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# The sectional formation technology of an anthropogenic deposit with its subsequent mining using a hydraulic pull shovel

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**Abstract.** The paper provides a justification for the parameters of the designed technology for the sectional formation of tailing dumps and its subsequent mining using hydraulic pull shovels. The authors have found dependences for the amount of man-made feedstock lost in a section upon the section width due to economic and technical factors. During the study, a modern approach was used to solve the tasks assigned — comprehensive research that included estimation of the existing state of knowledge for anthropogenic deposit mining, study of the spatial structure and the relationship of the pull shovel specifications with the anthropogenic facility. The study has shown that high-grade tailing materials were diluted during the mining of an anthropogenic deposit due to losses and clogging, thus also reducing mining efficiency. The designed technology for the sectional formation of an anthropogenic deposit ensures selective excavation, decreasing the raw material dilution within sections, increasing mining safety and intensity, and reducing the mining costs in the future.

**Key words:** anthropogenic (man-made) deposit, formation, hydraulic shovel, losses, parameters, sections, mining

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# Технология посекционного формирования техногенного месторождения с последующей отработкой гидравлическим экскаватором «обратная лопата»

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**Аннотация.** В статье представлено обоснование параметров разработанной посекционной технологии формирования и отработки хвостохранилища гидравлическими экскаваторами «обратная лопата». Выявлены зависимости потерь техногенного сырья в секции от ее ширины по экономическим и техническим факторам. При проведении исследования был использован современный подход к решению поставленных задач – метод комплексного исследования, включающий анализ существующего состояния изученности вопроса освоения техногенных месторождений, изучение пространственной структуры и отношения технологических параметров экскаватора типа «обратная лопата» к техногенному обьекту. Исследования показали, что при разработке техногенного месторождения, представленного хвостами обогащения, происходит разубоживание кондиционного техногенного сырья за счет потерь и засорения, а также снижается эффективность ведения горных работ. Разработанная технология формирования посекционного техногенного месторождения при использовании гидравлического экскаватора типа «обратная лопата» позволяет обеспечить селективную выемку, снизить разубоживание техногенного сырья в пределах секций, повысить безопасность и интенсивность ведения горных работ, а также снизить себестоимость добычи в будущем.

**Ключевые слова:** техногенное месторождение, формирование, гидравлический экскаватор, потери, параметры, секции, разработка

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## Introduction

Today, the inevitable depletion of reserves and deterioration of geological and mining conditions result in the need to search for new inexpensive raw material sources [1–3]. Mill waste at metallurgical plants and waste dumps of low-grade non-commercial ores are promising raw sources [4–6]. Their amount increases at mining facilities with each year [7–9]. They accumulate a lot of valuable components, the content whereof in waste in some cases exceeds that in natural resources; considerable land areas are disturbed [10–12]. Due to these reasons, the importance of anthropogenic deposits increases significantly, and their mining is a topical issue of the nearest future [13–16]. Therefore, it is a certainty that finding a justification for the parameters of the technology for the sectional formation of tailing dumps with their subsequent mining is a very well-timed research direction; this would increase the safety, intensity, and profitability of mining [17–20]. When calculating the economic efficiency of anthropogenic deposit mining, one should consider not only the factor of obtaining additional products but also the reduction in the costs due to waste storage, damage from environmental pollution, and the mining costs due to the reduction in the expenses for preparing rocks before their excavation and in the processing costs [21–24].

Leading researchers – M.I. Agoshkov, S.E. Gavrishev, A.M. Demin, Yu.E. Kapustin, N.V. Melnikov, B.M. Nikitin, K N. Trubetskoy, V.N. Umanets, G.A. Kholodnyakov et al. – have devoted their studies to the integrated mining of mineral resources and their efficient management [25–27].

They were the first to systematize and classify man-made deposits and formations; generalize exploration methods; reveal specific features of the internal structure and spatial variability of target mineral content; justify the financial viability for the accompanying mineral mining. They have created an economic and mathematical model that allowed optimizing the amount of utilized crude minerals of different grades, defining the minimum industrial content of useful components in commercial reserves, and selecting the most efficient ways to use anthropogenic feedstock and mining routes [28–30].

Thus, fundamental concepts have been designed for the transfer to low-waste technologies for mineral deposit mining by the targeted formation of man-made deposits and mining of existing ones [31, 32].

Efficient processing routes and parameters, which would ensure high productivity and simultaneous safety of mining operations, have not been yet developed and justified for tailing waste mining despite the availability of an extensive theoretical potential and scientific procedural background.

**The objective of this paper** is to substantiate the parameters of the technology for the formation and development of technogenic deposits, represented by iron-containing enrichment tailings, to increase the productivity of excavation and loading equipment, the completeness of extraction and reduce the impoverishment of the produced technogenic raw materials.

## Methods and materials

During the study, a modern approach to solving the tasks was used – the method of complex research:

1. Analytical method, which includes the analysis of technogenic formations and the methodological base for involving them in development, the assessment of the prerequisites for the application of loss

reduction methods, their analysis and comparison, the study of the dynamics of cryogenic processes.

2. Computer modeling method, including 2D and 3D modeling of technological schemes using walking and hydraulic excavators, the influence of the parameters of a helical continuous winding on the flow structure (subject to the conditions of dynamic similarity according to the Reynolds number).

3. Experimental method, including physical modeling of controlled segregation and study of the behavior of polydisperse mixtures during the formation of a man-made deposit, study of the behavior of a walking excavator bucket, determination of the physical and mechanical properties of enrichment tailings.

4. Mathematical analysis of the results obtained, including the identification of dependencies, plotting, calculation of technological and economic parameters.

5. Synthesis of the results of private research in various fields of science.

## Results

The designed technology for the sectional formation of an anthropogenic deposit comprises a main dam, which may be designed in a different, rectangular, shape. The resulting reservoir is divided into sections by walls made of rock overburden. The rock wall is made along the reservoir length leaving a water discharge gap between said wall and the dam. Anthropogenic raw materials are dumped by a distributed release into each section via pipes carrying coarse (rich) fraction and into the active tailing dump via pipes carrying fine (poor) fraction of the anthropogenic feedstock. Pipe branches coming out of the device may be of different design. Coarse (rich) and fine (poor) fractions are separated by a separation control device when forming the man-made deposit. Sections are mined after their filling. Extracted raw materials are transported to the dressing plant for their further processing and application in various industries.

It is necessary to form the sections that separate raw materials with consideration for the application of pull shovels. This type of mining and loading equipment provides the possibility of fully implementing the selective mining of anthropogenic raw materials at the expense of the complex kinematic pattern of the shovel bucket motion [33–36]. Rock walls are dumped with the following parameters using dumpers (Fig. 1).

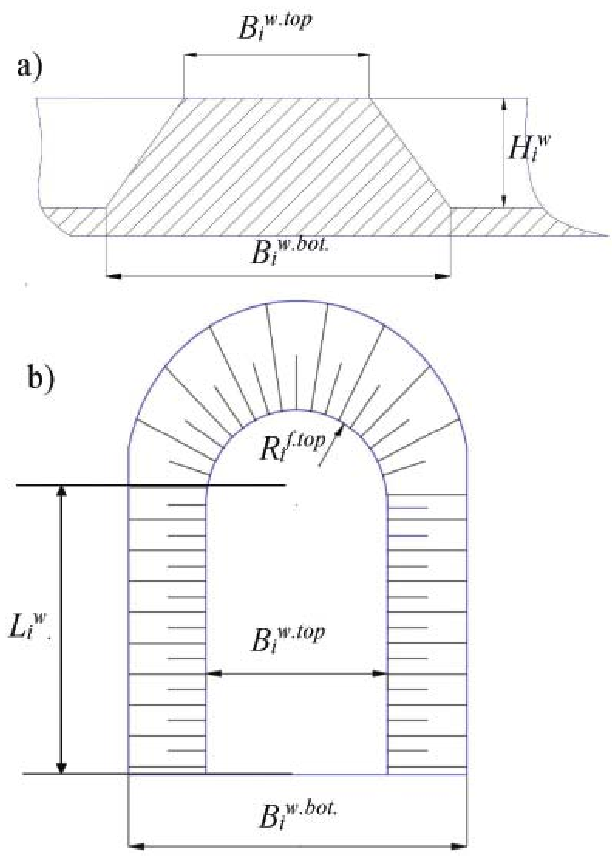


***Fig. 1.*** *Parameters of the rock overburden wall:*
*a – the wall cross section; b – the wall top view;*
*$B_i^{w.bot}$ – the width of the rock wall at the bottom, m;*
*$B_i^{w.top}$ – the width of the rock wall at the top, m;*
*$R_i^{fw.top}$ – fill radius at the top, m; $H_i^w$ – rock wall height, m;*
*$L_i^w$ – the length of the rock wall without the round-shaped fill, m (compiled by the authors)*

***Рис. 1.*** *Параметры перегородки из скальной вскрыши:*
*а – поперечное сечение перегородки;*
*б – вид перегородки сверху; $B_i^{п.н}$ – ширина скальной перегородки по низу, м; $B_i^{п.в}$ – ширина скальной перегородки по верху, м; $R_i^{о.в}$ – радиус насыпи по верху, м; $H_i^{п}$ – высота скальной перегородки, м; $L_i^{п}$ – длина перегородки из скальной вскрыши без учета насыпи круглой формы, м (составлено авторами)*

The rock wall height is calculated by the equation:

$$H_i^w = H^{d.h}, \text{ m}, \quad (1)$$

where $H^{d.h}$ is the maximum digging height of the shovel, m.

The wall width at the top is:

$$B_i^{w.top} = B_{min}, \text{ m}, \quad (2)$$

where $B_{min}$ is the minimum width of the work site, m.

The amount of overburden rock used to form the wall is calculated using the formula:

$$V_i^{wall} = \left( \frac{\hat{A}_i^{w.top} + \hat{A}_i^{w.bot}}{2} L_i^{w.top} H_i^{w} \right) +$$
$$+ \frac{1}{6} \pi H_i^{w} \left( R_i^{f.top2} + R_i^{f.top} R_i^{f.bot} + R_i^{f.bot2} \right), \text{ m}^3, \quad (3)$$

where $L_i^w$ is the length of the rock wall without the round-shaped fill, m; $R_i^{f.top}$ is the fill radius at the top, m; $R_i^{f.bot}$ is the fill radius at the bottom, m.

The total required amount of rock overburden is:

$$V_w^{total} = V_i^{wall} + V_{i+1}^{wall} + V_n^{wall}, \text{ m}^3,$$

where $n$ is the number of sections in the anthropogenic deposit being formed, pcs.

The number of sections is set by the required amount of the selected grades for the dumped material extracted from anthropogenic raw materials and the tailing dump capacity.

The amount of anthropogenic raw materials in the section is calculated by the equation:

$$V_c = \frac{B_i^{s.top} + B_i^{s.bot}}{2} L_i^s H_i^s \beta_{i\,\text{section}}\, v, \text{ m}, \quad (4)$$

where $B_i^{c.top}$ is the section width at the top, m; $B_i^{c.bot}$ is the section width at the bottom, m; $L_i^c$ is the section length, m; $\beta_{i\,cection}$ is the section filling rate, fractional units.

The section may be built above the ground surface, depressed, or by combination of the above two methods. For the complex design of the section, its height will be the sum of the heights of the above-ground and depressed parts.

The wall length is limited by the boundaries of the free land plot within the land permit. The double-sided shovel arrangement will increase the mining intensity within the section and section width (Fig. 2).

The section maximum width is:

$$B_i^{s.top} = R_{1W.A} + R_{2W.A} - 2z -$$
$$-2\left( R_{1W.A} - \sqrt{R_{1W.A}^2 - a^2} \right), \text{ m},$$

where $z$ is the safe distance from the shovel axis to the bench edge, m; $a$ is the distance from the site to the shovel axis, m; $R_{1W.A}$ is the work area radius for the first pull shovel, m; $R_{2W.A}$ is the work area radius for the second pull shovel, m.

At the same time, the work area radii of the pull shovels used are their maximum excavating radii, which may overlap either in one or in two points, or not overlap at all. The overlap area size may vary depending on the distance between shovels, and impacts the section width, losses and capacity, accordingly.

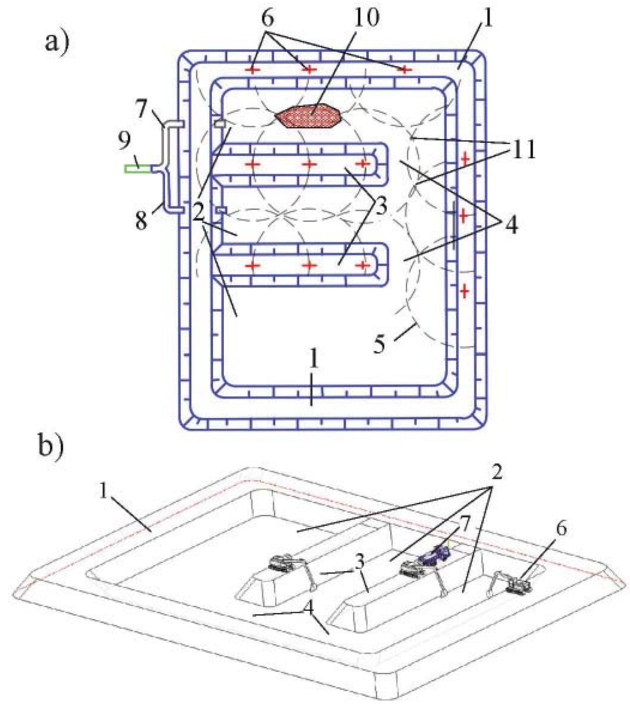


*Fig. 2. The diagram of pull shovel arrangementwhen mining the formed anthropogenic deposit: a – plane view; b – 3D model; 1 – main dam; 2 – sections; 3 – rock walls; 4 – section-connecting gap; 5 – shovel work areas; 6 – location of the mining and loadingequipment; 7 – pipe carrying rich/coarse fraction of material; 8 – pipe carrying poor/finefraction of material; 9 – separation control device when forming the man-made deposit; 10 – overlapping work areas of shovels; 11 – overlap points of shovel work areas (compiled by the authors)*

*Рис. 2. Схема расположения выемочно-погрузочного оборудования при разработке сформированного техногенного месторождения: а – вид в плане; б – 3д модель; 1 – основная дамба; 2 – секции; 3 – перегородки из скальной вскрыши; 4 – промежуток, соединяющий секции; 5 – рабочие зоны экскаваторов; 6 – экскаваторов «обратная лопата»; 7 – труба с богатой/крупной фракцией материала; 8 – труба с бедной/мелкой фракцией материала; 9 – устройство по управлению сегрегационном процессом; 10 – область перекрещивания рабочих зон экскаваторов; 11 – точки пересечения рабочих зон экскаваторов (составлено авторами)*

The formed man-made deposit should be mined using a hydraulic pull shovel from the work area edges to the pit wall made of rock overburden as shown in Fig. 3.

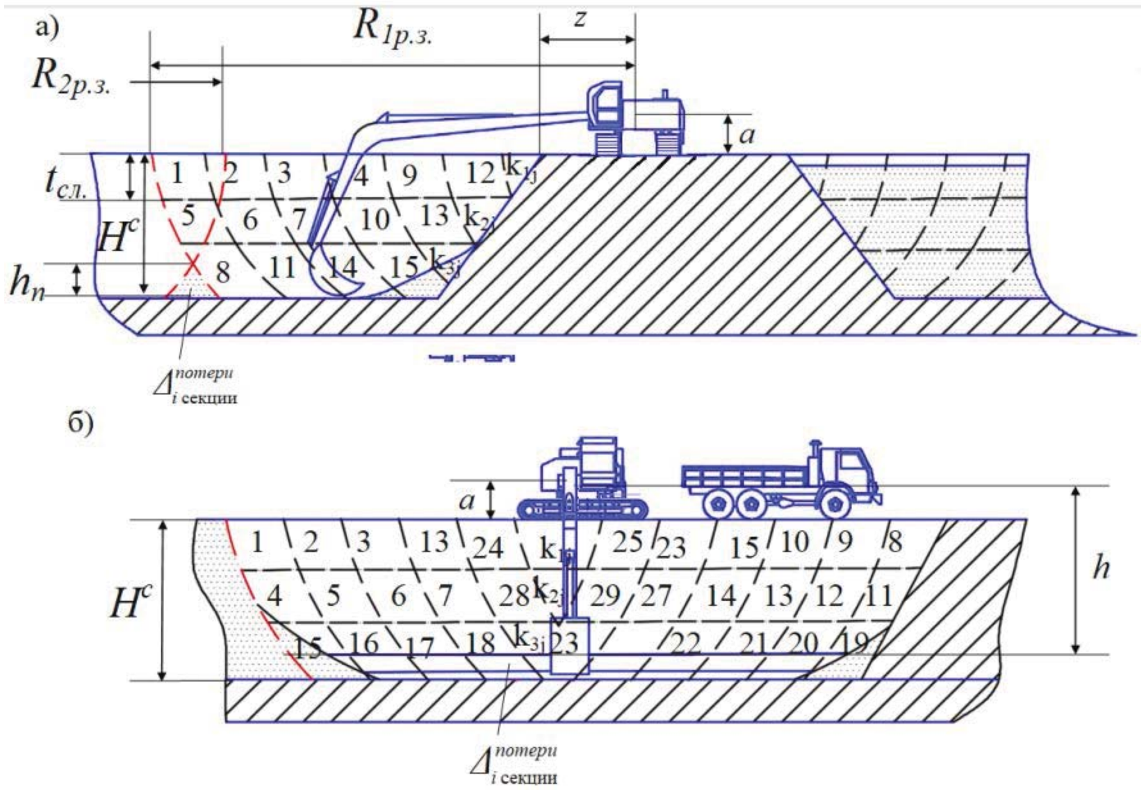


***Fig. 3.** Section mining sequence using a pull shovel: a – side view; b – front view; $R_{2W.A}$ – work area radius for the first pull shovel, m; $R_{2W.A}$ – work area radius for the second pull shovel, m; $t_{layer}$ – raw material layer thickness, m; $\Delta^{loss}_{i\,section}$ – material loss due to overlapping work areas of pull shovels in the $i^{th}$ section, m$^3$; $h_{loss}$ – loss height, m; 1,2,3,...,$k_{1j}$, $k_{2j}$, $k_{3j}$, $k_{nj}$ – material block mining sequence; z – safe distance to the bench edge, m; a – height from the rock wall surface to the boom, м (compiled by the authors)*

***Рис. 3.** Порядок отработки секции с использованием экскаватора «обратная лопата»: а – вид сбоку; б – вид спереди; $R_{1Р.З}$ – радиус рабочей зоны 1-го экскаватора «обратная лопата», м; $R_{2Р.З}$ – радиус рабочей зоны 2-го экскаватора «обратная лопата», м; $t_{сл}$ – мощность слоя материала, м; $\Delta^{потери}_{i\ секции}$ – величина потерь при пересечении рабочих зон экскаваторов «обратная лопата» в i-й секции, м$^3$; $h_n$ – высота потерь, м; 1,2,3,...,$k_{1j}$, $k_{2j}$, $k_{3j}$, $k_{nj}$ – порядок отработки блоков материала; z – безопасное расстояние до бровки уступа, м; a – высота от поверхности перегородки из скальной вскрыши до стрелы, м (составлено авторами)*

This mining sequence for the anthropogenic deposit decreases the risk of slope slide, increases the safety margin factor for the rock overburden site due to the presence of a relieving wall to the bench slope [37–40].

Existence of loss is characterized by the distance between the pull shovels. At the same time, a strong decrease in this distance will result in a considerable reduction of the section width, which, in turn, impacts its capacity at constant height and length, and leads to increased costs required to form sections [41–43].

Calculation of the optimal section width should be based on the loss amount that occurs due to overlapping work areas of the shovels facing each other. (Fig. 4).

Let us derive a set of equations to define the coordinates of overlappoints for shovel work areas assuming that the coordinates of the first shovel are $x_{s1}$=0 and $y_{s1}$=0. Then:

$$\begin{cases} x^2 + y^2 = R^2_{1W.A}; \\ (x - x_{s2})^2 + (y - y_{s2})^2 = R^2_{2W.A}, \end{cases} \quad (6)$$

where $x_{s2}$, $y_{s2}$ are the coordinates of the 2nd shovel; $x$, $y$ are the coordinates of overlappoints for shovel work areas.

At $y_{s2} \neq y_{s1}$, when shovels are located at different digging levels and at different distance, we can put $x$ in the curve equation for the first shovel work area, resulting in the following quadric equation:

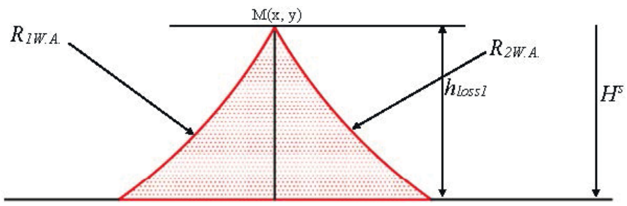


***Fig. 4.*** *Loss of raw materials due to overlapping work areas of pull shovels at point M(x;y): $h_{loss1}$ is the lost material height at the maximum digging depth, m; $H^c$ is the section depth at the maximum digging depth, m; $R_{1W.A}$ is the work area radius for the first pull shovel, m; $R_{2W.A}$ is the work area radius for the second pull shovel, m (compiled by the authors)*

***Рис. 4.*** *Потери техногенного сырья в рабочих зонах гидравлических экскаваторов «обратная лопата» в точке M(x;y): $h_{n1}$ – высота потерь при максимальной глубине черпания, м; $H^c$ – глубина секции при максимальной глубине черпания, м; $R_{1Р.З}$ – радиус рабочей зоны 1-го экскаватора, м; $R_{1Р.З}$ – радиус рабочей зоны 2-го экскаватора, м (составлено авторами)*

$$y^2\left(y_{s2}^2+x_{s2}^2\right)-2y_{s2}cy+\left(c^2-R_{1W.A}^2x_{s2}^2\right)=0. \quad (7)$$

Let us introduce variables to simplify the solution:

$$f=y_{s2}^2+x_{s2}^2; \quad (8)$$

$$g=-2y_{s2}c; \quad (9)$$

$$m=c^2-R_{1W.A}^2\cdot x_{s2}^2. \quad (10)$$

Then

$$D=g^2-4fm. \quad (11)$$

If $D<0$, shovel work areas do not overlap, resulting in the biggest loss of anthropogenic feedstock (this case is not studied).

If $D=0$, shovel work areas have one common overlap point:

$$y=\frac{-g+\sqrt{D}}{2f};\ \ x=\frac{c-yy_{s2}}{x_{s2}}. \quad (12)$$

Section would have the maximum width in this case.

If $D>0$, shovel work areas have two overlap points, whereat the lowest loss of anthropogenic feedstock is achieved:

$$y_1=\frac{-g+\sqrt{D}}{2f}; \quad (13)$$

$$x_1=\frac{c-y_1y_{s2}}{x_{s2}}; \quad (14)$$

$$y_2=\frac{-g-\sqrt{D}}{2f}; \quad (15)$$

$$\frac{c \quad y_2y_{s2}}{s2} \quad (16)$$

Let take the overlap point with coordinates ($x_2$; $y_2$) for further calculations since losses occur in the bottom part.

At $y_{s2}=y_{s1}$, when shovels are at the same digging level, let find the solution through $y$ resulting in:

$$H_L=b=(H^c+a)-y,\ \text{m}, \quad (17)$$

where $H^c$ is the section height, m; $a$ the distance from the upper site to the shovel axis, m.

Area of lost materials in the section is:

$$\begin{aligned}S_{loss}&=x(|b|-|y|)-\\&-\left(\frac{R_{(1W.A)}^2}{4}\left|\left(\pi\frac{\left|\text{arctg}\left(\frac{x}{y}\right)\right|}{90°}-\left|\sin\left(2\text{arctg}\left(\frac{x}{y}\right)\right)\right|-\pi\frac{\left|\text{arctg}\left(\frac{x_b}{b}\right)\right|}{90°}+\left|\sin\left(2\text{arctg}\left(\frac{x_b}{b}\right)\right)\right|\right)\right|\right)-\\&+(x_{s2}-x)(|b|-|y|)-\\&-\left(\frac{R_{2W.A}^2}{4}\left|\left(\pi\frac{\left|\text{arctg}\left(\frac{x_{s2}-x}{y}\right)\right|}{90°}-\left|\sin\left(2\text{arctg}\left(\frac{x_{s2}-x}{y}\right)\right)\right|-\pi\frac{\left|\text{arctg}\left(\frac{x_b}{b}\right)\right|}{90°}+\left|\sin\left(2\text{arctg}\left(\frac{x_b}{b}\right)\right)\right|\right)\right|\right),\end{aligned} \quad (18)$$

where $x$, $y$ are the coordinates of the overlap point of shovel work areas.

Generally, the section width at the top part is:

$$\begin{aligned}B_i^{s.top}&=-2z-R_{1W.A}+2x+R_{2W.A}=\\&=x_{s2}-x_{s1}-2z,\ \text{m}.\end{aligned} \quad (19)$$

The amount of lost material in the section will be:

$$\Delta_{i\,\text{section}}^{loss} = S_{i\,loss} \cdot L_i^{s.bot}, \text{ m}^3, \quad (20)$$

where $L_i^{s.bot}$ is the section length at the bottom, m.

Thus, the dependence of the lost material amount on the section width and the costs required to eliminate it are shown in Fig. 5–6.

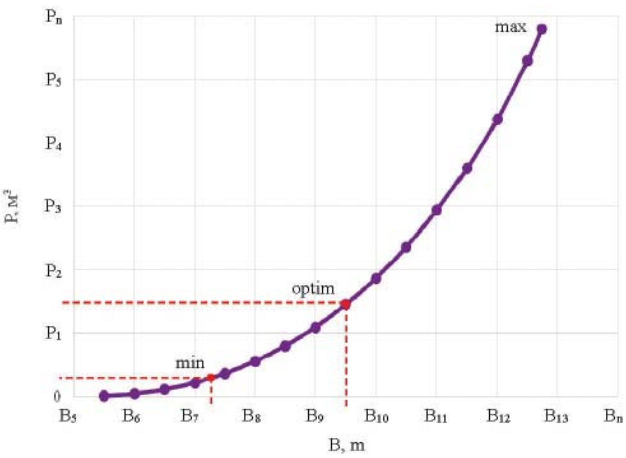


***Fig. 5.*** *Lost material amount vs. section width: P – loss amount, m³, B – section width, m (compiled by the authors)*

***Рис. 5.*** *Зависимость величины потерь от ширины секции: P – величина потерь, м³, B – ширина секции, м (составлено авторами)*

The costs necessary to reduce the loss of anthropogenic feedstock depend on the method applied [44–46].

Taking into account the structure of the anthropogenic deposit formed in sections, the following methods may be proposed to decrease the loss of raw materials during their mining using pull shovels:

1. Arrange ramps in the sections and place mobile equipment in them to move the remaining anthropogenic feedstock into the work area of the shovels.
2. Decrease the height of the mined section by the value equal to the OY coordinate of the overlap point of shovel work areas.
3. Decrease the width of the section being mined by the length of the loss triangle base.

This paper considers the first method intended to decrease the raw material loss since both other ones would lead to the decrease of section capacity and, as a result, to the increase of the costs necessary to form it. It is possible to use a bulldozer, small-capacity dredger or loader as mobile equipment. However, the dredger is the most expensive device to operate among the above-listed hardware. Leaving the high height of the loss triangle for its application feasibility is unsafe [33, 46]. According to the study performed, the application of bulldozers is economically unviable due to the limited specifications, namely the maximum angle of approach and dumping height [41]. Therefore, the application of a front loader is more prudent and may be explained by the break-even point of loss decrease based on the economic factor (Fig. 6).

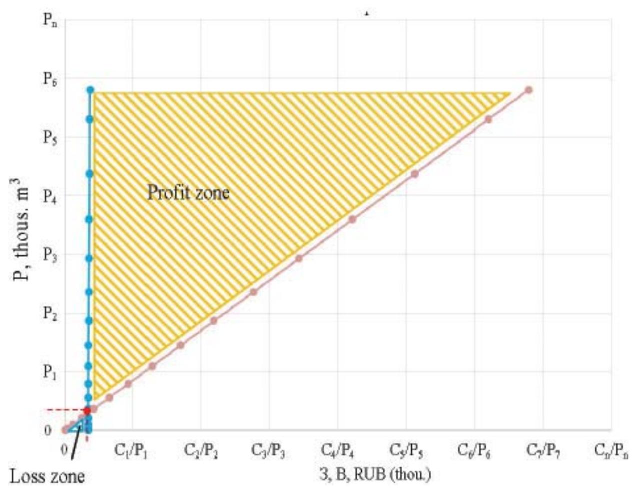


***Fig. 6.*** *Dependence of the cost amount required to reduce material loss and profit upon the loss value (compiled by the authors)*

***Рис. 6.*** *Зависимости затрат на сокращение потерь и выручки от величины потерь (составлено авторами)*

## Discussion

The technology for the sectional formation of ananthropogenic deposit should consider the performance characteristics of the pull shovel used. This consideration will increase the deposit mining efficiency in the future. Our study has revealed a direct dependence of the parameters of enclosing walls between the sections upon the performances of mining and loadingequipment, which equals the maximum height of shovel digging and the minimum width of the work area for safe mining. The wall length is limited by the land plot boundaries within the land permit.

The width of sections filled with anthropogenicraw materials is largely dependenton the radius of the shovel work area, the mining face extraction sequence, the amount of equipment used, and the lost feedstock volumes, as well as on economic factors. A lower quantity of the applied mining and loadingequipment leads to a decrease in the section volume, which, in turn, results in a productivity decrease and often in considerable losses. In this case, loss of feedstock occurs in the area opposite to the barrier wall side, and this indicator increases in direct proportion to the section width. When using two shovels, material loss occurs at the overlap of their work areas and increases as the section width increases. The concept of processing the mining face from the sides to the centre reduces the risk of the wall slope slide due to thepresence of a relieving wall made of anthropogenicraw materials.

Figure 6 shows that the intersection of the loss reduction costs and revenue dependencies upon the loss value will yield a section width, at which loss reduction costs will be compensated by the revenue, and the industrial facility will start making a profit when reducing the loss of each successive cubic metre of feedstock.

Let us find the break-even point and, therefore, the section width at the top, at which the company starts making a profit; the maximum profit is at the point with maximum deviation of the graphs from each other. The maximum loss height is defined by the functionality of the mobile equipment used to reduce losses and the safety of the mining operations. Optimum width of the section is defined by comparing the values obtained.

## Conclusion

Recently, mining of anthropogenic deposits is becoming an increasingly important problem accompanied by the decrease in productivity of mining operations due to sudden collapses of mining faces, downtime of mining and loading equipment, severe losses of man-made feedstock in the shovel work areas, and high production costs. Due to these factors, mining processes for industry-induced deposits have become no longer economically profitable in some cases. More efficient mining technologies may be a way to solve these problems.The results of this study have revealed the possibility of increasing the mining efficiency for such deposits by the purposeful formation of ananthropogenic deposit for a particular type of mining and loadingequipment planned to be used for its mining in the future.

The technology considered in this article makes it possible to reduce dilution, which features a decrease in mineral quality due to losses and clogging.

The article presents the justification for the parameters of the designed sectional technology for the formation and mining of anthropogenic deposits by hydraulic pull shovels. The authors have established the dependences for the amount of loss of anthropogenic feedstock in a section upon its width due to economic and technical factors. They will give a new round in the further development of anthropogenic deposit mining.

## Resume

1. The article presents the results of a study to justify the parameters of the developed section-by-section technology for the formation and development of a tailings dump using hydraulic backhoe excavators.

2. The dependences of losses of technogenic raw materials in a section on its width according to economic and technical factors have been identified.

3. The developed technology for the formation of section-by-section technogenic deposits using a hydraulic backhoe type excavator allows for selective excavation, reducing the dilution of technogenic raw materials within sections, increasing the safety and intensity of mining operations, and also reducing the cost of production in the future.

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Ligotsky D.N. – development of methodology. Argimbaeva K.V. – conducting laboratory studies, processing the results, identifying dependencies.

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The authors declare no conflict of interest

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