UDC 622.1:622.834(083.74) DOI: https://doi.org/10.15407/geotm2023.167.119

DETERMINATION OF DESIGN INDICATORS OF EARTH SURFACE DEFORMATIONS FOR MINEABLE BUILDINGS AND STRUCTURES

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Abstract. Coal is one of the main sources of energy in Ukraine. Underground coal mining is concentrated in the areas of Eastern and Central Donbas, Western Donbas, and in the Lviv-Volyn region. Development of coal seams leads to displacement of rocks and uneven subsidence of the surface. Surface movements and deformations cause serious damage to the environment. They affect residential and industrial infrastructure, and can cause destruction or disruption of operating conditions. Risks to surface structures can be reduced by predicting subsidence and surface deformation over underground workings. In Ukraine, the method of typical subsidence and deformation distribution functions is used for forecasting. This is a simple and universal method, but it does not take into account the differences in deformations in different zones of the shear trough depending on the direction of movement of the face. For this reason, incorrect predictive estimates of the impact of mining operations on the earth's surface, man-made natural, industrial and civilian objects arise. This paper presents a methodology for determining the estimated deformations of the foundations of civilian buildings that are being faked, taking into account the assessment of the estimated impact of mining operations, which takes into account the peculiarities of the formation of the shear trough in space and time. This methodology was developed to supplement and clarify the "Temporary technical conditions for the protection of structures and natural objects from the impact of underground mining operations. KD 12.00159226.013-95" for the conditions of underground mining of coal seams in the Western Donbas, as well as other deposits with similar conditions and parameters of the earth surface displacement process. It is based on modern concepts of rock and earth surface movements during underground mining of coal seams with horizontal and gentle rock occurrence; results of analysis of numerous instrumental surveying observations, including frequency ones, at observation stations of mines in Western Donbas. The obtained regularities allow for a more objective selection and application of protection measures for civil buildings. This reduces the risks during the operation of buildings, makes it possible to plan repair and restoration work, and to make a rea-sonable assessment of buildings and territories in the real estate market.

Keywords: coal seams, longwall, surface subsidence, deformations, buildings and structures, displacement trough.

1. Introduction

Coal seam mining results in rock displacement and uneven surface settlement. Displacements and surface deformations cause serious damage to the environment. They affect residential and industrial infrastructure facilities, and can cause destruction or disruption of operating conditions [1–6]. Reducing the risks to aboveground structures is possible by predicting subsidence and deformation of the surface above underground workings. The estimated impact of underground workings on protected buildings and structures is assessed by the calculated indicator of total deformations due to the impact of planned mining operations.

The value of the calculated total deformations directly depends on the values of the expected tensile (compressive) deformations and curvature of the earth's surface within the perimeter of the object being mined.

The general methodology for calculating the expected deformations of the earth's surface due to the impact of coal seams development and the calculated indicator of total deformations is regulated by TTU-95 [7]. The regulatory documents do not contain any guidelines and recommendations on how to determine the specific calculated deformations of the foundations of the objects being mined in order to predict their damage. There is a possibility of ambiguity of the calculated indicators obtained according to TTU [7, 8] and discrepancies between them.

2. Methods

For unambiguous interpretation of further research and conclusions regarding the scope of the proposed methodology, we provide the basic concepts and terms used in the presentation of the material [9, 10].

Earth surface displacement process is a consistent change in the spatial position of points, lines and areas of the earth's surface over time due to the disturbance of equilibrium and redistribution of stresses in the rock mass caused by mining operations.

Earth surface displacement trough is a section of the earth surface that has been and/or is being displaced under the influence of mining workings.

Dynamic displacement trough is a trough in the process of displacement of the earth's surface under the influence of mining workings.

Static trough is a trough in a state of steady state equilibrium of rocks after their processing. It characterizes the state of the earth's surface after the end of the displacement process.

Flat bottom of a displacement trough is a part of the displacement trough where the points of the earth's surface have maximum subsidence and remain unchanged with further increase in the size of the excavated space.

Main sections of the displacement trough – vertical sections of the trough along the strike and across the formation, passing through the points with maximum subsidence of the earth's surface.

The area of displacement trough formation is a dynamic trough from the moment the earth surface displacement process starts until the moment when the displacement trough wing from the side of the excavated space stops changing its geometry and starts moving in a plane-parallel manner with the face of the working face.

The synchronous displacement area is a part of the dynamic trough that follows the formation area of the shear trough, in which points of the earth's surface at equal intervals before or after the passage of the working face line under them acquire the same displacement and deformation values. It is characterized by the constancy of the surface shape of the semi-trough moving along the face at any given time. On the earth's surface, it is limited to the position of the kinetic trough boundary at the time of stopping the working face.

The damping region of the displacement process is a part of the dynamic trough that follows the synchronous displacement region. It characterizes the displacement of the earth's surface from the moment the working face is stopped until the end of the displacement process.

Area of unambiguous deformations – a section of the earth's surface where deformations of one sign or both signs are manifested in the process of its forging at insignificant deformation values of one of them.

The area of alternating deformations is a section of the earth's surface, where deformations of both signs are equally large in the process of its forgery.

Boundary angle δ_0 – an angle external to the excavated space formed on a vertical section along the main section of the trough by a horizontal line and a line (consistently drawn in bedrock, Mesozoic sediments and sediments) connecting the boundary of the excavation with the boundary of the zone of influence of underground mining on the earth surface ($\delta_0 = 65°$).

Angle of total displacement ψ – an angle internal to the mined space formed on a vertical section along the main section of the trough by the plane of the seam and the line connecting the border of the workings with the border of the flat bottom of the trough of displacement ($\psi = 55°$).

Angle δ_6 is the internal angle relative to the excavated space formed on a vertical section along the main section of the trough in the zone of synchronized displacement by the formation plane and the line connecting the face boundary with the inflection point of the subsidence Curve (also known as the point of maximum inclinations and horizontal displacements, zero values of curvature and horizontal deformations). It characterizes the amount of rock overhang above the moving face ($\delta_6 = 78°$).

Angle ω is an angle internal to the working space formed on a vertical section along the main section of the trough provided that the displacement process is completed by the formation plane and the line connecting the working face with the inflection point of the subsidence curve (also known as the point of maximum slopes and horizontal displacements, zero values of curvature and horizontal deformations). It characterizes the amount of rock overhang at the end of the displacement process ($\omega = 86°$).

The calculated indicator of deformations of the earth surface (base of the structure) characterizes the effects of faulting on buildings and structures, which are determined based on the calculated values of deformations of the earth surface, taking into account the type of structure and the peculiarities of its interaction with the base.

3. Theoretical and experimental parts

The accumulation and distribution of displacements and deformations in the displacement trough is not uniform. Depending on the time of occurrence, general patterns of formation and distribution of deformations, the displacement trough areas can be classified as follows by the degree of formation:

– *static trough* – characterizes the state of the earth's surface at the end of the displacement process;

– *dynamic trough* – characterized by constantly growing sizes and time- and space-varying values of displacements and deformations of the earth's surface, the final state is static trough;

by the activity of the displacement process:

– surface areas in the initial stage of displacement;

– surface areas in the active stage of displacement;

– surface areas in the stage of displacement attenuation;

by the nature of accumulation of displacements and deformations (Fig. 1):

– the area of formation of the displacement trough;

– area of synchronous displacement of the earth's surface;

– the area of displacement attenuation;

by the nature of deformation distribution (Fig. 2):

– the zone of comprehensive stretching of the earth's surface;
– zone of comprehensive compression of the earth's surface;
by the variability of deformations of the earth's surface (Fig. 3):
– zone of unambiguous deformations;
– zone of alternating deformations.

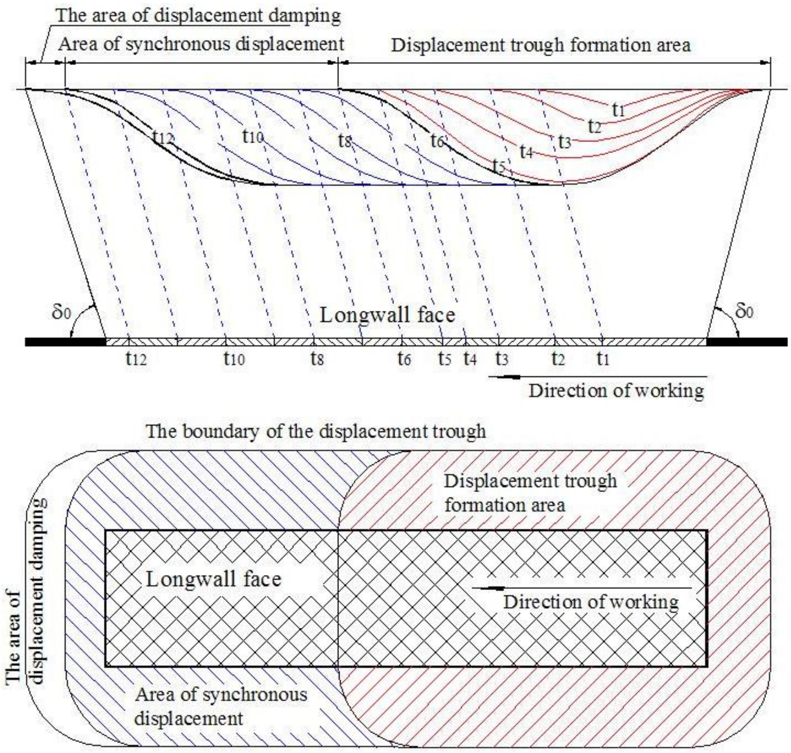


Figure 1 – Classification of displacement trough areas by the nature of accumulation of displacements and deformations

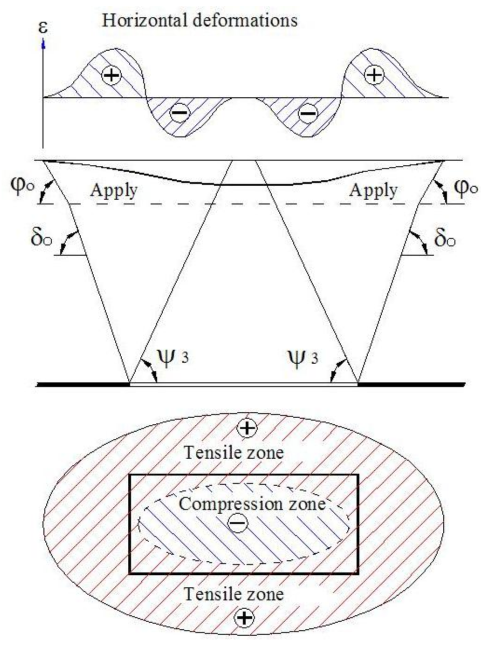
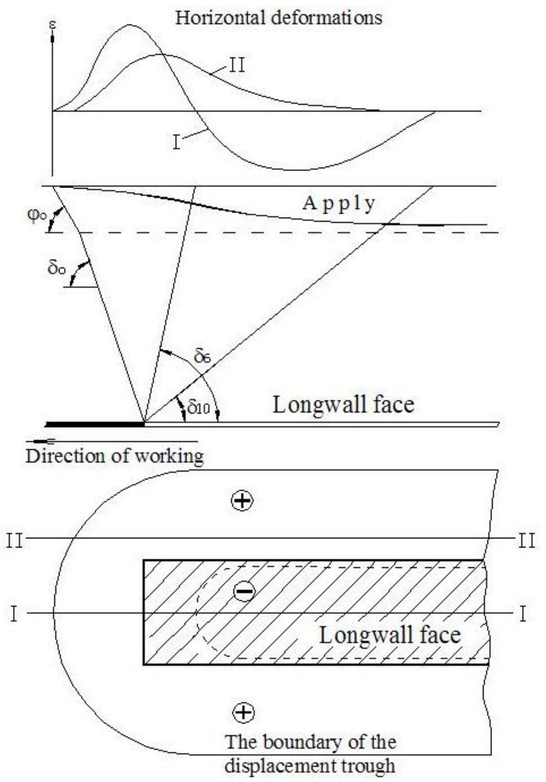


Figure 2 – Classification of displacement trough areas depending on the nature of the deformation distribution



I – zone of alternating deformations; II – zone of unambiguous deformations

Figure 3 – Classification of the displacement trough areas depending on the deformation variability

The division of the displacement trough into the listed areas and sites is rather arbitrary, but the general patterns of the displacement process in them allow us to distinguish the following characteristic zones in the trough (Fig. 4).

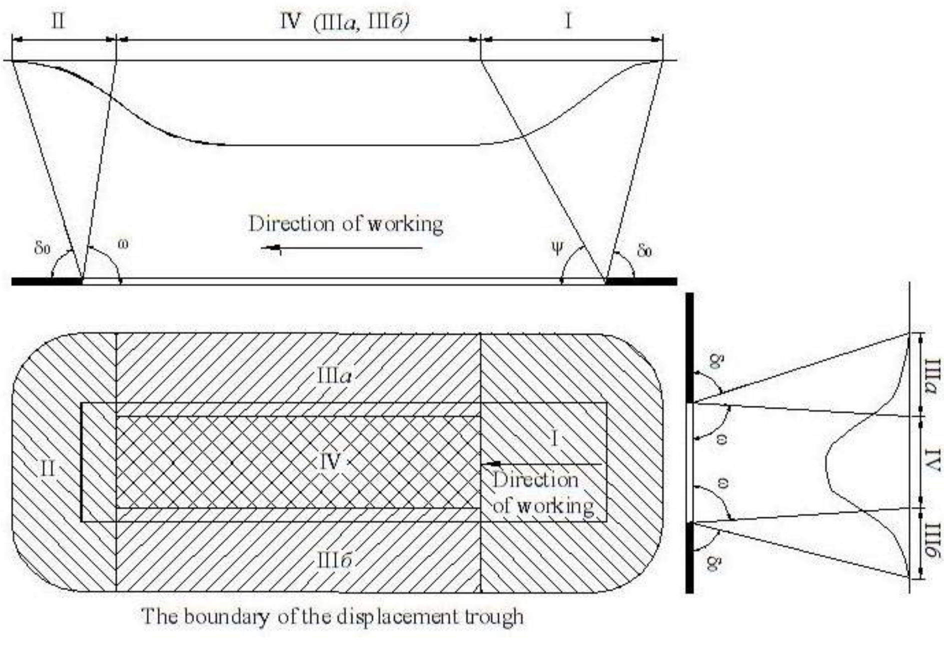


Figure 4 – Classification of displacement trough zones by general patterns of distribution of earth surface deformations

Zone I is characterized by a gradual accumulation of positive and negative deformations reaching maximum values at the end of the shear process. The zone is confined to the area of formation of the displacement trough and is bounded on the section on the one hand by the boundary angle δ_0, and on the other hand by the angle of total displacement ψ.

Zone II is characterized by the accumulation of deformations of the same sign (tensile and bulge curvature). The final value of deformations is taken as the static trough deformation values. The zone covers the damping region of the displacement trough and the edge part of the synchronous displacement region. On the section in the direction of the face movement, it is bounded by the boundary angle δ_0, and the angle ω, which characterizes the position of the inflection point of the subsidence curve at the end of the displacement process.

Zones III*a* and III*b* are located between zones I and II. In the direction perpendicular to the advancement of the face, they are bounded on the one hand by the boundary angle δ_0 and on the other by the angle ω. In the direction of the face advancement, positive deformation values (tension and convexity curvature) prevail with no or insignificant negative deformation values (compression and concavity curvature). In sections perpendicular to the direction of the face advancement, positive deformations accumulate, with a maximum when the displacement process is complete. Zones III*a* and III*b* are located in the area of synchronous displacement of the earth's surface.

Zone IV is located in the middle part of the displacement trough between zones I, II, III*a* and III*b*. The deformations in this zone in the direction of cross-face advancement vary depending on the position of the face, and their maximum values correspond to the deformations along the main section in the static trough, i.e., when the displacement process is over. In the direction of the face advancement, the deformations of the earth's surface acquire alternating values (alternately positive and then negative). Each point of the trough in this direction experiences extreme deformation values equal to or close to the maximum values. Zone IV belongs to the area of synchronous displacement.

The peculiarities of accumulation and distribution of deformations within the mentioned zones of the displacement trough allow choosing a specific methodology for determining the calculated deformations of the earth surface in relation to the task of estimating the calculated indicator of total deformations of the building being forged.

1. Within zones I and II, the determination of deformations of the base of the building being falsified in any direction is performed according to the method of calculating the expected deformations for the conditions of the completed displacement process, given in TTU-95 [7].

2. If the building to be tampered with is located in zones III*a* or III*b*, then in the direction perpendicular to the movement of the longwall, the deformations of the building foundation are determined by the TTU-95 method [7].

In the direction of the longwall movement, the base of the building to be rigged is subjected to tensile deformations and convexity curvature, which are calculated taking into account the methods [7] and [11] by the following formulas:

$$\varepsilon = +0{,}6\frac{m}{H}S(z_y); \tag{1}$$

$$K = +\frac{8m}{(0{,}8H+h)^2}S(z_y), \tag{2}$$

where: m – is the thickness of the formation to be excavated, m; H – is the average depth, m; h – is the thickness of sediment, m; *S(zy)* – is the value of the sediment distribution function in the cross direction of the working face movement, which corresponds to the position of the center of the building to be tampered with [8].

3. In the case of the location of the civilian building to be faked in Zone IV, the deformation of the foundation in the direction of cross-flow of the working face is determined by the method [8].

In the direction that coincides with the line of advancement of the longwall, the base of the building is subjected first to tensile deformations ε_p and convexity curvature $K_{вп}$,, then to compression ε_c and concavity curvature $K_{вг}$..

The deformation values are calculated by the following formulas [7, 8]

$$\varepsilon_p = +0{,}6\frac{m}{H}; \tag{3}$$

$$\varepsilon_c = -\frac{m}{H}; \tag{4}$$

$$K_{вг} = K_{вп} = +\frac{8m}{(0{,}8H+h)^2}. \tag{5}$$

4. Results and discussion

At present, none of the existing methods regulates the method of determining the calculated deformation values of the foundations of buildings that are being forged in order to determine the calculated values of total deformations. These can be deformations in the center of the building or in several of its characteristic points. The error of this or that method is determined by the position of the building to be falsified in the mullet and the ratio of the building dimensions to the estimated length of the half- trough, which depends on the mining and geological conditions of the seams.

When determining the calculated deformations according to the TTU-95 method [7] using the functions of distribution of displacements and deformations that define typical curves (zones I, II and zones IIIa, IIIb, IV – in the direction of cross-movement of the longwall), the most acceptable method for engineering calculations is to determine the deformations of the foundations in accordance with the position of the building center. However, the calculated values are obtained with the largest errors.

This method is recommended for cases of falsification when the ratio of the building length *l* to the length of the calculated half- trough *L* does not exceed 0,15 (calculation error is no more than 10%).

For values of *l/L*, from 0,15 to 3,0, the expected deformations of the foundation of the building being forged should be determined at three points: at the edges and in the center of the building. In this case, the total deformation index is calculated by the deformation values.

$$\varepsilon = 0{,}25(\varepsilon_1 + 2\varepsilon_2 + \varepsilon_3); \tag{6}$$

$$K = 0.25(K_1 + 2K_2 + K_3). \tag{7}$$

where: ε_2 – horizontal deformations of the earth's surface in the center of the building; $\varepsilon_1, \varepsilon_3$ – horizontal deformations of the earth's surface at the extreme points of the building; K_2 – deformations of the earth's surface curvature in the center of the building; K_1, K_3 – deformations of the earth's surface curvature at the extreme points of the building.

If *l/L* is greater than 3.0, then sufficient accuracy of calculations is achieved by determining the expected deformations at four equidistant points of the building. The total deformation index is calculated using the following deformation values:

$$\varepsilon = \frac{\varepsilon_1 + 2\varepsilon_2 + 2\varepsilon_3 + \varepsilon_4}{6}; \tag{8}$$

$$K = \frac{K_1 + 2K_2 + 2K_3 + K_4}{6}. \tag{9}$$

In zones III*a*, III*b*, and IV, the deformation values are calculated using formulas (1), (2), (3), (4), and (5), regardless of the size of the building and the length of the half -trough.

5. Conclusions

The choice of protection measures for objects located on the earth's surface in the zones of influence of coal mine workings is carried out depending on the calculated deformations. These deformations are determined by a regulatory methodology that does not show differences in deformations in different zones of the displacement trough. Surface deformations at specific points depend on the direction of movement of the longwall face, the position of these points in the displacement trough, and the completeness of the subsidence process. These factors are not taken into account by the standard methodology for calculating deformations.

For this reason, incorrect predictive estimates of the impact of mining operations on the earth's surface, natural, industrial and civilian objects arise. This paper specifies the methodology for determining the design deformations of civilian building foundations that fall into the area of mining. Mathematical dependencies are proposed for determining the calculated deformations of the foundations of protected civil buildings, depending on their location in the displacement trough, conditions of coal seams development, and kinetic manifestations of the displacement process in time and over the area of the subsidence trough.

The obtained regularities allow for a more objective selection and application of protection measures for civil buildings. This reduces the risks during the operation of buildings, makes it possible to plan repair and restoration work, and to make a reasonable assessment of buildings and territories in the real estate market.

The results of the work are intended to be used by specialists of coal mines and design organizations of the coal industry to predict the impact of mining operations on industrial and civilian facilities, as well as in the educational process for in-depth training of mining specialists.

These recommendations have been developed for the Western Donbas deposit for the following conditions:

– undisturbed rock mass;
– complete and incomplete mining of the earth's surface;
– horizontal and gentle occurrence of rocks;
– depth of reservoir development – up to 500 meters;
– roof control – complete collapse;
– the process of displacement is completed and developing;
– in the directions of the main and parallel cross-sections of the trough;
– the speed of the longwall movement – up to 100 m/month;
– location of the objects to be mined – arbitrary, within the displacement trough, provided that the process of earth surface displacement has ended.

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ВИЗНАЧЕННЯ РОЗРАХУНКОВИХ ПОКАЗНИКІВ ДЕФОРМАЦІЙ ЗЕМНОЇ ПОВЕРХНІ ДЛЯ ПІДРОБЛЮВАНИХ БУДІВЕЛЬ І СПОРУД

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Анотація. Вугілля є одним з основних джерел енергії в Україні. Підземний видобуток вугілля зосереджено в районах Східного та Центрального Донбасу, Західного Донбасу та у Львівсько-Волинському районі. Розробка вугільних пластів призводить до зміщення гірських порід і нерівномірного осідання поверхні. Зрушення і деформації поверхні завдають серйозної шкоди екологічному середовищу. Вони впливають на об'єкти житлової та промислової інфраструктури, можуть стати причиною руйнування або порушення умов експлуатації. Зменшення ризиків для наземних споруд можливе на основі прогнозування осідань і деформацій поверхні над підземними виробками. В Україні для прогнозування застосовується метод типових функцій розподілу осідань і деформацій. Це простий і універсальний метод, але він не враховує відмінностей деформацій у різних зонах мульди зрушення залежно від напряму руху очисного вибою лави. З цієї причини виникають невірні прогнозні оцінки впливу гірничих розробок на земну поверхню, підроблювані природні, промислові та цивільні об'єкти. У цій роботі представлено методику визначення розрахункових деформацій основ цивільних будівель, що підробляються, з огляду оцінки розрахункового впливу гірничих робіт, що враховує особливості формування мульди зрушення в просторі та в часі. Цю методику розроблено на додаток і уточнення "Тимчасових технічних умов з охорони споруд і природних об'єктів від впливу підземних гірничих розробок. КД 12.00159226.013-95" для умов підземного відпрацювання вугільних пластів на Західному Донбасі, а також інших родовищ з подібними умовами та параметрами процесу зрушення земної поверхні. В основу покладено сучасні уявлення про зрушення гірських порід і земної поверхні під час підземного розроблення пластових родовищ із горизонтальним і пологим заляганням порід; результати аналізу численних інструментальних маркшейдерських спостережень, зокрема частотних, на спостережних станціях шахт Західного Донбасу. Отримані закономірності дозволяють об'єктивніше обирати та застосовувати заходи охорони цивільних будівель. Це зменшує ризики під час експлуатації будинків, дає можливість планувати ремонтні та відновлювальні роботи, а також здійснювати обґрунтовану оцінку будівель і територій на ринку нерухомості.

Ключові слова: вугільні пласти, лава, осідання поверхні, деформації, будівлі та споруди, прогин зсуву.