STUDYING OF SOIL SURFACE SUBSIDENCE UPON LONG LENGTH UNDERGROUND PIPELINES PENETRATION

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Abstract: *Initial stresses of soil body are important upon penetration of long length underground pipelines (tunnels) into soil. If there is a free space between casing (lining) and body the soil grains move to the free space. Value of free space is called* ***"soil loss"****. Movements may occur due to this free space filling with soil at the daylight surface. If the movements reach a great significance, aboveground structures and neighboring underground structures may be significantly damaged. Therefore, an evaluation of soil subsidence and pipeline (tunnel) stability are of great concern upon the pipelines (tunnels) designing.*

KEY WORDS: PIPELINE PENETRATION, SUBSIDENCE, DISPLACEMENTS, ALVEOLE, TUNNELS

1. Introduction

According to methods used for calculation of soil surface subsidence in consequence of the pipeline penetration, the soil subsidence trough is bell-shaped [1-5]. It is supposed that subsidence trough volume will be equal to the total volume of "lost soil" occurring upon the pipeline penetration. "Soil loss" volume is generally expressed in a percentage from the volume of all excavated soil. Value of "soil loss" depends on various factors, the most important of which are methods of pipeline construction, quality of works and geotechnical conditions. Experience of construction engineers is also of big importance. Maximum value of soil subsidence and width of subsidence trough depend on the soil loss volume, pipeline (tunnel) burial depth, geologic properties of rocks, etc. Methods for subsidence trough parameters detection are described in details in the first chapter. The authors of the paper divide the soil surface subsidence by shielding into four categories [6-9]:

- *subsidence's before and above the face;*
- *subsidence's occurred due to earth excavation;*
- *subsidence's occurring in the process of grout injection outside of the pipeline casing (tunnel lining);*
- *long lasting subsidence's connected with deformation of the pipeline casing (tunnel lining).*

2. Materials and Methods

Reasons of the subsidence's by shielding are in Figure 1. Lack of balance between the soil and soil water pressure and shield head backpressure. If an advance speed and excavated soil delivery speed are not synchronized with an earth pressure balance in the shield, pressure in a face chamber becomes different from the soil and soil water pressure in the face, this leads to the soil movement before and above the shield. If the chamber pressure is lower than the soil and soil water pressure, the surface subsidence takes place. Otherwise the surface is lifted. These events are determined by a release of one of counter pressures in the face and occurrence of elastoplastic deformations by higher pressure. Disturbance of soil conditions by the shield moving. A change of soil condition in consequence of the shield moving and shield's external surface friction on soil may lead to lifting or subsidence of surrounding soil or surface. An external tapping of soil for changing of the shield machine direction may also produce a soil softening.

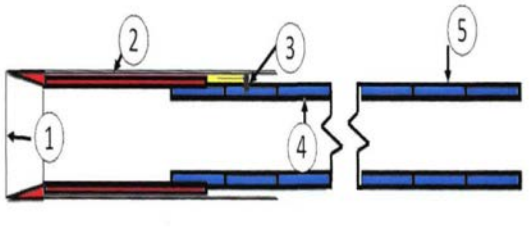


Fig. 1: *Sources of shield subsidence. 1 elastic or plastic deformation; 2 cutover, cornering, shield inclination angle; 3 tail free space; 4 deformations of pipeline casing (tunnel lining); 5 consolidation*

Generation of the free space beyond the tail casing by the shield machine movement and unsatisfactory injection of the grout. In view of generation of the mentioned free space soil on the shield casing is subsided, herewith the elastoplastic deformations take place in the soil, which are caused by the release of surrounding soils stressing. However, value of soil subsidence depends on grout material, time and places of injection, as well as pressure and volume of injection. Excessive injection pressure may be a reason of temporary lifting of soils.

Deformation and displacement of primary tunnel lining: if joint bolts of the tunnel lining are not tightened enough, tunnel rings may be deformed. This increases the soil subsidence after coming of next tunnel ring out of the lining tail in consequence of *increasing of the free clearance or lining deformation under unbalanced (uncompensated) loads.*

Reduction of ground water level: if water runs out of the face to the shield or runs out of the primary casing (lining) through joints, the level of ground water is reduced and this leads to the soil subsidence. These subsidence's are caused by increase of soil effective pressure. The subsidence's caused by water-bearing soil may be conventionally divided into two categories, which are actually dependant. The first category includes subsidence's occurring immediately upon earth excavation. The second category includes long-term *subsidence's occurring especially in soft, compressible rocks.*

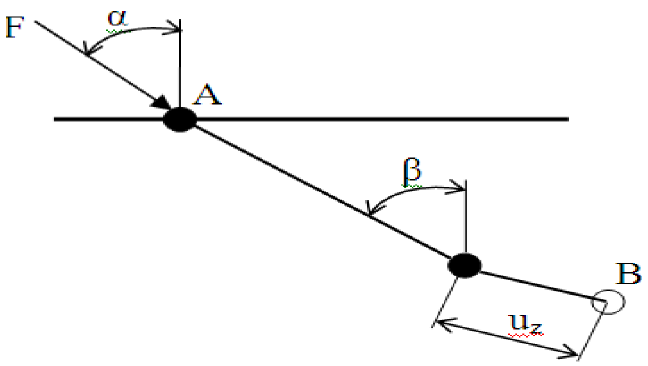
Moreover, the subsidence sources may be vibrations from drilling and operation of rock loaders. Such subsidence's have been marked in running soils of different types and in solid rocks with soft rocks above.

In paper there are the following main constructive and technology factors, upon which depend the soil surface subsidence's by shield construction of pipelines (tunnels) [10]:

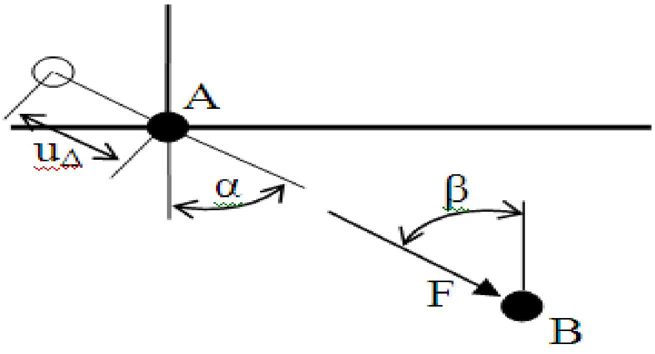
i Excess and release of rocks in the face;
ii Movement of shields with angle of attack,
iii Increased construction clearance,
iv Lining flexibility,
v Deformation of shields and their vibrations.

An interesting fact provided in the paper of T.W. Hulme, etc [11]. shall be pointed out. Upon a scientific follow up of the Singapore MRT construction an equivalent model had been created. A bench test of the equivalent model enabled determination that the subsidence's may appear due to soils consolidation in consequence of change of pore pressure caused by creation of supplementary pressure in the face zone upon the pipeline penetration.

2.1. Application of reciprocal theorem for evaluation of the soil surface subsidence upon the pipelines (tunnels) penetration: *An analytical method of the soil surface subsidence based on the reciprocal theorem may be as follows. If constant force F applied to in α direction at a point A of elastic, anisotropic, nonhomogeneous space generates at other point B in β direction a movement equal to u, then the same force F applied at point B in β direction will generate at point A in α direction a movement equal to u (see Fig. 2).*



a) Coordinate axes



b) Calculation model

Fig. 2: *Constant force F applied to in point A,B*

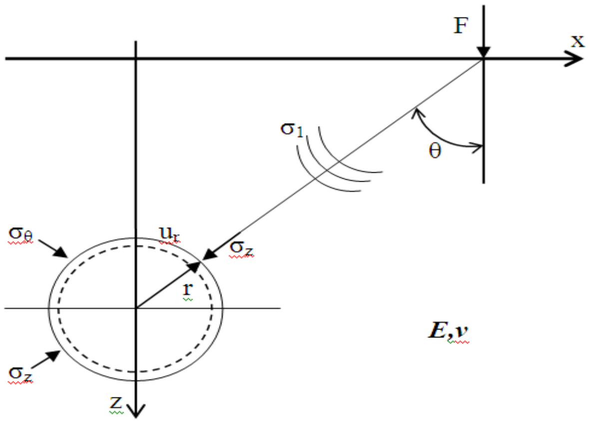


Fig. 3: *Calculation model for detection of movements in space upon the vertical force influence*

Known analytical solutions for movement of soil points of elastic space upon influence of vertical forces are used for this purpose. An initial data for calculation of vertical movements of soil surface are functions of movement of alveole contour provided in Figure 3.

Lining boundary stresses are defined based on Flamant solution [12]:

$$\sigma_r = \frac{2F}{\pi r}\cos\theta = \frac{2F\,z}{\pi r^2} \qquad (1)$$

Normal stresses in two orthogonally related directions: along the tunnel axis $\sigma_z = \frac{\nu}{1-\nu}\sigma_r$ *and in normal direction* θ, $\sigma_\theta = \frac{\nu}{1-\nu}\sigma_r$. *Radial displacements of contour upon action of normal stresses directed perpendicular to the cylinder axis (see Fig. 4) have been obtained by S.P. Timoshenko .*

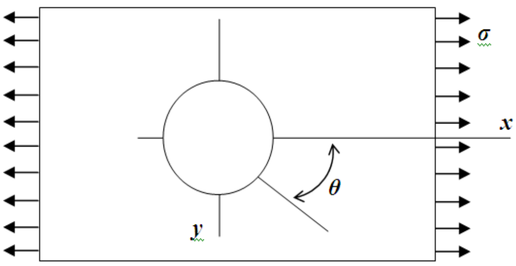


Fig. 4: *Calculation method for radial displacement of contour upon action of normal stresses* σ

where $\sigma = S$ *, stresses function is defined in a form [13]:*

$$\varphi = \left(A r^2 + B r^4 + C\frac{1}{r^2} + D\right)\cos 2\theta$$

$$\sigma_r = \frac{1}{r}\frac{\partial\phi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\phi}{\partial\theta^2} = -\left(2A + \frac{6C}{r^4} + \frac{4D}{r^2}\right)\cos 2\theta$$

$$\sigma_\theta = \frac{\partial^2\phi}{\partial\theta^2} = \left(2A + 12Br^2 + \frac{6C}{r^4}\right)\cos 2\theta$$

$$\tau_{r\theta} = \frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial\phi}{\partial r}\right) = \left(2A + 6Br^2 - \frac{6C}{r^4} + \frac{2D}{r^2}\right)\sin 2\theta$$

where

$$A = -\frac{S}{4};\quad B = 0;\quad C = -\frac{a^4}{4}S;\quad D = \frac{a^2}{2}S$$

after substitution of values of A, B, C we will get

$$\sigma_r = \frac{S}{2}\left(1 - \frac{a^2}{r^2}\right) + \frac{S}{2}\left(1 + \frac{3a^2}{r^4} + \frac{4a^2}{r^2}\right)\cos 2\theta$$

$$\sigma_\theta = \frac{S}{2}\left(1 + \frac{a^2}{r^2}\right) - \frac{S}{2}\left(1 + \frac{3a^2}{r^4}\right)\cos 2\theta$$

$$\tau_{r\theta} = -\frac{S}{2}\left(1 - \frac{3a^2}{r^4} + \frac{2a^2}{r^2}\right)\sin 2\theta$$

Following the Hooke's law

$$\varepsilon_r = \frac{\partial u}{\partial r} = \frac{1}{E}\left(\sigma_r - \nu\sigma_\theta\right)$$

$$\varepsilon_\theta = \frac{\partial v}{\partial \theta} = \frac{1}{E}\left(\sigma_r - \nu\sigma_r\right)$$

$$\gamma_{r\theta} = \frac{1}{G}\tau_{r\theta}$$

Substituting σ_r *and* σ_θ *to the Hooke's law:*

$$\frac{\partial u}{\partial r} = \frac{S}{2Er^4}\begin{pmatrix} r^4 - r^2a^2 + r^4\cos 2\theta + 3a^4\cos 2\theta - 4r^2a^2\cos 2\theta \\ -\nu r^4 - \nu r^2a^2 + \nu r^4\cos 2\theta + 3\nu a^4\cos 2\theta \end{pmatrix}$$

$$\frac{\partial v}{\partial \theta} = \frac{S}{2Er^4}\begin{pmatrix} r^4 + r^2a^2 - r^4\cos 2\theta - 3a^4\cos 2\theta + \nu r^4 - \nu r^2a^2 \\ \nu r^4\cos 2\theta + 3\nu a^4\cos 2\theta - 4\nu a^2r^2\cos 2\theta \end{pmatrix}$$

After integration we get

$$u = \frac{S}{2Er^3}\begin{pmatrix} -\nu r^4 + r^4 + \nu r^4\cos 2\theta - a^4\cos 2\theta + r^4\cos 2\theta \\ -\nu a^4\cos 2\theta + r^2a^2 + \nu r^2a^2 + 4r^2a^2\cos 2\theta \end{pmatrix} + f(\theta),$$

$$v=\frac{S}{2Er^3}\begin{pmatrix}\theta r^4+r^2a^2\theta-\frac{1}{2}r^4\sin 2\theta-\frac{3}{2}a^4\sin 2\theta+r^4\nu\,\theta\\ \frac{1}{2}\nu r^4\sin 2\theta+\frac{3}{2}\nu a^4\sin 2\theta-\nu r^2a^2\theta-2\nu r^2a^2\sin 2\theta\end{pmatrix}-\int f(\theta)d\theta+F(r)$$

where $r=a$ *and* $\theta=0$ *laying along x axis*

$$u_{r_1}=\frac{a\sigma_r}{E}\frac{\nu}{1-\nu}\left(1+2\theta\cos 2\theta\right) \qquad (2)$$

The radial displacements of contour by normal stresses perpendicular to the cylinder axis:

$$u_{r_2}=\frac{a\sigma_r\nu}{E(1-\nu)}\left(1-2\theta\cos 2\theta\right),$$ *(angle* θ *is replaced with angle* $\theta+\pi$ *).* (3)

The radial displacements of contour by normal stresses in the direction of the cylinder axis:

$$u_{r_3}=\frac{a\sigma_z}{E}\nu\Rightarrow u_r=\frac{a\sigma_r}{E}\frac{\nu^2}{1-\nu} \qquad (4)$$

Mean radial displacements at unsubstantiated alveole from a force applied at land surface are defined by formula:

$$\Delta u_r=\Delta u_{r_1}+\Delta u_{r_2}+\Delta u_{r_3}, \qquad (5)$$

After substitution of expressions for mean radial displacements takes the form of:

$$\Delta u_r=\frac{2a\sigma_r}{E}\left(\frac{\nu}{1-\nu}\right)+\frac{a\sigma_r}{E}\left(\frac{\nu^2}{1-\nu}\right)=\frac{a\sigma_r\nu(\nu+2)}{E(1-\nu)}$$ *or*

$$\Delta u_r=\frac{2aFz\nu(\nu+2)}{E\pi r^2(1-\nu)}. \qquad (6)$$

Having used the reciprocal theorem we will define the dependence of mean displacements on force F distributed along the alveole length (in z-direction) applied inside the alveole. For this purpose let us define the radial displacements (see Fig. 5) of alveole from uniform pressure [14]:

$$u(a)=\frac{(1-\nu)q}{E} \qquad (7)$$

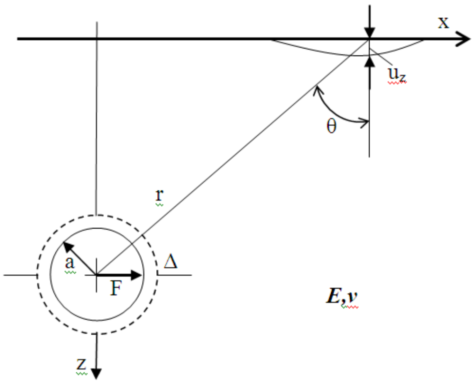


Fig. 5: *Calculation model for definition of soil surface displacements upon action of force applied in alveola*

3. Results and Discussion

Let us denote the mean radial displacements of lining from force F applied to inside the lining, Δ*. In accordance with the reciprocal theorem it is possible to write down an expression:*

$$F\,u(a)=q\,\Delta$$

$$F\frac{(1-2\nu)q}{E}=q\Delta\Rightarrow\quad F=\frac{\Delta E}{(1-2\nu)} \qquad (8)$$

For detection of the surface points' displacement from force applied to the alveole internal contour, the reciprocal theorem is also used. Let us denote: u_z *vertical displacement of soil surface,* $r=\sqrt{x^2+z^2}$, $\cos\theta=z/r$, $\sin\theta=x/r$. *According to the reciprocal theorem we will get:*

$$F\,u_z=\frac{\Delta E}{(1=2\nu)}\Delta u_r$$

where from,

$$u_z=\frac{2az\nu(\nu+2)\Delta}{\pi r^2(1-\nu)(1-2\nu)} \qquad (9)$$

Figure 6 represents calculated subsidence's profiles upon two pipelines (tunnels) penetration with use of the reciprocal theorem.

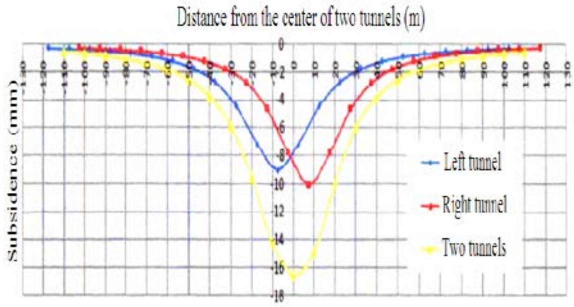


Fig.6: *Soil subsidence's troughs upon two pipelines (tunnels) penetration with use of the superposition method.*

3.1. Comparison of subsidence's troughs curves obtained by different methods and plaxis standard program complex: *Together with known solutions numerical calculations with use of PLAXIS program complex have been performed. The calculation considered an elasticoplastic nonlinear performance of soil with account of draining and without it.*

Typical values of volume loss for pipelines (tunnels) of diameters up to 6,6 m buried in marine clays are within the range from 2% to 3,5% depending on the penetration way [6]. This article uses the volume loss equal to 1%. Curves describing the soil subsidence upon two pipelines (tunnels) penetration are defined. Figure 7 represents displacements of soil layers and contour line scaled up to 100, obtained with use of PLAXIS program complex.

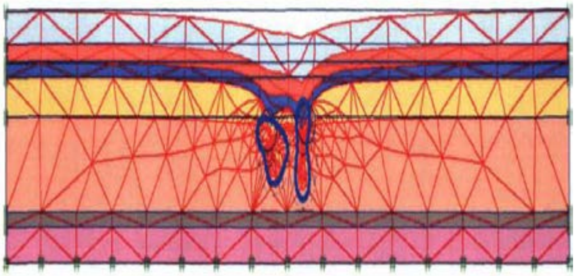


Fig.7: *Displacements of soil layers and contour line*

A curve of soil surfaces subsidence got on the basis of the function of Gauss errors is used for comparison of the results and the superposition method [15] is used for calculation of surface subsidence value upon penetration of two parallel pipelines (tunnels). The authors of the paper proposed to define the land surface subsidence by formula:

$$S_l = S_{\max A}\exp\left[-\frac{(x+L/2)^2}{2l_A^2}\right] + S_{\max B}\exp\left[-\frac{(x-L/2)^2}{2l_B^2}\right] - S_{AB} \qquad (10)$$

$$S_l = S_{\max A}\left\{\exp\left[-\frac{(x+L/2)^2}{2l^2}\right] + \exp\left[-\frac{(x-L/2)^2}{2l^2}\right]\right\}a \qquad (11)$$

Where S_{AB} = 0 (without regard to reciprocity), L=2D distance between two pipelines (tunnels) (see Fig.8). Increase of the distance between the pipelines (tunnels) causes reduction of subsidence in the central part between the pipelines (tunnels). If the pipelines (tunnels) have equal diameters and soil losses, then $S_{\max A} = S_{\max B}$ and $l_A = l_B$.

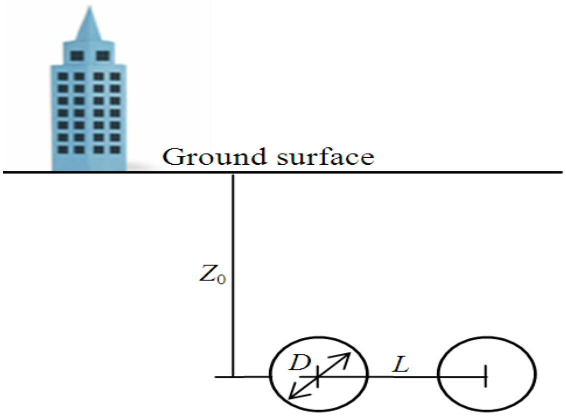


Fig. 8: *Model of two pipelines (tunnels)*

pipeline (tunnels) and total subsidence upon penetration of two parallel pipelines (tunnels) with use of the function of Gauss errors and the superposition method. Figure 10 represents the comparison of subsidence troughs curves obtained by empiric, analytic and numerical methods upon penetration of two parallel pipelines (tunnels) at 1% coefficient of volume loss.

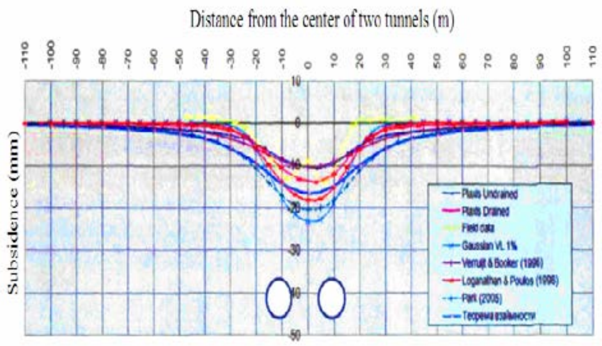


Fig. 9: *Profiles of subsidence's upon penetration of the left, right and two pipelines (tunnels)*

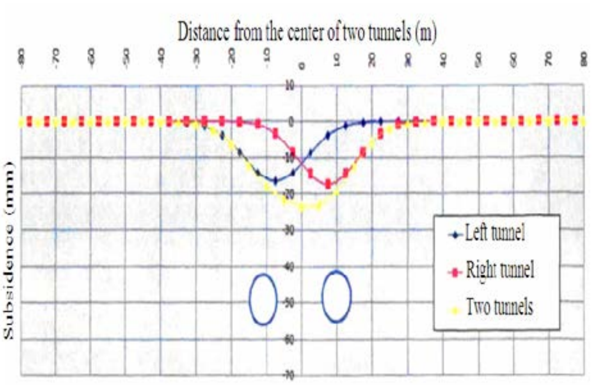


Fig.10: *Comparison of all subsidence's profiles upon penetration of two pipelines (tunnels)*

Total surface subsidence will be defined by expression: Figure 9 represents the curves of surfaced subsidence's upon penetration of the left and right.

It should be pointed out that the subsidence's profile made by PLAXIS program complex coincides with the subsidence's profile made on the basis of formulas of scientists Verruijt and Booker (1996).

The subsidence's profiles made by Loganathan and Paulo's (1998), Park (2005) and Gauss function a little bit differ from the preceding results.

Comparison of all profiles has shown that a curve obtained with use of the reciprocal theorem coincides with the results obtained by different methods, but differs upward from the data of field observations.

The represented results show that the analytic and empiric methods sufficiently describe the soil surface subsidence's.

Nevertheless, it should be pointed out that the numerical methods enabling accounting of soils nonhomogenity are more suitable for complex ground conditions.

4. Conclusions

1. There is a comparison of different methods for determination of curves values and forms describing the soil surface subsidence's upon penetration of underground pipelines (tunnels).

2. There is a new method for evaluation of the soil surface subsidence's based on the reciprocal theorems. The method may be used for forecasting of the soil surface subsidence's upon the pipelines designing.

3. Value of soil surface subsidence's upon penetration of pipelines (tunnels) may be reduced or fully avoided, if pressure in the face and injection beyond the pipeline casing (tunnel lining) are controlled. Pressure shall not exceed the limit value.

4. As a rule, actual soil surface subsidence's are smaller the forecasted ones, if the work process upon the pipelines (tunnels) penetration is dully observed.

5. If the pipelines (tunnels) are laid under the buildings of historical notability an instrumental monitoring in full-scale is required besides of the theoretical predictions.

5. References

1. *O'Reilly, M. P., & New, B. M, 1982. Settlements above tunnels in the United Kingdom their magnitude and prediction. The Institution of Mining and Metallurgy, London. 55-64*
2. *Attewell, P. B., & Woodman, J. P, 1982 Predicting the dynamics of ground settlement and its derivitives caused by tunnelling in soil. Ground Engineering,* ***15****(7), 13-22*
3. *Cherry, J.T.,Jr, 1962. The Asimuthal and Polar Radiation Patterns Obtained from a Horizontal Stress Applied at the Surface of an Elastic Half Space, Bull. SeismologicalSoc. vol.52, 27-36*
4. *Miller,G.F.,H.Pursey, 1954. The Field and Radiation Impedance of Mechanical Radiators on the Free Surface Semi-Infinite Isotropic Solid, Proc. Ro. Soc. London, Ser. A, vol.223, 521-541*
5. *Z. Shangguan, L. Shouju and L, 2008. Maotian "Determining Optimal Thrust Force of EPB Shield Machine by Analytical Solution", EJGE.,* ***6****(13), 6-8*
6. *Walter Wittke, et al, 2007. Stability Analysis and Design for Mechanized Tunneling Aachen, WB1 print 6, 202-250*
7. *Heelan, Patrick Aidan, 11953. Radiation from a Cylindrical Source of Finite Length, Geophysics,* ***№18****, 685-696*
8. *Rashidov T.R, 1973. The dynamic theory of seismic stability of complex systems of underground structures. Tashkent, Seismic effects on buildings and buried structures / 180s*
9. *Tsepenyuk I.F., Proskurin S.F, 1986. Mardonov V.M., Mubarakov Y.N., A.K. Kaumov Tashkent, 296*
10. *Dorman I.J, 1986. Seismic resistance of transport tunnels. Moscow, 176*
11. *Hulme, T.W., Shirlaw, J.N., Hwang, R.N, 1990. Settlements during the underground constructions of the Singapore MRT, Tenth Southeast Asian Geo-technical conference, 16-20*
12. *Kurbatskii E.N, 2005. The use of the reciprocity theorem to assess the levels of vibration on the surface of an elastic half-point source located inside the half. Bulletin of Engineering.* ***№13***
13. *Timoshenko, P., Goodier, J.N, 1970. Theory of Elasticity. McGraw-Hill, New York*
14. *Leblais, Y, 1995. Recommendations on Settlements Induced by Tunnelling. Association Franзaise des Travaux en Souterrain (AFTES). 132-134*
15. *Verruijt, A, 2005. Soil Dynamics - Elastostatics of a half space, 138-139*