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Numerical Analysis of the Distribution of Plastic Points in the Earth Dams Concerning the Water Level, Berm, and Displacement

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Abstract

Failure of earth dams under seismic conditions may cause disastrous economic damage and loss of lives. Therefore, it is necessary to conduct a seismic safety evaluation and numerical analysis effectively. This paper presents the results of the distribution of plastic points of earth dams. The analysis of plastic points shows the plasticize variations in the body of the earth dam in pre-failure conditions. An inhomogeneous embankment with an upright clay core, which is 10 m high, was studied in three different water levels considering harmonic and static mode using the PLAXIS 2D software. The existence of water causes increasing the number of plastic points in the structure and increasing the amount of displacement. As a result, it changes the situation of plastic points and the location of the appearance of the maximum displacements. The number of plastic spots in first, second and third modes are in order 26, 47 and 116. Also, the amount of maximum horizontal displacement in first, second and third modes are in order 72, 97 and 227 mm.

Keywords: *Numerical analysis, Plastic points, Earth dams, Water level, Berm.*

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Toprak Barajlardaki Plastik Noktaların Dağılımının Su Seviyesi, Banket ve Deplasmanına Göre Sayısal Analizi

Öz

Toprak barajların sismik koşullar altında çökmesi oldukça yıkıcı ekonomik hasarlara ve can kayıplarına neden olabilir. Bu nedenle sismik güvenlik değerlendirmesi ve sayısal analizlerin etkin bir şekilde yapılması gerekmektedir. Bu makale, toprak barajların plastik noktalarının dağılımının sonuçlarını sunmaktadır. Plastik noktaların analizi, göçme öncesi koşullarda toprak barajın gövdesindeki plastikleşme değişimlerini gösterir. 10 m yüksekliğinde dik kil çekirdekli homojen olmayan bir dolgu, PLAXIS 2D yazılımı kullanılarak harmonik ve statik mod dikkate alınarak üç farklı su seviyesinde incelenmiştir. Suyun varlığı yapıdaki plastik nokta sayısının artmasına ve yer değiştirme miktarının artmasına neden olmaktadır. Sonuç olarak, plastik noktaların durumunu ve maksimum yer değiştirmelerin görünümünün yerini değiştirir. Birinci, ikinci ve üçüncü modlarda plastik nokta sayısı 26, 47 ve 116'dır. Ayrıca birinci, ikinci ve üçüncü modlarda maksimum yatay yer değiştirme miktarı sırasıyla 72, 97 ve 227 mm'dir.

Anahtar kelimeler: *Sayısal analiz, Plastik noktalar, Toprak Baraj, Su Seviyesi, Banket.*

1. Introduction

Water flow in the body earth dam has several effects on soil or any structure that is in contact with it. These effects are different in soil. First, the water velocity tends to move soil particles and disturb the arrangement of fine particles toward the space between bigger particles. Due to the second effect of flow, the seepage or hydraulic gradient may transfer a part of soil mass downstream of the soil structure and lead to the boiling phenomenon.

The third effect is the erosion of soil mass that advances from exiting spots of backward water flow and creates a channel for free water flow in the earth's body of the dam. This phenomenon is known as piping. The last effect of internal pressures in existing water inside the body of the soil reduces the resistance of soil and eliminates internal friction, weakens soil mass, and destroy the dam (Sadrnezhad 2005). Lacy and Prevost (1987) numerically investigated the nonlinear seismic response of earth dams. Yegian, Marciano, and Ghahraman (1991) studied risk analysis of an earth dam considering the seismic condition. Chugh (2013) studied the stability of a circular dam for radial cracking considering three-dimensional numerical analysis. Salmasi and Mansuri (2014) evaluated the impact of using horizontal drains for decreasing the effect of seepage in a homogeneous earth dam. A weak form quadrature element method was used by Yuan and Zhong (2016) to analyze unconfined seepage in earth dams considering three-dimensional analysis. Pelecanos, Kontoe, and Zdravković (2016) studied dam-reservoir interaction on the dynamic response. The results showed that the acceleration could be notably affected by the upstream reservoir considering certain cases of concrete dams. Mortazavi Zanjani, Soroush, and Khoshini (2016) numerically investigated fault rupture propagation in earth dams considering steady-state seepage. Tan et al. (2017) conducted a seepage analysis of earth dams taking into account the spatial variability of hydraulic parameters. Rashidi and Haeri (2017) evaluated the behavior of the Gavoshan dam during construction and the first impounding. A numerical two-dimensional (2D) analysis was conducted based on a finite difference method (FEM) on the largest cross-section of the dam using the results of device measurements and back analysis. The stochastic finite element method (SFEM) was used by Mouyeaux et al. (2018) to perform a probabilistic analysis of an earth dam. Fukuchi (2018) evaluated the several empirical methods for predicting the seepage discharges and free surface locations in earth dams (Fukuchi 2018). Zhang et al. (2022) studied the dam deformation in the early stage of internal erosion by using a numerical method (Zhang, X., Wang, C. Y., Wong, H., Jiang, T., & Dong n.d.).

In earth dams, potential earthquake damage may be expressed using crest settlement as criterion, using dynamic analysis, or simplified approaches. Costigliola et al. (2022) compared the results obtained from different methods of soil dam seismic response analysis. They showed how the use of complete dynamic analysis and traditional approaches, rather than substituting for each other, could be synergistic in supporting the interpretation of the seismic response of the dam (Costigliola, R. M., Mancuso, C., Pagano, L., & Silvestri 2022).

Evaluation of seismic performance and post-earthquake operating conditions in earth dams is very important. Considering the soil resistance parameters of the dam and foundation, a proper definition of seismic scenarios at the dam site, the use of advanced methods to study the most critical seismic mods of the dam Is an effective factors in the optimal performance of the dam (Biondi et al. 2021).

In this study, the impact of water level on the distribution, number of plastic points, and location of the maximum horizontal displacement of earth dams are investigated by PLAXIS software. The plastic points' analysis provides an efficient method for studying the resistance of earth dams under earthquake loading. The earthquake-induced displacement could be used for examining the resistance of the earth dam. Also, this paper considers the fluid-soil interaction, which could have a significant effect on the dynamic reaction of the earth dam. Prediction of expansion of the plastic region could be an appropriate method for predicting the occurrence of cracks in the theory of plasticity. Using this method allows analyzing the structure through a linear or nonlinear elastic model and then predicting the occurrence of hydraulic cracking by a failure criterion such as the Mohr-Coulomb model**.**

2. Numerical procedure

As mentioned before, this study concerns the analysis of the dynamic evaluation of earth dams. In this section, the numerical procedure is defined as follows:

- The behavior of both the shell and clay core of the earth dam is described using the Mohr-Coulomb criterion.
- The analysis is performed using the finite element method (FEM) in the PLAXIS software. All analyses were performed under the plane strain condition.
- Fig. 1 shows the dimensions of the numerical model. The slope of crusts is 1 to 4 and the slope of the core in upstream and downstream is 2 to 3. The width of the embankment floor is 85 m, each crust is 26 m, and the width of the core floor was considered 33 m. Due to the permeability of the lower part of the foundation, the clay core did not extend in the foundation. It is of note that the behavior of the foundation of bed and clay core was considered untrained while the soil of the embankment crusts was considered drained. Also, the bottom boundary was fixed in both directions; however, the side boundaries were fixed in a horizontal direction.
- The soil characteristics of the embankment are represented in Table 1. Dam geometry (Fig. 1) and material properties (Table 1) are randomly selected.

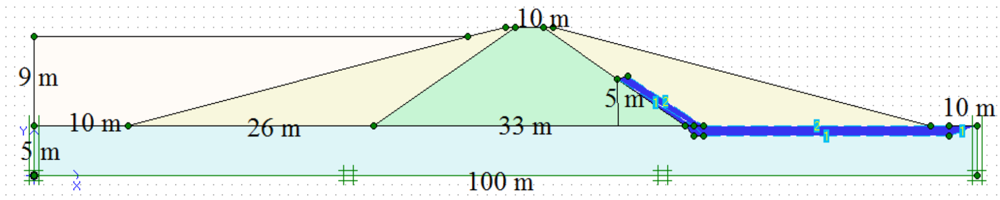

Figure 1. Geometry of the numerical model

The stages for the embankment making are as follows:

1. Bed stabilization
2. Making clay core perpendicular with 1 to 2 gradients
3. Making upstream crust with 1 to 4 gradients
4. Performing drainage in 1-m depth under the downstream crust and 5-m height oblique
5. Making downstream crust with 1 to 4 gradients
6. Performing drainage with 1-m depth under the downstream crust and 5-m height as oblique
7. Making downstream crust with 1 to 4 oblique
8. Bram construction with crust materials
9. Using filter materials at the boundary of the drainage layer and the body of the dam.

Table 1. Soil properties of the embankment

Soil properties	Up-stream crust	Down-stream crust	Dam core	Foundation	Drainage
Cohesion *(kN/m²)*	1	1	30	2	0
Angle of internal friction *(°)*	35	35	5	15	40
Dry unit weight of soil *(kN/m³)*	18	18	16.5	18	18
Saturated unit weight of soil *(kN/m³)*	21	21	18	19.5	22
Coefficient of permeability, for horizontal flow *(m/day)*	1	1	0.001	0.01	9
Coefficient of permeability, for vertical flow *(m/day)*	0.1	0.1	0.001	0.01	9
Modulus of Elasticity *(kN/m²)*	2×10^4	2×10^4	2×10^3	10×10^4	10×10^4
Poisons' ratio	0.3	0.3	0.3	0.3	0.3

Stages for making embankment were conducted in phase definition of computations and time for sedimentation was considered 120-day after dam impoundment.

- This study was done with 3 different modes of underground water level, where a harmonic analysis was done for each mode. In the first mode, the water level was at the bed of embankment. In the second mode, the water level was 9 m higher than the embankment bed and the phreatic line did not enter the downstream crust. In the third mode, the water level was 9 m higher than the embankment bed the phreatic line enters downstream crust. The phreatic line is drawn for hypothetical modeling simplicity.
- Regarding the harmonic analysis of embankment, the time for applying harmonic load was 10 s and the frequency of 10 Hz was applied to the model.
- The expansion of the plastic area in the PLAXIS software is taken as a plastic point**.**
- The slope of the ground is zero. The lower boundary is bounded in both directions, and the displacement of the lateral boundaries is bounded horizontally.
- A relatively medium mesh was used for the regions.

3. Results and Discussion

The plastic points created at the body of earthen dams are indeed the same region in which the strain of plastic has been created. So, it could be concluded that the development of cracks occurs due to loading within the same plastic region. In fact, after loading, due to the pressure of the water or any other loading of the crack, it forms a Δa within the plastic region. In this case, the desired area reached softness. After that, the full plastic regions are formed.

The results obtained from graphical diagrams show that the maximum plastic points in the heel of earth dam and dam crest were developed in clay core on the boundary of upstream crust and in the downstream foundation on the adjoin boundary of downstream crust. The mentioned points are critical positions in earth dams. Fig. 2 shows the position of plastic points of the model in harmonic mode with fine mesh considering three loading phases: a) First loading phase (initial state), b) Second loading phase, and c) Third loading phase.

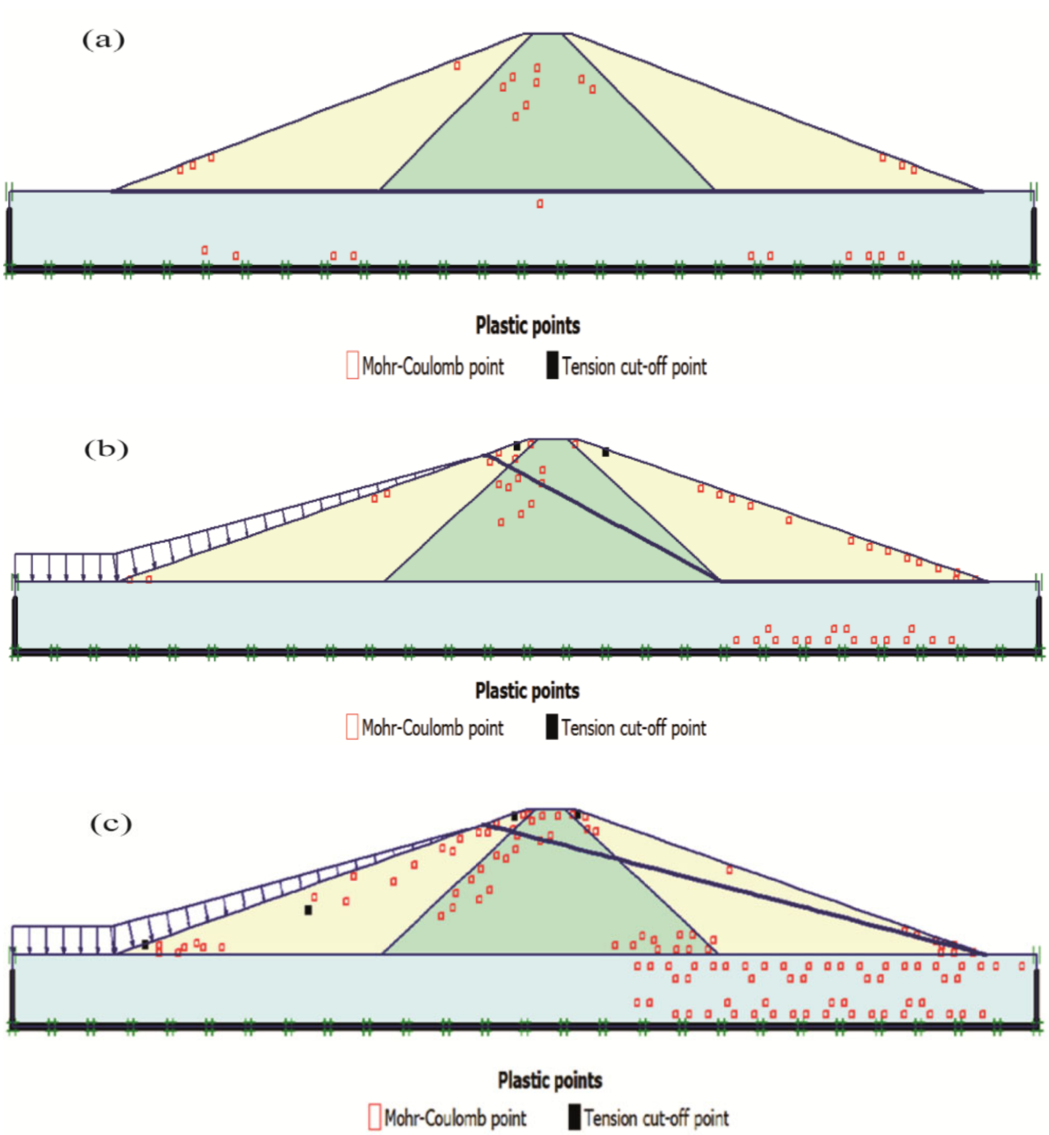

Figure 2. (a) Distribution of plastic points in first loading phase (initial state), (b) distribution of plastic points in second loading phase, (c) distribution of plastic points in third loading phase.

The analysis results revealed that the number of plastic points increased with increasing water heights. Compared with the first loading phase, the number of plastic points increased by 80% and 346% in the second loading phase and third loading phase, respectively. Tension cut-off point: There are places where the soil is stretched (black points).

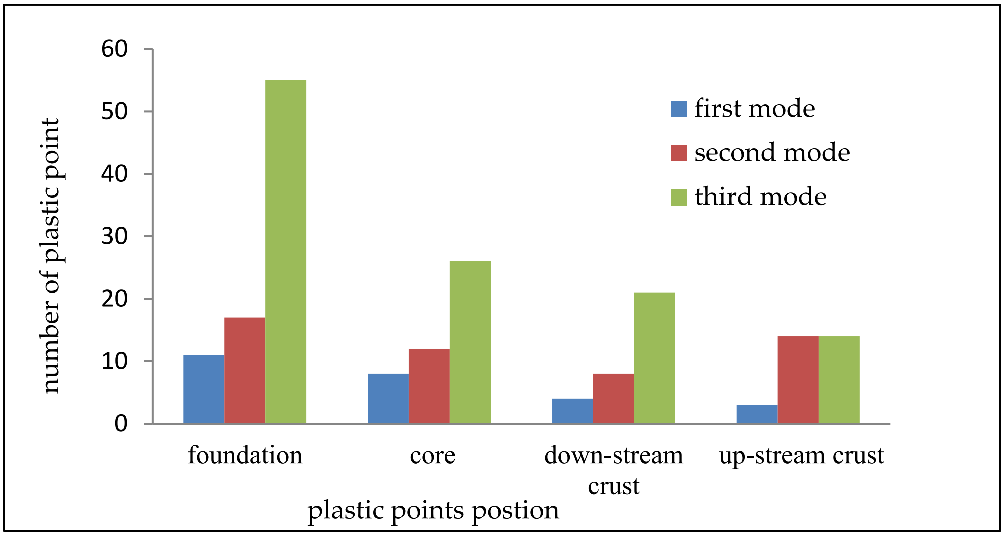

Figure 3. The number of plastic points of the model in harmonic mode considering fine mesh.

According to the results represented in Fig. 3, by increasing the water level the number of plastic points increased, as well. The existence of water increases plastic points in the body embankment and foundation bed. It also increases the amount of displacement and changing the situation of plastic points and the location of maximum displacement. The number of plastic points in the first, second, and third modes is 26, 47, and 116, respectively. Also, the amount of maximum horizontal displacement in the first, second, and third modes is 72, 97, and 227 mm, respectively. The highest increase in the number of plastic points is related to the foundation and core of the earth dam; i.e., 24 and 21%, respectively. Moreover, the least increase in the number of plastic points is related to the upstream and downstream crust; i.e., 26% and 15%, respectively.

According to Fig. 4 and 5, with constructing drainage and increasing the berm height, the number of the plastic points was decreased. The existence of drainage caused the prevention of entering the water to the downstream housing crust and a 54% reduction in plastic points at the body of embankment and bed of foundation, leading to a change of the plastic region situation.

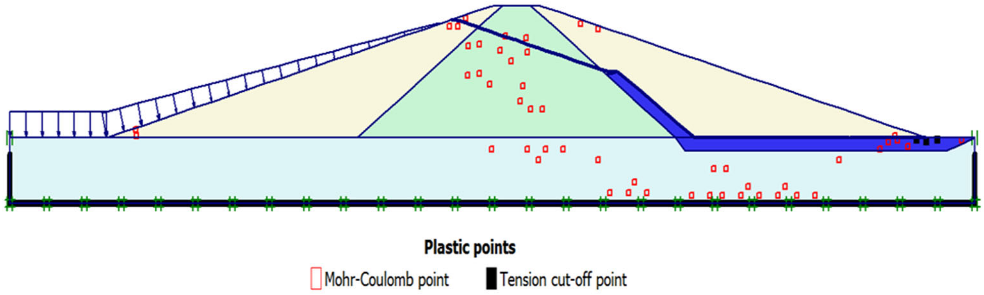

Figure 4. Distribution of plastic points at the body of soil dam and drainage

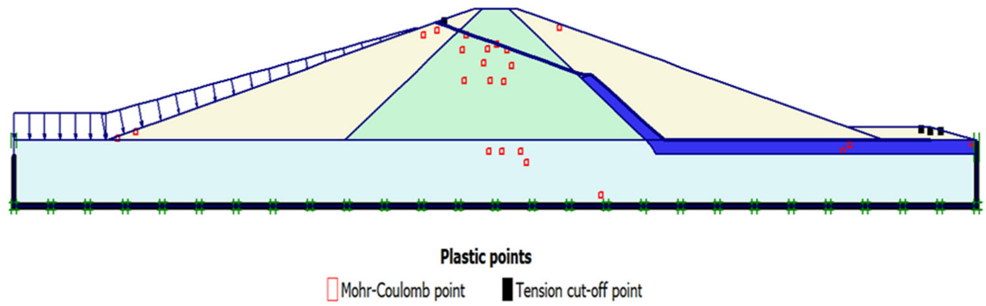

Figure 5. Distribution of plastic points at the earth dam, height of drainage and berm is 1-meter

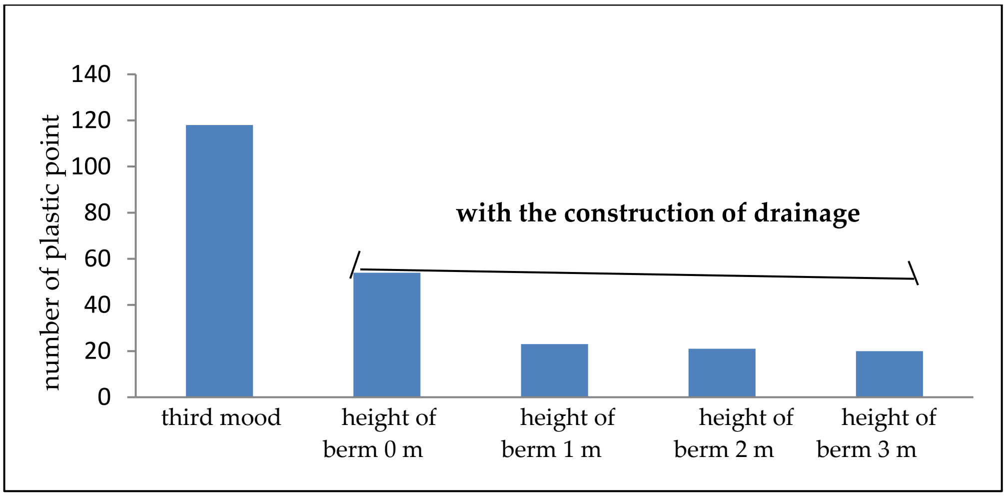

Figure 6. Comparison of the number of plastic points at the different modes.

Figure 6 compares the number of plastic points in five modes: without berm and drainage (third mode), constructing of drainage, constructing of drainage with constructing berm at three heights of 1, 2, and 3 m. The results showed that by constructing a berm at a height of 1 m, the number of plastic points is significantly reduced. Afterward, no large decrease occurs in the number of points with increasing berm height. After making 1 m of the berm, the number of plastic points in the heel of the dam (possible place of boiling) declines while further increasing the height of the berm reduces the displacement of the embankment. Hence, the 1-m berm was sufficient in this model.

By increasing the water level, the maximum horizontal displacement and strain increase in the dam crest in harmonic and static modes. Overall, in the static mode, the water level increases 9 m from the embankment bed, and the maximum horizontal displacement increases from 72 mm to 227 mm. These changes in the maximum strain in the dam crest are caused by changes in water level, this strain increases from 0.0005% in the first mode to 0.95% in the third mode. By increasing the water level, the additional pore water pressure created in the center of the embankment core. This strain was increased by increasing the water level. The results obtained from the analysis of displacement and pore water pressure are represented in Table 2. Increasing the displacement in the embankment leads to the creation of tensile and pressure points in the structure. With increasing stress at these points, the strain increases and leads to the formation of a plastic region at this point, and then in one larger part. In this zone, materials cannot have much resistance against the applied stresses and thus the strain in the sample is sharply increased. Plastic deformation ends with material failure. The results obtained from displacement analysis and expansion of plastic points are presented in Fig. 7 to 10.

Table 2: The maximum value of horizontal displacement in dam crest in static and harmonic modes and the extreme excess pore pressure in harmonic mode

Mode of water level	Maximum of horizontal displacement *(mm)*	Extreme excess pore pressure, harmonic *(KN/m²)*	Extreme principal strain
1	*69.32*	*239.34*	*0.0426*
2	*96.85*	*254.13*	*0.0508*
3	*117.19*	*254.85*	*0.0628*

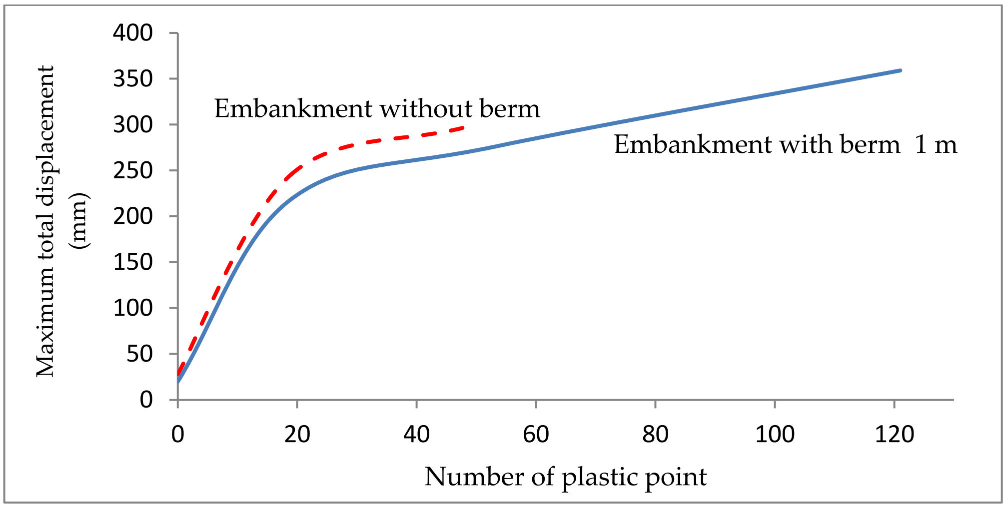

Figure 7. Maximum total displacement of the dam against the number of plastic points.

Figure 7 presents the maximum total displacement of the body of the dam against the number of plastic points. As can be seen, by increasing the number of plastic points, the maximum total displacement is increased. The solid line represents the maximum total displacement of the dam against the number of plastic points for the embankment with a berm height of 1 m in the downstream. One the other hand, the dashed line is for the embankment without berm. Building a berm will control the movement and reduce of displacement of the dam.

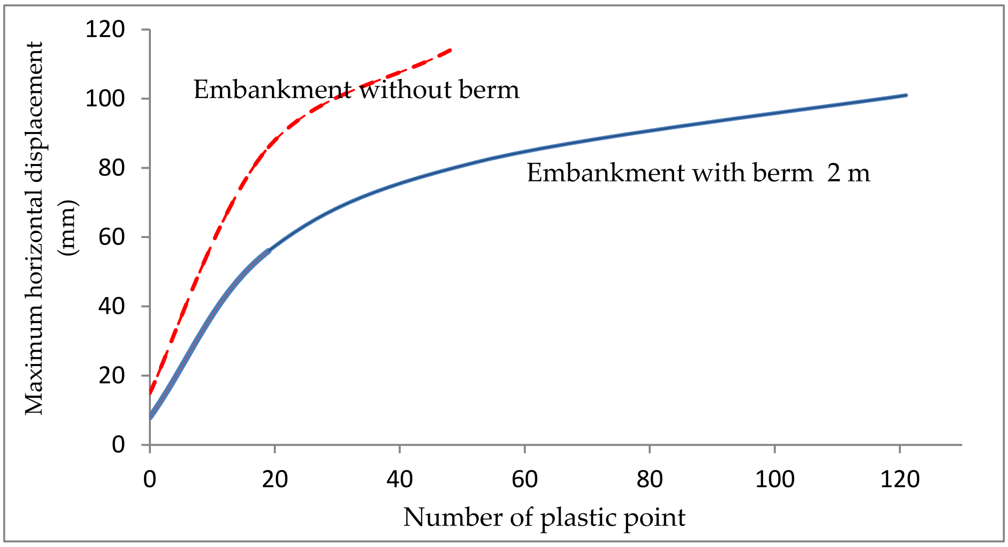

Figure 8. Maximum horizontal displacement of dam against the number of plastic points.

Fig. 8 illustrates the maximum horizontal displacement of the dam against the number of plastic points. With an increase in the area of the plastic zone, the maximum horizontal displacement was increased as well. The solid line represents the maximum horizontal displacement of the dam against the number of plastic points for the embankment with a berm height of 2 m in the downstream. Also, the dashed line indicates an embankment without berm. The construction of the berm reduces the horizontal displacement of the embankment.

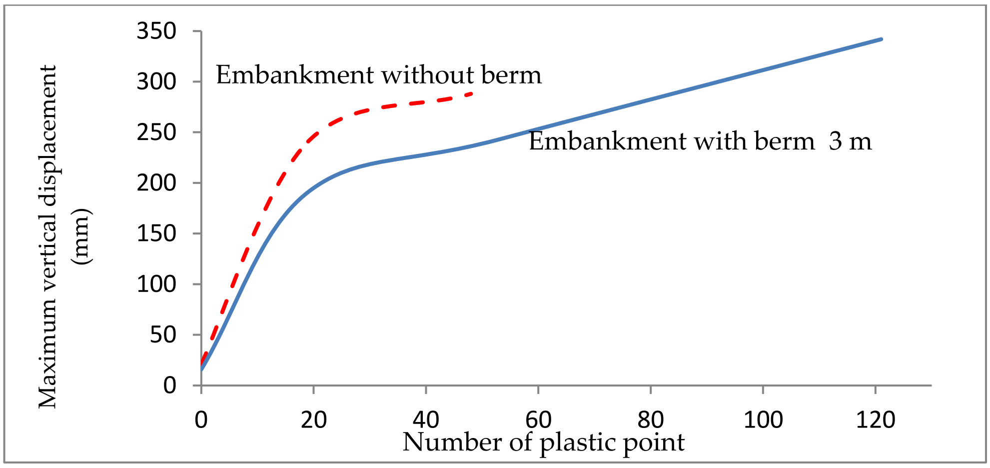

Figure 9. Maximum vertical displacement of dam against the number of plastic points.

Figure 9 shows the maximum vertical displacement of the dam against the number of plastic points. An increase in the plastic area results in a consequent increase in the maximum vertical displacement of the soil. The solid line represents the maximum vertical displacement of the dam against the number of plastic points for the embankment with a berm height of 3 m in the downstream. Besides, the dashed line shows the embankment without the berm. The construction of the berm reduces the vertical displacement of the embankment.

Figure 10 indicates the relation between total strains of dam body against the number of plastic points. By increasing the plastic area, the total strain in the dam is increased as well. In some models due to soil uplift in the downstream, the strain is increased suddenly (The 5th point). This increase is apparent in cases where the berm did not construct at the downside of the dam. In such cases, the tensile zone was created in the dam body. The reason for the sudden increase in strain at the 5th point (Fig. 10) was soil piping in downstream of the earth dam. Thus, by making berms with a height of 1 and 2 meters, the value of strain was tempered in the 6th and 7th points, respectively.

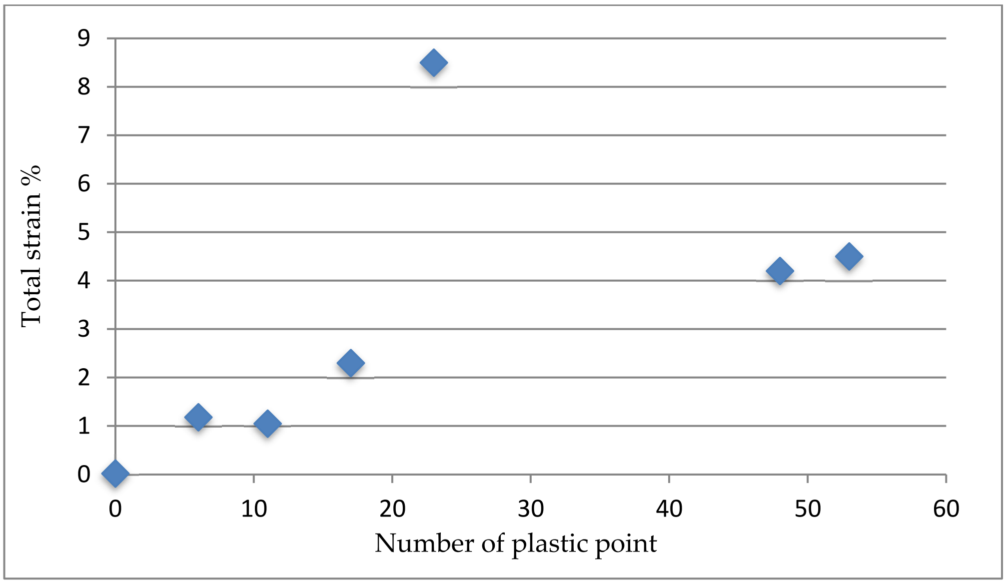

Fig. 10. Maximum total strain of the dam against the number of plastic points.

4. Conclusions

The present study was conducted to predict the failure path by expanding the plastic area in the body of the earthen dam. The failure in the body of the earthen dam begins with the appearance of plastic points in critical areas. Next, the number of plastic points and their joining increase in the plastic area. Finally, the failure line is created. The study of the expansion of plastic points is of great assistance to predict the location of the failure as well as taking measures to prevent failure. In this paper, the effect of drainage and bromine construction on the expansion of the plastic area is investigated. Soil and water interaction by influencing the resistance parameters of soil and tension surface changes in the soil had remarkable effects on the bearing capacity of the soil. Also, they considerably affected the value of displacements and the changes originated from executing the embankment.

- The analysis results showed that when the water level was placed in the embankment floor, the plastic and maximum displacement points were located in the center of the embankment crest, heel, and head of crusts. In the harmonic mode, the maximum displacement took place in the embankment crest.
- In the second mode of loading, the maximum displacement and plastic points increased 44% and the situation of plastic points in clay core moved toward the upstream crust. In the harmonic mode, the maximum amount of displacement took place in

embankment crest and upstream crust.

- In the third mode of loading, by increasing of phreatic water level inside the body, the value of displacement and plastic points increased by 77%. As a result, the plastic points formed not only on the surface of crusts but also in embankment heel and head and clay core heel.
- By increasing the water level to the height of 9 m, the maximum displacement position in harmonic mode from dam crest in the first mode moved toward dam heel and head in the third mode.

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