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A New Analytical Solution for Determination of Acceptable Overall Settlement of Heap Leaching Structures Foundation

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Abstract
There are some artificial and natural materials on foundation of heap leaching structures. Geomembrane liner is the most important artificial isolated layer of these structures, which its thickness is about 1 to 2 mm. Foundation overall settlement of such structures changes the primary length of the geomembrane layer. If the strain of geomembrane become more than the allowable one, the layer will be failed and acid will leak out of the heap foundation. In this paper, foundation of the heap leaching structures is modeled with a hyperbolic curve and the length of geomembrane liner is determined before and after loading. Next, acceptable overall settlement of heap foundation is computed according to the allowable strain of geomembrane materials. Then, a design chart is presented for quick estimation of acceptable overall settlement of these structures. Finally, the abovementioned approach is utilized to determine foundation overall settlement of the Tarom heap leaching structure as a case study. The analysis shows that geomembrane liner of this case will not be failed due to the foundation overall settlement.

Keywords: *heap leaching structures, acceptable overall settlement, geomembrane, analytical method, Tarom mine.*

1. Introduction

Heap leaching structures are constructed to extract the copper from copper oxidized soil. A large space with smooth dip is required to construct these structures so that the pregnant solution can move and exit gravitationally through the mass gravitationally. The natural (compacted clay and cushion) and artificial (geomembrane and geotextile) layers are used to isolate the bed of leaching mass. Geomembrane layer is the most sensitive part of the heap leaching bed. To In order to protect this part, the geomembrane layer is placed between two layers of fine-grained natural soil (cushion) or artificial protective layer (geotextile) which seen is shown in Figure 1. Then, a layer of gravel with high permeability is placed over the upper cushion layer. A filter layer is placed on the drainage layer to prevent the its clogging of it. Finally the layers of ore with a height of 5 to 15 meters are dumped on over the heap bed to be leachleached. Each layer is leached 60 to 180 days and afterward the next layer is placed on over it. The final height of mineral masses is about 50 to 150 meters [1, 2]. The application of geomembrane liner in hydrometallurgy process causes to protection of the environment. The geomembrane liner is used in hydrometallurgical processes to protect the environment. Increasing the height of ore deposit pile on heap leaching structure causes toeffects on the overall settlement of the bed. Because of the placement of the geomembrane liner on the bed, this layer also is also settled with the bed and increases increased its length [3, 4]. If In case the strain of the geomembrane liner exceeds the allowable limit (4 to 8 percent), it may fail and the acid leaks may leak into the ground [5, 6].

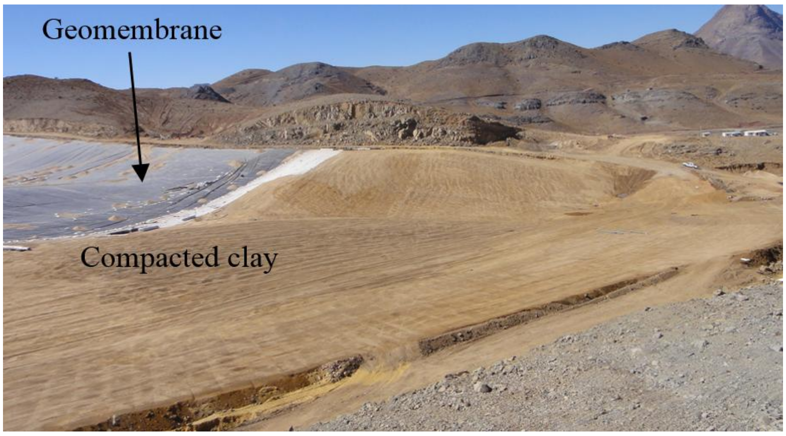

Figure 1. Isolated layers of the bed of heap leaching structure (Miduk 1 heap leaching structure)

2. Literature review

Giroud (1995) evaluated the foundations containing geosynthetic materials and presented a theoretical method to determine the allowable local settlement in these foundations [7]. He modeled the transverse profile of foundation with a flat line before loading and with aparabolic curve after loading FigureFigure2). According to the above mentioned research, the strain of geosynthetic materials on the mentioned foundation are calculated by Equation (1).

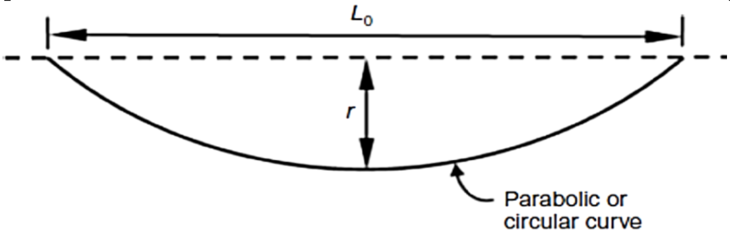

Figure 2. The theoretical model of Giroud for determining the strain of foundations containing geosynthetic materials

$$\varepsilon = \left[\frac{L_0}{4r} + \frac{r}{L_0}\right] \sin^{-1}\left[\frac{1}{\frac{L_0}{4r} + \frac{r}{L_0}}\right] - 1 \qquad (1)$$

where r and L0 are the depth and width of foundation, respectively, and ε is the geomembrane strain. In 2009, Sivakugan and Shukla modeled the foundation surface using some combined curves (including parabolic and circular) and obtained a new relationship to determine the geomembrane strain [8]. The theoretical model proposed by these researchers is shown in Figure 3. The presented Equation (2), as well, to determine the strain. This model and the Giroud model have almost identical results.

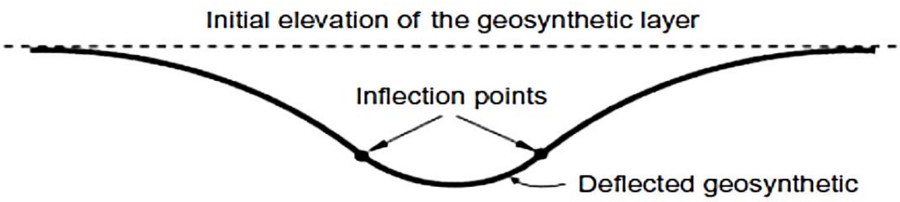

Figure 3. The theoretical model of Sivakugan and Shukla (2009) for determining the strain of foundations containing geosynthetic materials

$$\varepsilon = \frac{r}{L_0}\left[\sqrt{1+\left(\frac{L_0}{r}\right)^2} + \frac{1}{\left(\frac{L_0}{r}\right)} \times \ln\left(\left(\frac{L_0}{r}\right) + \sqrt{1+\left(\frac{L_0}{r}\right)^2}\right)\right] - 1 \qquad (2)$$

where r and L0 are the depth and width of foundation, respectively.

The bed surface of leaching structures has a valley shape before and after loading, therefore it is not possible to utilize the mentioned models to determine the geomembrane deformation at such structures. In present research, the surface of heap foundation have been modeled before and after loading using hyperbolic curve, and the length of the geomembrane liner is calculated in these conditions. Then, considering the allowable strain of the geomembrane liner, an analytical relationship is presented to specify the acceptable overall settlement of the foundation. Although, the foundations of most real case studies do not exactly fit on a hyperbolic curve, but the results of these assumptions are more realistic than existing relationships. Hence, if the deviations between longitudinal section of a case study and the theoretical curve is high, application of this approach will have some errors.

3. The overall settlement analysis of heap leaching structures

The overall dip of heap's bed varies between 2% to 15%. If the dip exceeds 15%, the instability of leaching mass will be inevitable, and therefore the placement of cushion and gravel on the geomembrane liner will not be possible. On the other hand, if the dip is less than 2%, the pregnant solution will not be drained out properly. Thus, the heap's bed is usually a saddle-shaped curve with a soft dip. Considering the characteristics of hyperbolic curve, this kind of curve is selected to model the foundation of heap structure. The hyperbolic shape of a heap leaching structure is shown Figure 4.

Figure 4. Hyperbolic shape of heap leaching structures foundation (Valley 2, Sharcheshmeh 2 heap leaching structure)

Therefore, as mentioned above, the bed of heap has been modeled by the positive part (y>0) of a vertical hyperbolic curve. Such a curve in the Cartesian coordinate system is shown in Figure 5 and has general relationships as revealed Equations (3) and (4).

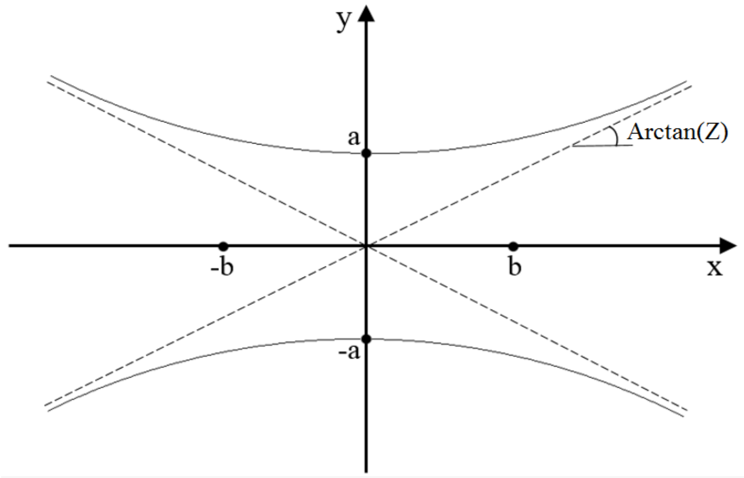

Figure 5. Vertical hyperbolic curve in Cartesian coordinates

$$\frac{y^2}{a^2} - \frac{x^2}{b^2} = 1 \tag{3}$$

$$Z = \frac{a}{b} \tag{4}$$

In these equations, "a" and "b" are the constants of vertical hyperbolic curve and "Z" is the asymptotes dip. The schematic fitting of this curve on the heap bed before loading is presented in Figure 6. As seen in this figure, "L" and "H" are the geometrical parameters of heap structure.

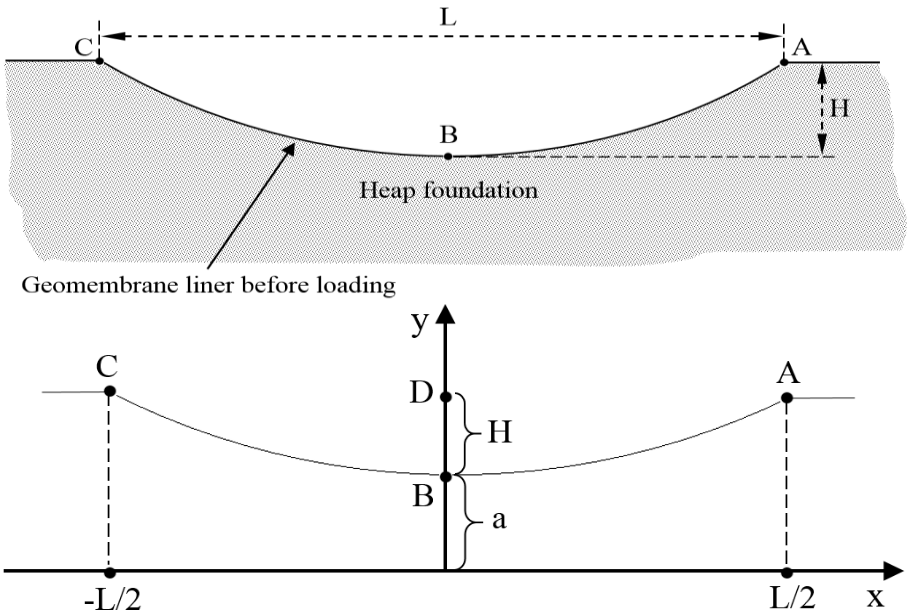

Figure 6. The fitting of vertical hyperbolic curve on the heap foundation before loading

Considering Figure 6, three points of the fitted curve including $A(\mathrm{L}/2, \mathrm{a}+\mathrm{H})$, $B(0, \mathrm{a})$ and $C(-\mathrm{L}/2, \mathrm{a}+\mathrm{H})$ have known coordinates. Equation (5) is achieved by replacing the coordinates of points A and B in Eq. (3).

$$\frac{(\mathrm{a}+H)^2}{a^2} - \frac{\left(\frac{L}{2}\right)^2}{b^2} = 1 \tag{5}$$

By solving Equations (4) and (5), the constants *a* and b are obtained as follows:

$$a = \frac{Z^2 L^2 - 4H^2}{8H} \tag{6}$$

$$b = \frac{Z^2 L^2 - 4H^2}{8HZ} \tag{7}$$

Equation (8) is the relationship of fitted curve on the heap bed which resulted by substituting the mentioned constants in general equation of hyperbolic curve (Eq. (3)).

$$\frac{y^2}{\left(\frac{Z^2L^2-4H^2}{8H}\right)^2}-\frac{x^2}{\left(\frac{Z^2L^2-4H^2}{8HZ}\right)^2}=1 \quad (8)$$

Therefore, the Eq. (8) have the known parameters including L, H. As mentioned, Z is the dip of asymptotes and should be tangible. It is possible to make a relationship between Z and the dip of tangent lines of the fitted hyperbolic curve. The desired dips can be determined with deriving from Eq. (8) as follows:

$$y'(x)=\frac{\partial y}{\partial x}=\frac{Z^2x}{\sqrt{Z^2x^2+\left(\frac{Z^2L^2-4H^2}{8H}\right)^2}} \quad (9)$$

By using Eq. (9), the dip of tangent lines is computable in a point (x,y). The maximum dip of fitted hyperbolic curve (named "n" in this research) is related to the points A and C. So, through replacing the coordinates of these two points in Eq. (9), the parameter n , a geometrical parameter of heap structure, is calculated according to Equation (10).

$$n=y'\left(\frac{L}{2}\right)=\frac{Z^2\left(\frac{L}{2}\right)}{\sqrt{Z^2\left(\frac{L^2}{4}\right)+\left(\frac{Z^2L^2-4H^2}{8H}\right)^2}} \quad (10)$$

Also, the Eq. (10) is rewritten with respect to the parameter Z as follows:

$$\left(\frac{m^2n^2}{16}-1\right)Z^4+\left(\frac{3}{2}n^2\right)Z^2+\frac{n^2}{m^2}=0 \quad (11)$$

In this equation, the terms of "L/H" have been replaced with "m". Thus, the parameter Z will be specified according to the parameters H, L and n by solving Eq. (11). To simplify the calculations, the above equation can also be displayed graphically as a design chart. In Figure 7, the approximate solution of this equation is presented in terms of the parameters "n" and "L/H". So, Z is a known parameter which can be determined using the graph.

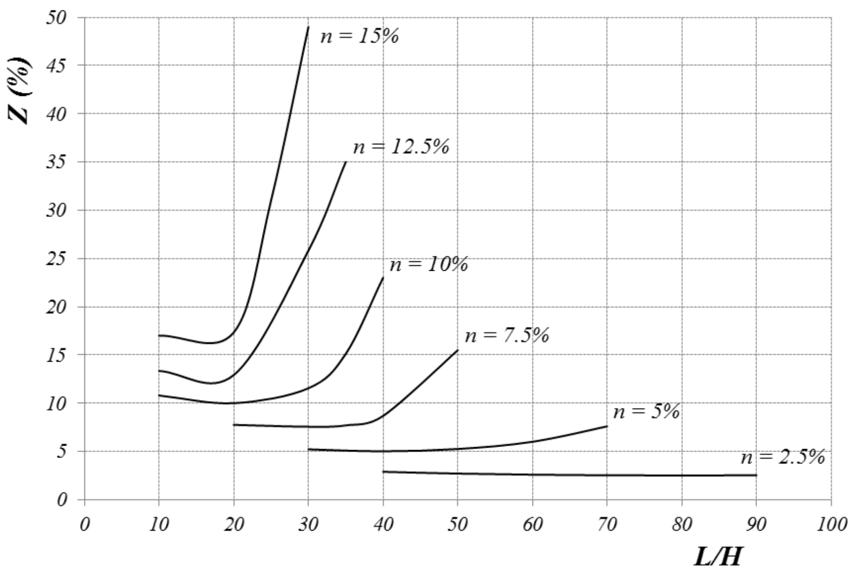

Figure 7. Determination of "Z" according to the geometrical parameters of heap leaching structure

The length of heap bed or the geomembrane liner (L_1) can be achieved by the following integral resulted of Eq. (9).

$$L_1=\int_{-\frac{L}{2}}^{+\frac{L}{2}}\sqrt{1+\left(\frac{\partial y}{\partial x}\right)^2}\,dx=2\int_0^{+\frac{L}{2}}\sqrt{1+\frac{Z^4x^2}{Z^2x^2+\left(\frac{Z^2L^2-4H^2}{8H}\right)^2}}\,dx \quad (12)$$

After loading a heap, the mineral mass is piled in a bench form with a height of 5 to 10 meters. As the overall height of the mass increases, and considering the ground properties, the beneath foundation of the geomembrane liner will settle. According to Figure 8, the heap bed is modeled after loading by a vertical hyperbolic curve which has 3 known points including $A(\mathrm{L}/2, \mathrm{a}+\mathrm{H})$, $B'(0, \mathrm{a'})$ and $C(-\mathrm{L}/2, \mathrm{a}+\mathrm{H})$. The maximum overall settlement of the foundation belongs to the deepest point of the heap (point B) that has a vertical overall settlement equal to “δ” so that the new coordinates of this point will be $B'(0, a-\delta)$.

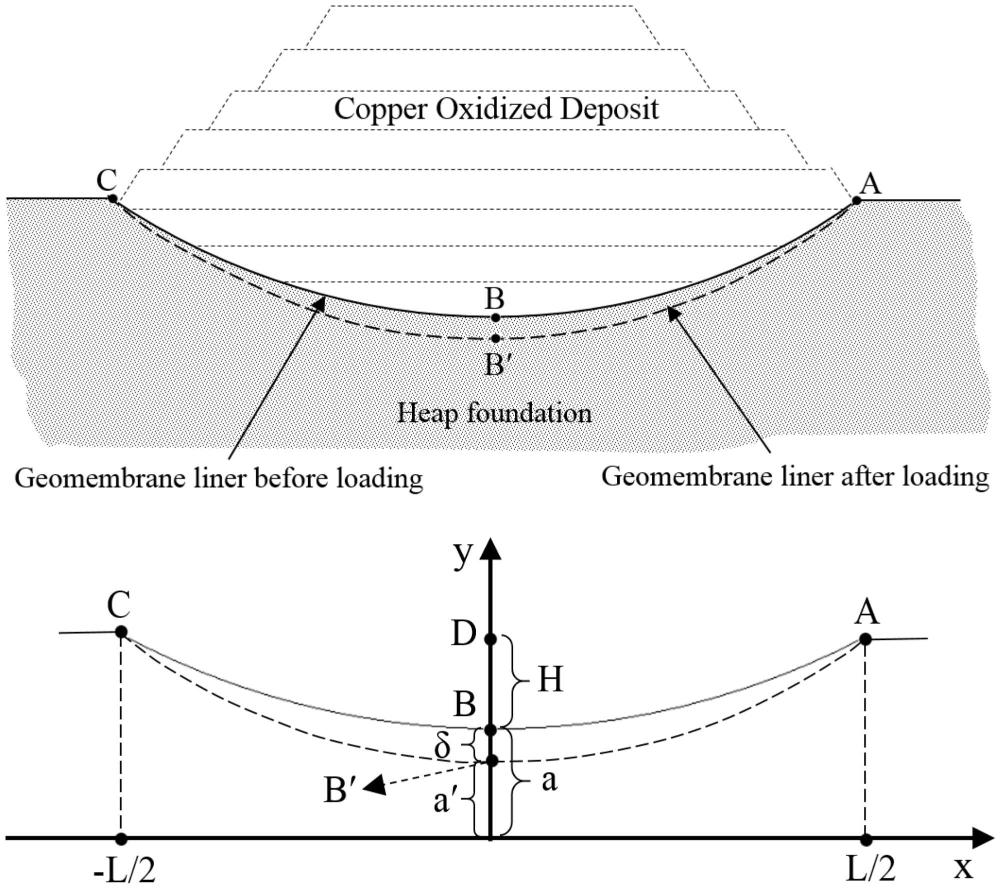

Figure 8. The fitting of vertical hyperbolic curve on the heap foundation after loading

The relationship of this fitted hyperbolic curve is obtained such as previous state in terms of the parameters L, H, Z and δ as Equation (13).

$$y=\sqrt{\left(\frac{L^2Z^2(H+\delta)-4\delta H(H+\delta)}{HL^2}\right)x^2+\left(\frac{L^2Z^2-4H^2-8\delta H}{8H}\right)^2} \quad (13)$$

Afterwards, the length of the geomembrane liner after loading (L2) is calculated through deriving from Eq. (13) and using the general integral for length of a curve (similar to L1 relationship) as follows:

$$L_2=2\int_0^{+\frac{L}{2}}\sqrt{1+\frac{(L^2Z^2(H+\delta)-4\delta H(H+\delta))^2\,\mathrm{x}^2}{H^2L^4\left(\left(\frac{L^2Z^2(H+\delta)-4\delta H(H+\delta)}{HL^2}\right)x^2+\left(\frac{L^2Z^2-4H^2-8\delta H}{8H}\right)^2\right)}}\,dx \quad (14)$$

The Equations (12) and (14) show the length of geomembrane liner before and after loading, respectively, in terms of parameters L, H, Z and δ. However these integrals have no parametric analytical solutions, but it should be noted that for each particular example, the parameters L, H, and

Z have numerical values and the integrals will be simple partly. Having determined the length of liner before and after the overall settlement, it is possible to obtain its strain and to compare with allowable values. According to Figure 9, to prevent tearing the geomembrane liner, a part of this layer is released freely and then locked so that about 1 meter of the liner can be deformed [9]; Because in the foundation of the heaps the overburden pressures on the geomembrane liner is so high and the liner is not free to have appropriate elongation. So, 1 meter of geomembrane at each side of heap structure is free between heap foundation and anchors to balance the strain. On the basis of this concept, the geomembrane is in the safe condition.

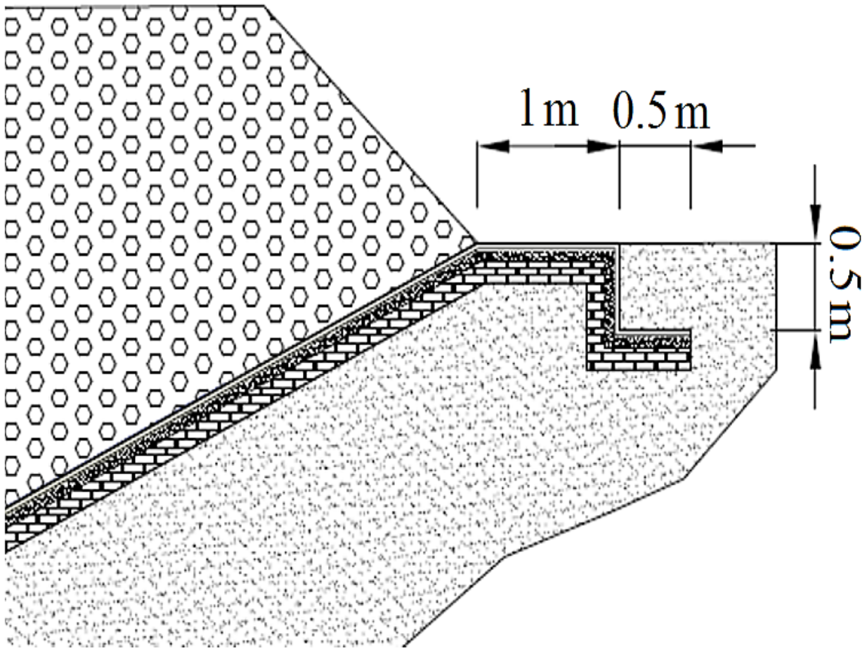

Figure 9. Typical released and locked length of geomembrane liner in heap leaching structures

The maximum change in liner length can be equaled with allowable value of free part. This concept can be expressed analytically as Equation (15).

$$L_2 - L_1 = L_{Free} \times \varepsilon_{Allowable} \quad (15)$$

In this equation, LFree is the length of the free part. The allowable strain of geomembrane HDPE is about 4% to 8% [10]. Thus, the allowable deformation of liner, due to overall settlement, can be determined by Equation (16).

$$L_2 - L_1 = 2 \times (0.04 \, to \, 0.08) = 0.08 \, to \, 0.16 \quad (16)$$

The acceptable overall settlement of heap bed will be obtained by replacing L1 and L2 from Equations (12) and (14) in Equation (16). As mentioned, this relationship have no parametric solution but there are some numerical solutions. So the acceptable overall settlement (δ) can be determined for various values of geometrical parameters.

To have a conservative design, the value of 0.04 is considered for allowable strain of the geomembrane liner. Eventually, Eq. (16) is solved in order to obtain parameter δ through diverse values of L, H and Z which are shown in Figure 10. By having the geometrical parameters of the heap and using this graph, it is possible to easily determine the acceptable overall settlement of foundation of such structures. According to Figure 10, as the width of heap (L) increases or its depth (H) decreases, the value of overall settlement is increased. Also, as the transverse dip of heap (indicating by Z) grow, the overall settlement declines.

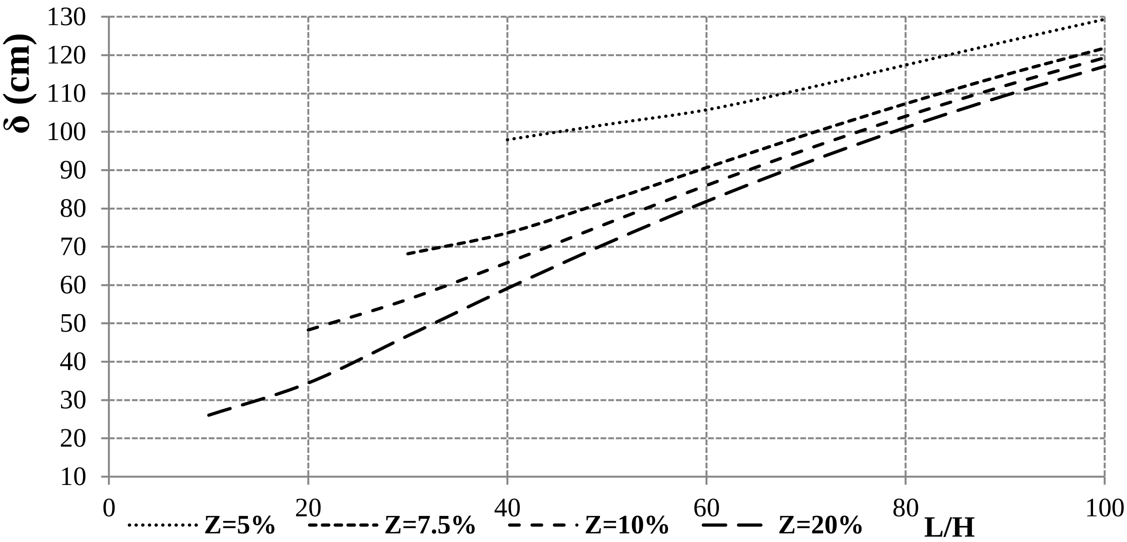

Figure 10. The acceptable overall settlement values of heap foundation in terms of its geometrical parameters

4. Case Study: Tarom heap leaching structure

The primary mineral exploration of "Tarom" copper mine was carried out with 3 exploratory tunnels in 1942. These investigations showed that the deposit is laminar, and the host rock is Tuff. The deposit consists of oxide copper mineral (malachite), but the grade and the volume of the deposit were not reasonable and establishment of hydrometallurgy complex was not economical since the price of copper was low. This mine was not excavated until 2001. Until then, new investigations showed that the excavation of this mine was economical [11]. Hence, a hydrometallurgy process with heap leaching and solvent extraction-electrowining has been designed to extract 12000 ton copper per year from the copper oxide mineral. As shown in Figure 11 and 12, this heap has 280,000 m2 area and has been founded over a natural valley. Subsurface Geotechnical investigation in this site showed that the foundation of this heap formed from fine soil such as Clay, Silt and Sand. Hence, the elastic and overall settlements consolidation in foundation of the heap, due to ore loading, was so large and vital. Therefore, systematic geotechnical investigation such as continuous diamond drilling, in situ in hole tests and plate load tests carried out on this site. In this study, based on suggested method, acceptable overall settlement of the heap is presented. Considering Figure 11, section AB which has the highest width is selected to estimate the acceptable overall settlement of this heap. The required parameters of this section are L=585m, H=10 m and n=4%. By using the diagrams of Figure 7, the parameter Z will be approximately 5%. Now, the presented design chart in Figure 10 can be used to calculate the value of allowable overall settlement. Therefore, by considering the values of L, H and Z, the maximum acceptable overall settlement of the heap leaching structure of Tarom mine is about 105 cm on the toe of the valley and zero on the crown of the valley. This analysis shows that the acceptable overall settlement of the heap is so high and the geomembrane is in the safe side.

Figure 11. Foundation of Tarom heap leaching structure.

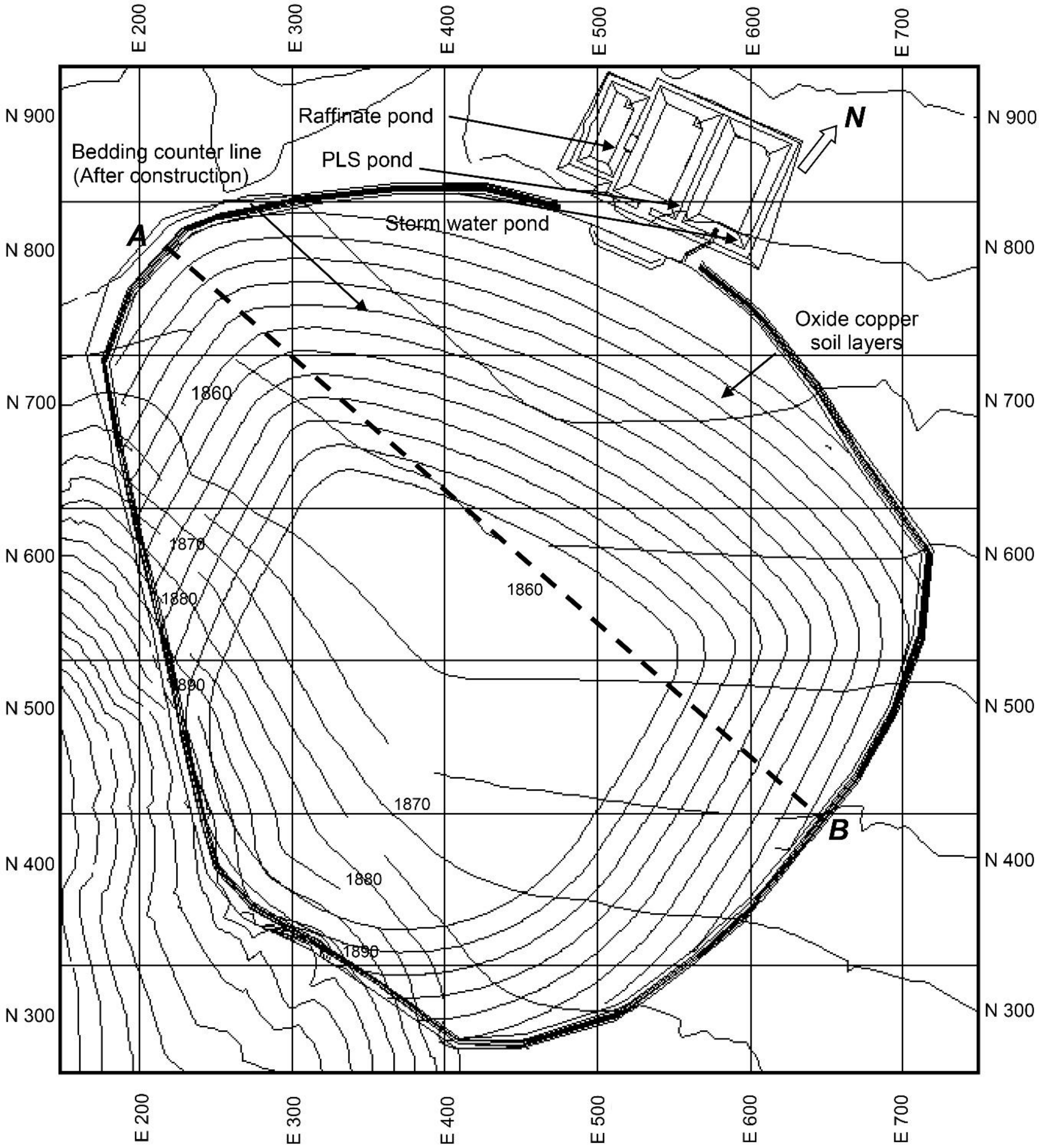

Figure 12. Tarom heap leaching structure

5. Conclusions

In this paper, the foundation of heap leaching structures was fitted using a hyperbolic curve before and after dumping the oxidized copper mass (loading). Then, the acceptable overall settlement of foundation has been determined based on the geometrical parameters of heap bed and allowable strain of the geomembrane liner. Also, to simplify the procedure, a graph has been presented in terms of known parameters which helps to quickly specify the value of overall settlement. Overall settlement analysis of Tarom heap leaching structure with suggested method shows that the foundation settlement of the heap is in the safe side.

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