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Research Article

DETERMINATION OF CONVEX SHAPE OF THE TRAJECTORY OF THE QUARRY BOARD TRAJECTORY BY THE METHOD OF CUBIC SPLINES

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ABSTRACT

This paper deals with the problem of determining the convex shape of the curb trajectory in order to ensure the stability of the curb, enhance the safety of overburden stripping and open pit mining. The method of cubic splines is used to determine the trajectory of the side. For application of this method the length of the pit base (or ledge) is divided into arbitrary n parts and in each partial segment the corresponding cubic spline function is constructed, being combined, each curve into a common curve, gives a common curve corresponding to the profile of the trajectory of the pit face.

KEYWORDS

scarp slopes, destruction, stability, ridge, convex shape of the ridge trajectory, interpolation, spline function, cubic spline method, algebraic polynomial.

INTRODUCTION

One of the primary objectives in open-pit mining is to maintain the stability of pit walls (Norov Yu.D. et. Al, 2015). Extensive research has been conducted in this field, resulting in various advancements. It has been observed that ensuring stability in stripping operations and open-cast mining involves three main approaches, which are determined by the trajectory of the pit walls (Demin A.M. et. al., 1973). The trajectory of pit walls can be convex, concave or inclined straight (Rybin V.V., 2016). The type of pit walls depends on many factors, such as soil structure, terrain, methods of work, equipment and personnel. In the process of determining the stability of the pit walls, of course, financial, material and other costs are taken into account. It is on these criteria that one of the three types of pit wall trajectory mentioned above is chosen. On cost considerations, when conducting stripping works, the most profitable is the convex form of the pit wall trajectory, if it is possible to choose a more accurate angle of slope of the wall (Zairov Sh.Sh. et. al., 2020). However, given the above factors, mining is carried out as a concave or inclined straight form of the pit walls. In all forms of defining the trajectory of the pit wall special attention is paid to the angle of slope of the wall, which is one of the most important parameters in the process of open pit mining (Stechkin S.B. et. al., 1976).

The following problem is discussed: how to ensure the convex shape of the pit wall (ledge), so that the pit wall is stable and the cost of overburden removal is minimal?

The task is solved in three stages:

Determination of the convex pit walls trajectory;

Finding the coordinates of the center of mass of the studied ledge;

Determination of the pit wall stability factor using the results of the above two steps.

This paper attempts to solve the first part of the problem, i.e. determining the convex shape of the pit walls, using the cubic interpolation spline method.

To solve this problem, we use the cubic spline interpolation method, as this method provides a smooth curve interpolating the trajectory of the pit wall (ledge).

The idea of using the cubic interpolation spline method (Norov Yu.D. et. al., 2016) is that the section developed by the project, both horizontally and vertically, is arbitrarily divided into several parts, horizontally and vertically. We denote these sections horizontally by [a; b], the vertical section by [c; d]. Subdivide segment [a; b] by points a=x_0,x_1,x_2,…,x_n=b and segment [c; d] by c=y_0,y_1,y_2,…,y_2= d into partial segments. On each partial segment [x_i,x_(i+1)], where i=¯(0,n-1), define a cubic polynomial. Then, the obtained polynomials are docked, under some conditions, which will be outlined below in the construction of the cubic spline, resulting in a single smooth curved line, which eventually defines the desired trajectory of the pit walls. Suppose we are given data points of a function and we want to determine the function's values at points between the given data. This problem is known as interpolation and frequently arises in practical applications. For instance, in geology, samples are taken from a mineral deposit to determine mineral concentration at specific points, and interpolation can be employed to estimate the concentration at

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intermediate points. There are numerous other real-world scenarios where interpolation finds its application (Norov Yu.D. et. al., 2017).

THE OBJECTIVES OF THE RESEARCH

Our objective is to determine the most accurate representation of the function based on the given data. One approach to achieve this is to utilize spline interpolation. In this regard, we refer to relevant literature (Zairov Sh.Sh. et. al., 2017) for valuable insights and techniques that will guide our future analysis.

Spline - a function that, together with several derivatives, is continuous over the entire given segment $[a, b]$, and on each partial segment separately is some algebraic polynomial $[x_i, x_{i+1}]$. A cubic spline taking the same values of f_i at the nodes as some function is called an interpolation spline and serves to approximate the function f on the interval $[a, b]$together with several derivatives. In practice, cubic splines are most often used $S_3(x)$- splines of the third degree with a continuous, at least, first derivative In this case, the value $m_i = S_3(x_i)$ is called the slope of the spline at the point x_i. Here x_i is determined by the formulas:

$$m_i = \frac{f_{i+1} - f_{i-1}}{2h}, i = 1,2, \dots, N-1 \quad (1)$$

$$m_0 = \frac{4f_1 - f_2 - 3f_0}{2h}, m_N = \frac{3f_N - f_{N-2} - 3f_{N-1}}{2h} \quad (2)$$

These formulas are formulas for numerical differentiation of the second order of accuracy with respect to the step $h = (b-a)/N$, according to (Sayfidinov O., et. al., 2022).

We now move to the numerical solution, i.e., to the direct presentation of the solution to the problem, illustrating it with a concrete example.

Example. Determine the trajectory of the stability of the pit walls, if as a result of the experiments, some dependence of the function $y = f(x)$ x on the variable was obtained, in the form of a table (Table 1).

Tab. 1. As a result of the experiment, the dependence of the function y=f(x) on the variable x was obtained. i-number of points, x-values of the variable, y-values of the function.

i	0	1	2	3	4
x	0	4	8	12	16
y	0	9	14	18	20

Here, the first row contains the ordinal numbers of the variable x and the function $y = f(x)$The second and third rows of the table contain the corresponding values of the variable x and the function $y = f(x)$. Next, let's write a general view of the cubic spline for number i, where: $i = \overline{0,4}$ $\mathbf{y_i = S_i = a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3}$

METHODOLOGY

Now let us write the cubic polynomials for each value of variable x and function $y = f(x)$, i.e. on each partial segment $[x_i, x_{i+1}]$, according to the values given in Table 1, then we obtain

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$$y_0 = S_0 = a_0 + b_0x + c_0x^2 + d_0x^3$$

$$y_1 = S_1 = a_1 + b_1(x-4) + c_1(x-4)^2 + d_1(x-4)^3$$

$$y_2 = S_2 = a_2 + b_2(x-8) + c_2(x-8)^2 + d_2(x-8)^3 \quad (3)$$

$$y_3 = S_3 = a_3 + b_3(x-12) + c_3(x-12)^2 + d_2(x-12)^3$$

Thus, 4 cubic polynomials are obtained. Next, we find the derivatives of the first and second order from each function:

$$y_0' = S_0' = b_0 + 2c_0x + 3d_0x^2,$$

$$y_1' = S_1' = b_1 + 2c_1(x-4) + 3d_1(x-4)^2,$$

$$y_2' = S_2' = b_2 + 2c_2(x-8) + 3d_2(x-8)^2$$

$$y_3' = S_3' = b_3 + 2c_3(x-12) + 3d_3(x-12)^2$$

$$y_0'' = S_0'' = 2c_0 + 6d_0x \quad (4)$$

$$y_1'' = S_1'' = 2c_1 + 6d_1(x-4)$$

$$y_2'' = S_2'' = 2c_2 + 6d_2(x-8)$$

$$y_3'' = S_3'' = 2c_3 + 6d_3(x-12)$$

Now, according to the template, we find the following:

1) polynomial values

$$y_0 = S_0 = a_0 + b_0x + c_0x^2 + d_0x^3 \quad (5)$$

at points ($x_0 = 0;\ y_0 = 0$) and ($x_1 = 4;\ y_1 = 9$):

$$\begin{cases} a_0 = 0, \\ a_0 + 4b_0 + 16c_0 + 64d_0 = 9 \end{cases} \Rightarrow \begin{cases} a_0 = 0, \\ 4b_0 + 16c_0 + 64d_0 = 9. \end{cases} \quad (6)$$

As a result, the first system of a linear algebraic equation consisting of two equations with two unknowns. Now for the remaining functions $S_i$also substitute the corresponding values of x_i and y_i from Table 1:

$$2)\ y_1 = S_1 = a_1 + b_1(x-4) + c_1(x-4)^2 + d_1(x-4)^3 \quad (7)$$

at points ($x_1 = 4;\ y_1 = 9$) and $x_2 = 8;\ y_2 = 14$):

$$\begin{cases} a_1 = 9, \\ a_1 + 4b_1 + 16c_1 + 64d_1 = 14, \end{cases} \Rightarrow \begin{cases} a_1 = 5, \\ 4b_1 + 16c_1 + 64d_1 = 5. \end{cases} \quad (8)$$

3) $y_2 = S_2 = a_2 + b_2(x-8) + c_2(x-8)^2 + d_2(x-8)^3$

at points $(x_2 = 8;\ y_2 = 14)$ and $(x_3 = 12;\ y_3 = 18)$:

$$\begin{cases} a_2 = 14 \\ a_2 + 4b_2 + 16c_2 + 64d_2 = 18 \end{cases} \Rightarrow \begin{cases} a_2 = 14 \\ b_2 + 4c_2 + 16d_2 = 1. \end{cases} \quad (9)$$

4) $y_3 = S_3 = a_3 + b_3(x-12) + c_3(x-12)^2 + d_2(x-12)^3$

at points $(x_3 = 12;\ y_3 = 18)$ and $(x_4 = 16;\ y_4 = 20)$:

$$\begin{cases} a_3 = 18 \\ a_3 + 4b_3 + 16c_3 + 64d_3 = 20 \end{cases} \Rightarrow \begin{cases} a_3 = 18 \\ 2b_3 + 8c_3 + 32d_3 = 1. \end{cases} \quad (10)$$

5) $y_0' = y_1'$ at point $(x_1 = 4;\ y_1 = 9)$:

$$b_0 + 8c_0 + 48d_0 = b_1 \text{ or } b_0 + 8c_0 + 48d_0 - b_1 = 0. \quad (11)$$

6) $y_0'' = y_1''$ at point $x_1 = 4;\ y_1 = 9$:

$$2c_0 + 24d_0 = 2c_1 \text{ or } c_0 + 12d_0 - c_1 = 0. \quad (12)$$

7) $y_1' = y_2'$ at point $(x_2 = 8;\ y_2 = 14)$:

$$b_1 + 8c_1 + 48d_1 = b_2 \text{ or } b_1 + 8c_1 + 48d_1 - b_2 = 0. \quad (13)$$

8):$y_1'' = y_2''$ at point $(x_2 = 8;\ y_2 = 14)$:

$$2c_1 + 24d_1 = 2c_2 \text{ or } c_1 + 12d_1 - c_2 = 0. \quad (14)$$

9) $y_2' = y_3'$ at point $(x_3 = 12;\ y_3 = 18)$:

$$b_2 + 8c_2 + 48d_2 = b_3 \text{ or } b_2 + 8c_2 + 48d_2 - b_3 = 0. \quad (15)$$

10) $y_2'' = y_3''$ at point $(x_3 = 12;\ y_3 = 18)$:

$$2c_2 + 24d_2 = 2c_3 \text{ or } c_2 + 12d_2 - c_3 = 0. \quad (16)$$

11) a) boundary conditions $y_0'' = S_0'' = 0$ at point $x_0 = 0$:

$$2c_0 = 0 \text{ or } c_0 = 0 \quad (17)$$

b) boundary conditions $y_3'' = S_3'' = 0$ at point $x_4 = 16$:

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$$2c_3 + 24d_3 = 0 \text{ or } c_3 + 12d_3 = 0 \qquad (18)$$

Combining the expressions obtained above, after some elementary transformations, we will compose the following system:

$$\begin{cases} a_0 = 0 \\ a_1 = 9 \\ a_2 = 14 \\ a_3 = 18 \\ c_0 = 0 \\ 4b_0 + 16c_0 + 64d_0 = 9 \\ 4b_1 + 16c_1 + 64d_1 = 5 \\ b_2 + 4c_2 + 16d_2 = 1 \\ 2b_3 + 8c_3 + 32d_3 = 1 \\ b_0 + 8c_0 + 48d_0 - b_1 = 0 \\ c_0 + 12d_0 - c_1 = 0 \\ b_1 + 8c_1 + 48d_1 - b_2 = 0 \\ c_1 + 12d_1 - c_2 = 0 \\ b_2 + 8c_2 + 48d_2 - b_3 = 0 \\ c_2 + 12d_2 - c_3 = 0 \\ c_3 + 12d_3 = 0 \end{cases} \Rightarrow \begin{cases} a_0 = 0 \\ a_1 = 9 \\ a_2 = 14 \\ a_3 = 18 \\ c_0 = 0 \\ 4b_0 + 64d_0 = 9 \\ 4b_1 + 16c_1 + 64d_1 = 5 \\ b_2 + 4c_2 + 16d_2 = 1 \\ 2b_3 + 8c_3 + 32d_3 = 1 \\ b_0 - b_1 + 48d_0 = 0 \\ -c_1 + 12d_0 = 0 \\ b_1 - b_2 + 8c_1 + 48d_1 = 0 \\ c_1 - c_2 + 12d_1 = 0 \\ b_2 - b_3 + 8c_2 + 48d_2 = 0 \\ c_2 - c_3 + 12d_2 = 0 \\ c_3 + 12d_3 = 0 \end{cases} \qquad (19)$$

For brevity, we write this system in matrix form as $AX = B$, here A - is the matrix of coefficients, X - is the matrix-column of unknowns, B - is the matrix-column of free numbers.

In this case, we have derived 16 equations, with 5 coefficients known and the remaining 11 coefficients to be determined. This system of equations leads to 11 equations with 11 unknowns, indicating that a unique solution exists. To solve this system, we organize the coefficients of the unknowns in a matrix format, as shown in Table 2.

Tab. 2. The matrix of coefficients of unknowns corresponding to the system of linear algebraic equations (3)

No.	a_0	a_1	a_2	a_3	b_0	b_1	b_2	b_3	c_0	c_1	c_2	c_3	d_0	d_1	d_2	d_3
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
6	0	0	0	0	4	0	0	0	0	0	0	0	64	0	0	0

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7	0	0	0	0	0	4	0	0	0	16	0	0	0	64	0	0
8	0	0	0	0	0	0	1	0	0	0	4	0	0	0	16	0
9	0	0	0	0	0	0	0	2	0	0	0	8	0	0	0	32
10	0	0	0	0	1	-1	0	0	0	0	0	0	48	0	0	0
11	0	0	0	0	0	1	-1	0	0	8	0	0	0	48	0	0
12	0	0	0	0	0	0	1	-1	0	0	8	0	0	0	48	0
13	0	0	0	0	0	0	0	0	0	-1	0	0	12	0	0	0
14	0	0	0	0	0	0	0	0	0	1	-1	0	0	12	0	0
15	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	12	0
16	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	12

Next, we find the inverse matrix, using a ready-made program in EXCEL for this purpose. The inverse matrix is given in the form of a table (Table 3): Define the inverse matrix A^{-1} to matrix A as follows: {=МОБР($a_0$1: $d_3$16)}

Tab. 3. Inverse matrix corresponding to the matrix of coefficients of unknowns.

1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0.316964	-0.08482	0.089286	-0.00893	-0.26786	0.071429	-0.01786	-0.61905	0.166667	-0.04762	0.02381
0	0	0	0	0	0.116071	0.169643	-0.17857	0.017857	-0.46429	-0.14286	0.035714	1.238095	-0.33333	0.095238	-0.04762

0	0	0	0	0	-0.03125	0.15625	0.625	-0.0625	0.125	-0.5	-0.125	-0.33333	1.166667	-0.33333	0.166667
0	0	0	0	0	0.008929	-0.04464	0.678571	0.232143	-0.03571	0.142857	-0.53571	0.095238	-0.33333	1.238095	-0.61905
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	-0.05022	0.063616	-0.06696	0.006696	0.200893	-0.05357	0.013393	-0.53571	-0.125	0.035714	-0.01786
0	0	0	0	0	0.013393	-0.06696	0.267857	-0.02679	-0.05357	0.214286	-0.05357	0.142857	-0.5	-0.14286	0.071429
0	0	0	0	0	-0.00335	0.016741	-0.25446	0.100446	0.013393	-0.05357	0.200893	-0.03571	0.125	-0.46429	-0.26786
0	0	0	0	0	-0.00419	0.005301	-0.00558	0.000558	0.016741	-0.00446	0.001116	0.03869	-0.01042	0.002976	-0.00149
0	0	0	0	0	0.005301	-0.01088	0.027902	-0.00279	-0.02121	0.022321	-0.00558	0.056548	0.052083	-0.01488	0.00744
0	0	0	0	0	-0.0014	0.006975	-0.04353	0.010603	0.00558	-0.02232	0.021205	-0.01488	0.052083	0.056548	-0.02827
0	0	0	0	0	0.000279	-0.0014	0.021205	-0.00837	-0.00112	0.004464	-0.01674	0.002976	-0.01042	0.03869	0.105655

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RESULTS

The resulting inverse matrix is multiplied by the column-free members matrix $B^T = [0; 9; 14; 18; 0; 9; 5; 1; 1; 0; 0; 0; 0; 0; 0; 0]$, we find the unknown coefficients of the resulting SLAE. Multiplying the obtained inverse matrix by the matrix of free numbers, we obtain the values of the unknown coefficients, in the form of a table (Table 4): Since the equation $AX = B$ has a solution $X = B \cdot A^{-1}$, then the product $B \cdot A^{-1}$ on Excel is found as follows:

{=МУМНОЖ(B1:16;МОБР(a01: d316)}. Next, we find the unknown coefficients a_i, b_i, c_i, d_i $(i = \overline{0,3})$:

Tab. 4. The values of unknown coefficients are given for the corresponding cubic splines.

i	ai	bi	ci	di
0	0	2.508929	0	-0.01618
1	9	1.732143	-0.1942	0.018415
2	14	1.0625	0.026786	-0.0106
3	18	0.767857	-0.10045	0.008371

So, all unknown coefficients are defined. Substituting them into cubic polynomials, respectively, we obtain cubic splines that interpolate the desired function in given partial segments.

Now, in partial segments $[x_i, x_{i+1}]$, where $i = \overline{0,4}$, by setting a successive step, e.g. 0.5 or 1, we obtain a table (Table 5) of y values for the corresponding segments of x. As a result, we construct a graph of the cubic spline, which is shown in Figure 1.

Tab. 5. The table shows x and y values corresponding to partial segments $[x_i, x_{i+1}]$, where $i = \overline{0,3}$.

x	y	x	y	x	y	x	Y
0	0	4.5	9.819824	8.5	14.53662	12.5	18.35986
0.5	1.252441	5	10.55636	9	15.07868	13	18.67578
1	2.492746	5.5	11.22342	9.5	15.61823	13.5	18.95403
1.5	3.708775	6	11.83482	10	16.14732	14	19.20089
2	4.888393	6.5	12.40437	10.5	16.65799	14.5	19.42264
2.5	6.019461	7	12.94587	eleven	17.1423	15	19.62556
3	7.089844	7.5	13.47314	11.5	17.59229	15.5	19.81592

3.5	8.087402	8	14	12	18	16	20
4	9						

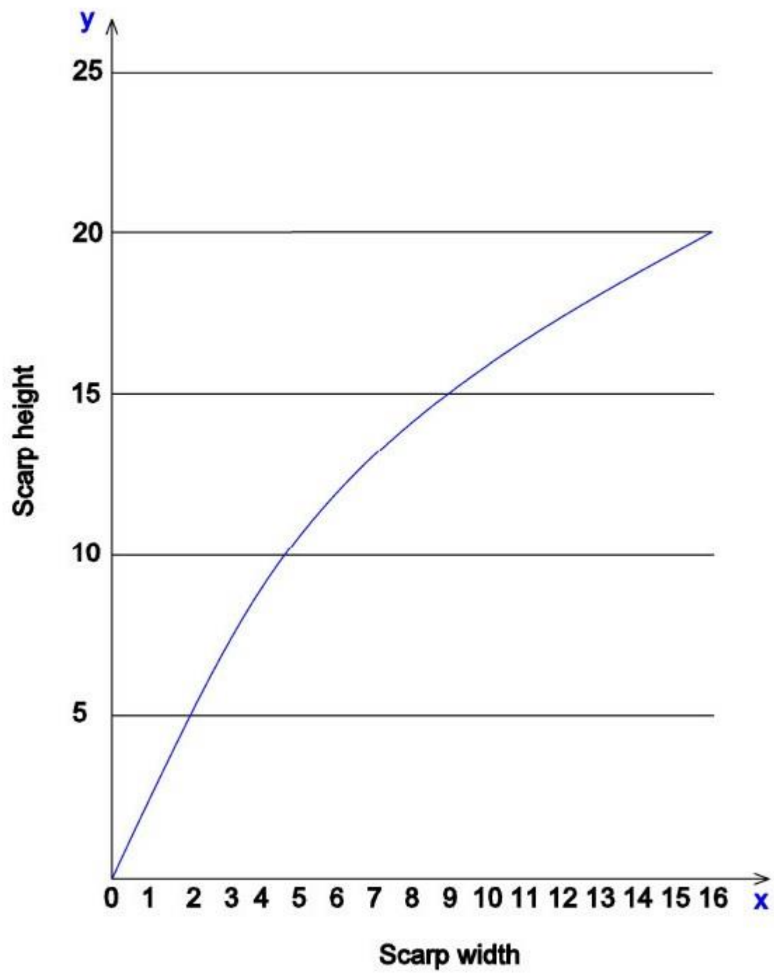

Fig. 1. Pit walls trajectory obtained with a cubic spline

Further, using Eqs. (1) and (2), we find the values of the slopes at the corresponding points, which, in fact, are the values for determining the slope angle for the function $y_i' = S_i'(x_i)$, where $i = \overline{0;3}$:

$$tg\alpha_0 = m_0 = \frac{4y_1 - y_2 - 3y_0}{2h} = \frac{4 \cdot 9 - 14 - 3 \cdot 0}{2 \cdot 4} = \frac{22}{8} = \frac{11}{4},$$

$$tg\alpha_1 = m_1 = \frac{y_2 - y_0}{2h} = \frac{14 - 0}{2 \cdot 4} = \frac{14}{8} = \frac{7}{4}, \qquad (20)$$

$$tg\alpha_2 = m_2 = \frac{y_3 - y_1}{2h} = \frac{18 - 9}{2 \cdot 4} = \frac{9}{8},$$

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$$tg\alpha_3 = m_3 = \frac{y_4 - y_2}{2h} = \frac{20 - 14}{2 \cdot 4} = \frac{6}{8} = \frac{3}{4}.$$

To determine the angle of inclination in degrees, we use the arc tangent function, then we get: $\alpha_0 = 70^{\circ}$, $\alpha_1 = 60^{\circ}$, $\alpha_2 = 48^{\circ}$ and $\alpha_3 = 37^{\circ}$.

As demonstrated in the solved example, the optimal trajectory of the pit walls (ledge) is determined as a third-degree convex curve. The specified slope angles ensure the stability of the pit walls by gradually increasing the slope from the bottom to the top of the wall, resulting in a decrease in slope degrees relative to the horizontal axis.

CONCLUSION

Thus, the first part of the set problem has been solved, i.e. cubic spline functions S_i, interpolating y_i in partial segments $[x_i, x_{i+1}]$, where $i = \overline{0,4}$ and all together giving a general picture, in the form of a curve, representing the function given by values of variable x and function $y = f(x)$ in tabular form are obtained. The resulting spline functions are good in that by setting different values of the variable x, you can get different graphs of the spline function. This means that they can be manipulated and the desired result can be obtained. Consequently, the proposed method provides an efficient and economical final result. From the obtained result of the demonstrated example, it follows that such profile of the pit wall at deformation of rock massif by virtue of its own gravity, does not contribute to sliding of rock, but on the contrary, serves its restraint. If the trajectory of the pit wall (ledge) is taken with a large inclined angle, from the bottom of the pit (ledge) to its top, for example 60°-70°, it is obvious that this result cannot be achieved. It is obvious, that a steep slope of a wall of a pit (ledge) promotes sliding of a rock and leads to an emergency situation in the form of a landslide. It is, obtained such result, i.e., gradual reduction of the angle of the curve describing the convex trajectory of the pit wall (ledge), will provide its stability and safety.

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