Optimization of soil movements when planning terrain

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Abstract. Earth work is considered when planning the terrain at the initial stage of construction. Instead of a manual method for calculating the volume of soil transportation, it is proposed to switch to the use of linear programming methods and computer solutions in the environment of the computing complex Matlab. The problem is stated, algorithms and a computer program are developed. The optimal plan for transporting soil masses from dredges to embankments was found for a specific task.

1. Introduction
Currently, a new informational “digital economy” is emerging under the influence of modern information and communication technologies. The program document “Digital Economy”, developed and submitted for consideration in 2017, was actively discussed by the representatives of the information technology market, specialists from all economic sectors, and structures of all government branches. As a result, they came to a unanimous opinion that the digitalization program is strategically necessary for the further development of society.

Major construction is one of the most important branches of material production, in which huge state budget allocations, funds of the business community and population are annually invested. In this regard, the formulation and solution of the problems of optimal design for structures and programming of production processes became necessary. However, the practical application of the long-developed methods of mathematical programming is constrained by their complexity, cumbersomeness, large amounts of computation, and the requirements of too high mathematical and programmer qualifications for industry specialists.

Regretfully, universities conducting educational activities for the training of builders do not currently provide sufficient qualifications to meet the challenges.

The objective of this work is to illustrate that the mentioned difficulties are easy to overcome with the help of the popular computing complex Matlab. The problem arising in the design of almost all construction projects, namely, earth work at the initial stage of construction are to be considered below. Earth work is one of the largest components of construction production [1, 2]. The volume of earth work is large and it is carried out during the construction of any building and structure and make up about 10 % out of the total labor intensity. Earth work is one of the most difficult and time-consuming types of construction work performed in difficult conditions and largely dependent on natural and climatic factors. Therefore, one of the tasks facing designers and specialists directly involved in construction projects is to develop and implement the methods and technologies contributing to the earth work reduction.
2. Problem statement

Projects for the construction work, as a rule, include the volume and methods of moving soil masses in the form of a sheet or cartogram, a schedule of earth work, indicate human, material resources and the choice of a set of machines. The present paper is considering one of the components of excavation being optimization of soil transportation from excavation sites to embankment sites with a vertical layout of the territory.

Well-known geometry formulas are used for calculating the volume of earth work on pits, embankments, trenches excavation. With complex forms of excavations and embankments, they are divided into a number of simpler geometric bodies, which are then summed up.

Let us consider the statement of the problem according to the general plan of the territory in Fig. 1. Two zones are shown here, namely, “excavation” and “embankment”, having a delimiting zero line. The area is covered with a grid of 100x100 m squares. The general slope of the area to the layout is shown by an arrow and is averagely equal 0.01.

According to geodesic surveys, the excesses of all grid points over the design surface were previously determined, spatial geometric figures of all the excavations and embankments were established. The volumes of the excavations and embankments presented in Table 1 are calculated from them, where the current numbers i, j are assigned to them. Zero balance between the total volume of excavations and embankments, desirable during excavation, is achieved by maneuvering the average level of the entire territory planning.

| Excavations, i | Volumes, m$^3$ | Embankments, j | Volumes, m$^3$ |
|---------------|----------------|----------------|----------------|
| 1             | 10220          | 1              | 6902           |
| 2             | 11208          | 2              | 1393           |
| 3             | 13936          | 3              | 11821          |
| 4             | 14822          | 4              | 11763          |
| 5             | 7696           | 5              | 9932           |
| 6             | 5975           | 6              | 6668           |
| 7             | 8294           | 7              | 2468           |
| 8             | 9464           | 8              | 8047           |
| 9             | 9075           | 9              | 15789          |
| 10            | 9758           | 10             | 14062          |
| 11            | 944            | 11             | 12342          |
| 12            | 3211           | 12             | 8999           |
| 13            | 5583           |                |                |
| Totally       | 110186         |                | 110186         |
Another important component in the problem statement is the distance of the routes for transporting soil from the recesses into the embankment. They are determined by Fig. 1, based on the signed dimensions and scale of the picture. The results are shown in table 2. Note that there are 156 different routes for transporting soil from 13 points to 12 points. The corresponding scheme is shown in Fig. 2.

| Table 2. Transportation distances (m) |
|--------------------------------------|
| H | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
| B |    |    |    |    |    |    |    |    |    |    |    |    |
| 1 | 139 | 153 | 186 | 214 | 279 | 358 | 437 | 265 | 307 | 330 | 418 | 484 |
| 2 | 162 | 139 | 224 | 200 | 232 | 302 | 288 | 300 | 316 | 360 | 404 |    |
| 3 | 232 | 148 | 320 | 223 | 209 | 246 | 302 | 325 | 316 | 300 | 316 | 334 |
| 4 | 325 | 246 | 358 | 282 | 232 | 218 | 255 | 390 | 326 | 288 | 260 |    |
| 5 | 395 | 312 | 418 | 334 | 270 | 223 | 218 | 442 | 395 | 326 | 288 | 260 |
| 6 | 56  | 107 | 130 | 158 | 233 | 326 | 419 | 204 | 246 | 293 | 363 | 442 |
| 7 | 116 | 60  | 163 | 121 | 149 | 233 | 323 | 214 | 209 | 233 | 279 | 344 |
| 8 | 200 | 121 | 233 | 140 | 112 | 153 | 242 | 256 | 214 | 200 | 219 | 265 |
| 9 | 302 | 209 | 316 | 224 | 140 | 130 | 172 | 326 | 283 | 224 | 200 | 209 |
| 10| 395 | 302 | 412 | 300 | 233 | 166 | 140 | 419 | 361 | 282 | 233 | 186 |
| 11| 233 | 121 | 219 | 116 | 60  | 102 | 195 | 219 | 177 | 140 | 163 | 209 |
| 12| 307 | 219 | 312 | 209 | 116 | 60  | 112 | 312 | 242 | 167 | 121 | 140 |

Figure 2. Scheme of transportation routes

3. Problem solving

Having determined the initial data given above, we can proceed with the distribution of earth masses according to the sections, where to transport soil to and in what volume. The ultimate goal in this case will be to ensure that the transportation scheme is optimal, i.e., that it corresponds to the minimum volume of traffic in the set of the acceptable plans. Manually determined transportation plans, on the principles of common sense and rough calculations cannot be considered optimal, and the economic losses from them will be significant, especially with large volumes of traffic.

Further, the problem is solved as a special case of linear programming problems with the name “transport task” [3–7]. There are several methods for solving it, including the most popular northwest corner method. Their application in this case will lead to a huge amount of calculations for converting large-sized tables, which is almost impossible to do manually. The way out is to use computing systems. For this purpose, we turn to the application package Matlab used for solving technical problems [8].

In the Matlab environment, linear programming problems are solved using the linprog function [9]. It solves the linear programming problem in the following statement (notation according to [9] is kept!)

\[
F(\mathbf{x}) = c \cdot \mathbf{x} \rightarrow \inf, \quad (\text{min}), \\
A \cdot \mathbf{x} \leq \mathbf{b}, \\
A_{eq} \cdot \mathbf{x} = \mathbf{b}_{eq}, \\
\mathbf{lb} \leq \mathbf{x} \leq \mathbf{ub}.
\] (1)
Here $F(x)$ is the objective function, whose value must be minimized, $c$ is the vector of distances of transporting soil of dimension 156, $x$ is the desired vector of transported goods of dimension 156, $A$ and $A_{eq}$ are the matrix of coefficients, in this case of the order of 25x156, $b$, $b_{eq}$ are the vectors of the right side of dimension 25, $lb$, $ub$ are the vectors bounding $x$ above and below dimension 25.

The optimizing function in the program has the form $[x, fval] = \text{linprog} (c, A, b, A_{eq}, b_{eq}, lb, ub)$. The author of the task only requires the ability to formulate his professional task in the form (1), which is easy to perform, and present in the very simple algorithmic Matlab language. In this case, there is no need to master the methods of algorithmization and programming for solving the problem. The main input data of linprog are as follows: matrices $A$, $A_{eq}$, vectors $c$, $b$, $b_{eq}$, $lb$, $ub$. In this case, inequalities will not be used in the system of equations (1), due to their absence. The vector $lb$ is zero in this problem, $ub$ is the vector with the components for the given task of 20,000, larger than any values of the samples and embankments indicated in Table 1.

If any of the input parameters is absent, put square brackets $[\ ]$ in its place, unless this is the last parameter in the list. For example, if you need to solve a problem without inequality restrictions, as in this case, then the linprog function call operator will be as follows:

$[x, fval] = \text{linprog}(c, [\ ]$, $[\ ]$, $A_{eq}$, $b_{eq}$, $lb$, $ub)$.

At the output, the linprog function gives the optimal plan $x$ of problem (1) and the minimum value of the objective function $fval$.

This approach to solving linear programming problems is universal, that is, it does not depend on their subject area, does not require high mathematical and programmer qualifications of the user, as well as sophisticated computing techniques, etc. The examples given in [10] confirm it.

Equality equations are easily compiled on the basis of the transportation scheme in Fig. 2. The system of equations consists of two groups. The essence of the equations of the first group is that the entire calculated soil volume from each excavation should be taken out according to Table 1. For example, for cell 2, the soil is transported to 12 embankments, with a total volume of 11,208 m$^3$ and therefore the equation is as follows (2).

$$x_{11} + x_{12} + x_{13} + x_{16} + x_{17} + x_{18} + x_{19} + x_{20} + x_{21} + x_{22} + x_{23} + x_{24} = 11208$$ (2)

Here, the required traffic volumes $x$, route numbers $k$ are indicated in the indices. They are calculated by the simple formula $k = 12 (i–1) + j$, where $i$ is the number of an excavation, and $j$ is the number of an embankment. The second group of equations states that all embankments should be completely filled with soil. For example, embankment 9 ($j = 9$) can receive soil from the excavations 1–13 ($i = 1–13$) Fig. 1.

$$x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14} + x_{15} + x_{16} + x_{17} + x_{18} + x_{19} + x_{20} + x_{21} = 1578$$ (3)

The elements of the matrix $A_{eq}$ are the coefficients of equations (2), (3) and the ones similar to them. It can be seen that they will take the values 0 or 1.

The components of the vector on the right side of the equations system are the volumes of the excavations and embankments indicated in Table 1. The components of the vector $c$ are the distances between the excavations and embankments indicated in Table 2.

The optimal (minimum) value of freight $F_{min}$ will be obtained in m$^3$km. If desired, the numerical result can be converted to other units of measurement t•km, rub. etc.

For this task, a small program in Matlab-e produced the optimal plan for soil transportation, presented in Table 3.

The total volume of transport work is $F_{min} = 22,251$ m$^3$ km
or in another unit of measurement when converting m$^3$ to tons
$F_{min} = 40,052$ t km.
In this case, the soil density is assumed to be 1.8 t/m$^3$, which is averagely taken in the calculations for clay and sand.

Traditional manual calculation gave the result $F = 54243$ t km, which is 35 % more than the optimal value.
### Table 3. Optimal plan for soil transportation

| Embankments no. | Excavations no., volumes, m$^3$ | Totally, m$^3$ |
|-----------------|---------------------------------|-----------------|
| 1               | 2 – 927, 6 – 5975               | 6902            |
| 2               | 3 – 1393                        | 1393            |
| 3               | 1 – 10220, 2 – 1601             | 11821           |
| 4               | 2 – 633, 3 – 9905, 7 – 1225     | 11763           |
| 5               | 3 – 2638, 8 – 744, 9 – 5606, 11 – 944 | 9932     |
| 6               | 4 – 760, 9 – 3469, 10 – 2439    | 6668            |
| 7               | 10 – 2468                       | 2468            |
| 8               | 2 – 8047                        | 8047            |
| 9               | 7 – 7069, 8 – 8720              | 15789           |
| 10              | 4 – 14062                       | 14062           |
| 11              | 5 – 7696, 10 – 1435, 12 – 3211  | 12342           |
| 12              | 10 – 3416, 13 – 5583            | 8999            |
|                 | Totally                         | 110186          |

### 4. Conclusion

1. A modern method for calculating earth moving during construction is proposed, which corresponds to the modern digital economy and is able to replace the currently used bulky calculations.

2. A certain example showed that the volume of work in traditional design is 35% more than the resulting optimal solution.

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