$

Since at the points of intersection of surfaces P = E, it means $A1x + B1y + C1xy + D1 = Ax + By + Cxy + D$ or it can be the same as $(A - A1)x + (B - B1)y + (C - C1)xy + (D - D1) = 0; \{(B - B1) + (C - C1)x\}y = (A1 - A)x + (D1 - D);$

$$y = \frac{(A1 - A)x + (D1 - D)}{(B - B1) + (C - C1)x} \quad (3)$$

This means that the equation of the line has been received, which divides the elementary section into positive and negative areas. The projection onto the XOY plane of the elementary section will be expressed by the area D, limited by straight lines:

1) $\frac{x-x_1}{x_2-x_1} = \frac{y-y_1}{y_2-y_1};$ 3) $\frac{x-x_3}{x_4-x_3} = \frac{y-y_3}{y_4-y_3};$

2) $\frac{x-x_2}{x_3-x_2} = \frac{y-y_2}{y_3-y_2};$ 4) $\frac{x-x_3}{x_4-x_3} = \frac{y-y_3}{y_4-y_3}$

Or it can also be expressed as:

1) $y = \frac{(y_2-y_1)x-y_2x_1+y_1x_1}{x_2-x_1} + y_1$

2) $y = \frac{(y_3-y_2)x-y_3x_2+y_2x_2}{x_3-x_2} + y_2$

3) $y = \frac{(y_4-y_3)x-y_4x_3+y_3x_3}{x_4-x_3} + y_3$

4) $y = \frac{(y_1-y_4)x-y_1x_4+y_4x_4}{x_1-x_4} + y_4$

from here, $y = k_i x + b_i$, where $k_i = \frac{y_{i+1}-y_i}{x_{i+1}-x_i}$, $b_i = y_i - k_i, i = \overline{1,4}$, if $i > 4$, so $i = 1$. The projected plane $P(x, y)$ can be specified as follows:

1) parallel to the X0Y-axis. Then it takes the following equation form: $Cz + D = 0$, or, by reducing in C, it will be: $z + d = 0$, where $d = z_0$ in the whole definition, the area to be controlled.

2) parallel only the X- and Y-axes. If $P(x, y)$ is parallel to the X-axis, then the plane has the form $By + Cz + D = 0$. If the slope to the Y-axis is specified, then the plane equation takes the form $\pm Iy + z + d = 0$, where $d = z_0$. If $P(x, y)$ is parallel to the Y-axis, then the plane has the form $Ax + Cz + D = 0$. If the slope to the X axis is specified, then the equation of the plane takes the form $\pm Ix + z + d = 0$, where $d = z_0$.

3) the plane has a slope both towards the X-axis and towards the Y-axis. In this case, its equation is $Ax + By + Cz + D = 0$. For given slopes towards the X- and Y-axes, the plane equation takes the form $\pm Ix + \pm Iy + \pm Iz + d = 0$, where $d = z_0$.

Slopes in cases 2 and 3 are assumed to be positive if they are directed to the origin (the accepted coordinate grid of the site), and negative otherwise. The relief surface is specified as a harmonic function, and the projected surface is specified as a plane. Since the functions $E(x, y)$ and $P(x, y)$ are continuous at all points in the region D, the volumes of the earth masses enclosed between these surfaces in the area can be represented by the mathematical model in the form of the difference of these functions $\{E(x, y) - P(x, y)\}$ and are calculated by a double integral in the domain D:

$$V_{fill} = \iint_{D-} \{E(x, y) - P(x, y)\}\, dx\, dy \quad (4)$$

$$V_{cut} = \iint_{D+} \{E(x, y) - P(x, y)\}\, dx\, dy \quad (5)$$

The optimal average elevation of the 0 grading is determined from the equality condition of the volume of the soil massif on the site before and after the grading. The volume of the soil massif on the site by region $S = D_1 + D_2 + \ldots + D_n$ can be calculated double integral:

$$V_{volume} = \iint_{S} E(x, y)\}\, dx\, dy \quad (6)$$

Since the function $E(x, y)$ is continuous on the closure $\bar{S}$ of the domain S, which is connected, then it has point x^0 such ($x^0 \in \bar{S}$) such that the equality $\iint_S E(x, y)\, dx\, dy = E(x^0) mS$, hence the value of the function $E(x, y)$ in the point x^0, $E(x^0) = \frac{\iint_S E(xy)\, dx\, dy}{S}$. Let the virtual plane have a mark z_v from absolute mark ± 0.000. Let us calculate the volume of the soil mass in the region S between the relief function $E(x, y)$ and the virtual plane $P_v(x, y)$. The volume between the surface of the relief and the virtual plane over the region S is then determined from the expression:

$$V_{cut} = \iint_{S} \{E(x, y) - P(x, y)\}\, dx\, dy \quad (7)$$

Therefore, the optimal average mark H_0, based on the equality of volumes: $H_0 = z_v + \frac{V_v}{S}$. Possible design surfaces of a construction site with its vertical layout can be represented as a bunch of planes in a Cartesian coordinate system centred at the point $F\{x_c; y_c\}$, the coordinates of which correspond to *xc* and *yc* — the middle of the area S and z — plan marks H_0. The equation of the beam of planes can be represented in the form $H_0 \pm I_x\, x \pm I_y\, y \pm I_z\, z = 0$ or $F_i(x, y) = H_0 \pm I_{ix}\, x \pm I_{iy}\, y,\ i = 1, \ldots, n$. Volumes of earth masses between the site relief and such planes:

$$V_S = \iint_{S} \{E(x, y) - F_i(x, y)\}\, dx\, dy = 0, \quad (8)$$

$$i = 1, \ldots, n.$$

Consequently, the statement that the equality of the volumes of embankments and excavations of the planned site meet the optimality conditions is not complete since expression (1) indicates many such situations. Then, the minimising functional of the amount of work on the construction site can be represented as

$$V_S = \iint_{S} \{E(x, y) - F_i(x, y)\}\, dx\, dy \xrightarrow[y \epsilon S+]{x \epsilon S+} min \quad (9)$$

Restrictions:

$$\iint_{S} \{E(x, y) - F_i(x, y)\}\, dx\, dy = 0; \quad (10)$$

$$\iint_{S+} \{E(x, y) - F_i(x, y)\}\, dx\, dy \geq 0; \quad (11)$$

$$F(x,y) \epsilon H_0 \pm I_{ix}\, x \pm I_{iy}\, y = I_z\, z); i = 1, \dots, n; \quad (12)$$

$$H_0 = E(x^0, y^0); x^0 \epsilon S; \; y^0 \epsilon S. \quad (13)$$

Therefore, it is possible to optimise the volume of the earthworks in the case of vertical levelling of the site, provided that the ground balance is zero. The optimality criterion is the coincidence of the relief surface and the planning plane. In this case, the optimisation vector of the volume of work is determined under the condition that the slopes of the terrain and the planning plane coincide in value and direction.

The methodology for determining the volume of earth masses, the distance of their movement, and their relationship with the mechanisation of work not only allow determining rational methods for carrying out earthworks at the construction site but also give a breakdown of the work in general, which must be considered when planning earthwork.

Discussion and conclusions

Engineering construction management is one of the most difficult construction processes. The success of the entire project depends on the management of the construction. To plan a proper engineering construction management process, it is necessary to know all the potential risks that may arise during the project. One of the solutions proposed in this article allows for accurate earthworks. The reviewed state of BIM technologies illustrates the importance of incorporating geotechnical survey data into the BIM process. The proposed information technology combines engineering and geological research and design of the foundations of buildings and structures into a single production engineering process and can be used as one of the elements in the composition of digital information systems of buildings and structures. Information modelling technology allows reducing the time and improve the quality of engineering–geological studies due to the automation of laboratory and field soil testing and the determination of soil characteristics with the simultaneous calculation of building foundations and facilities for limit states. The proposed model may have restrictions on its use if soil properties and species are incorrectly determined. Then, the soil optimisation task can be calculated incorrectly, so engineering planning and management would have inaccuracies. But the solution proposed in the article has strengths because the suggested optimisation method is beneficial in many areas, from project planning and project engineering management to specific construction works (foundation installation, etc.).

A literature and software review has shown that tools are currently being developed that calculate the scope of earthworks using BIM models. However, the analysis did not find any complex solutions that would include land type determination, land modelling, earthworks calculation and optimisation. Therefore, this paper presented a mathematical model that optimises earthworks.

This article also aims to invite researchers to further explore the topic of earthwork optimisation using BIM technology. The optimisation algorithm presented in this paper allows for performing further optimisation tasks related to the construction site organisation. This means that once a rational plan for earthworks and soil supply is known, the mechanisms to be used in the soil supply system are further selected. With the rational soil supply plan, the required number of trucks is determined on the construction site. Excavators and trucks are optimised for the purpose of this work: the required number of machines transporting the soil is made available for bringing the soil to the construction site when the soil is excavated with different mechanisms (excavators, loaders, draglines) to keep the total costs of machine downtime the lowest. After receiving a rational design solution for the soil spreading and soil supply plan, the required number of mobile trucks is integrated into the construction work documents (construction work technology project, estimates, work schedules, etc.).

This article examined one of the most important issues related to engineering management, i.e., the optimisation of earthworks. Other important issues for the organisation and management of construction are the planning of safe work on the construction site, depending on the type of soil. Geotechnical sections allow for planning a need for additional fortifications and their depths for safe work.

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