



Investigating the Influence of Penetration Length of Cut-off Wall on its Dynamic Interaction with Core and Foundation of Earth Dam

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Abstract

Seepage and flow of water in the soil is one of the most important issue and effective elements in designing embankment dams. One of the methods to control seepage in alluvial foundation of earth dams is to use a plastic concrete cutoff-wall. For better seepage control, the cutoff-wall extends inside the clayey core as the one of common method of connection of cut-off wall and the core. Due to the stiffness difference of the core material and cutoff-wall, and also due to geological situation, physical and mechanical properties of rock and foundation, interaction of core and foundation with cut-off wall in different static and dynamic load cases is very considerable. Failure of cut-off wall occurs in cut-off wall and core joint. So the study of their interaction, especially during an earthquake is very important. Karkheh dam cut-off wall with an area of about 150000 m² is chosen for this study. FLAC software has been used to study the effect of cutoff-wall penetration length variation, inside the clay core of Karkheh earth dam under dynamic loading. In numerical analysis of Karkheh earth dam model, all construction stages and seepage through dam are modelled. The model is first calibrated according to the results obtained from the dam instrumentations. After calibrating, according to available seismic studies of region, a suitable acceleration was selected and applied to the model. In this research, in order to find the optimum length, the effect of 0, 5, 10, 15 and 20 meters penetration length of cut-off wall in aforementioned conditions has been investigated. The results of the numerical study showed that the horizontal displacement and the maximum shear strain in the cutoff-wall is occurred adjacent to the clay core and the interface of core and foundation is a critical point for the cut-off wall, and also the stress in cut off wall joint increases with the elongation of penetration depth of the wall.

Keywords: Karkheh; Dam; Cut-off Wall; Core; Plastic Concrete; Seepage; Earthquake.

1. Introduction

A large amount of research and investigations in a dam is related to its foundation or bedrock, and the most important characteristic of the dam bedrock is the permeability of the various layers of the soil underneath the dam. One of the ways to control seepage in alluvial foundation of earth dams is to use a plastic concrete cut-off wall. The connection of the cutoff wall to the dam body is a very important and delicate issue, and should be studied with a great attention in order to have a proper and suitable performance of cutoff-wall. As for designing of cut-off wall in one hand, seepage through it depends on its thickness and permeability [1]. Kazemian [2, 3] and Mahboubi [4] studied characteristic of plastic concrete with different ratio of ingredients to each other, and showed that with increasing of permeability of cutoff-wall, its stiffness is also increasing to some extent. On the other hand, strength and horizontal stiffness of cutoff-wall is very important because the wall supposed to remain steady during its lifetime with exposure to different static,

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hydraulic and dynamic loads. Kazemian [5], Hekmatzadeh [6], and Liu [7] carried out numerical analysis to study the interaction of dam with its cutoff-wall.

The plastic concrete wall has a relatively high stiffness in comparison to that of clayey core. Although it is recommended by ICOLD [9] that the ratio of cut-off wall stiffness to the surrounding soil stiffness be between 4 and 5, at most. However, in many practical cases this ratio is much higher than the recommended value. As a result, this stiffness difference would lead to considerable stress in cut-off wall, and its adjacent soil, especially during an earthquake. In turn, this issue may cause the clayey core to crush and thus create a crack. The presence of a significant hydraulic gradient in this area causes that this crack expands and ultimately destroy the dam. Alternatively, due to considerable deformation, and significant stress in cutoff-wall, cracks may develop in wall itself, and finally led to its failure. As explained, one of the connection methods of cut-off wall to the dam core is its penetration into the core of dam [10] Since effectiveness of this method is highly depends on the length of penetration, in this paper, five penetration length of cut-off wall into the Karkheh dam core is modeled and studied.

In the present work, the aim is to study the Influence of penetration length of plastic concrete on dynamic interaction of core and foundation of dam with cut-off wall. Karkheh dam cut-off wall is chosen as the case study. The effect of cutoff-wall penetration length variation, inside the clay core of Karkheh earth dam under dynamic loading is modelled using FLAC software. After calibrating the model according to available seismic studies of region, a suitable acceleration is selected and applied to the model. Finally, the effect different penetration length of cut-off wall in aforementioned conditions is investigated to obtain the optimum length.

2. Characteristics and Geometry of Project

The Karkheh Dam is the largest Iran multi-purpose earth dam with a clayey core built in Khuzestan province on the Karkheh River in 2001. One of the prominent characteristics of the Karkheh dam is its plastic concrete cut-off wall which controls seepage through dam foundation. Karkheh cutoff-wall which 147000 m³ concrete has been used for its construction, with 2940 meter length is one of the biggest cut-off walls in the world. It has been built over layered bedrock with different deformability characteristics. The great height of dam along with geological location condition of it location, make it necessary to carefully examine the stress and strain values of the cut-off wall in different static and dynamic loading conditions. The cross section of the dam in the vicinity of the cutoff-wall is shown in Figure 1. The core materials are clay mixture and surface materials are mixture of river aggregates. The depth of the cutoff-wall varies in different locations, depending on the position of the relatively non-permeable layers of the lichen. Its depth is calculated based on the analysis of seepage analysis at different sections, available facilities and equipment, and economic considerations. Based on the allowable hydraulic gradient, and hydraulic fracture pressure, the thickness of cut-off wall is 0.6 to 1.2 meter. In this study, and in the model, this thickness is chosen to be 1 meter [11].

Due to the location of the cutoff-wall which is adjacent to the lichen lava (Mud-1 and Mud-2 in Figure 1), in the high elevation of the dam, the engineering properties of these two layers are more important in the results of numerical analysis and wall-foundation modeling. Since there is no assurance for the extension and continuity of lichen layers among conglomerate layers at the bottom of valley, the cut-off wall is extended up to reach the second lichen layer (Mud-2 in Figure 1) and penetrated into it.

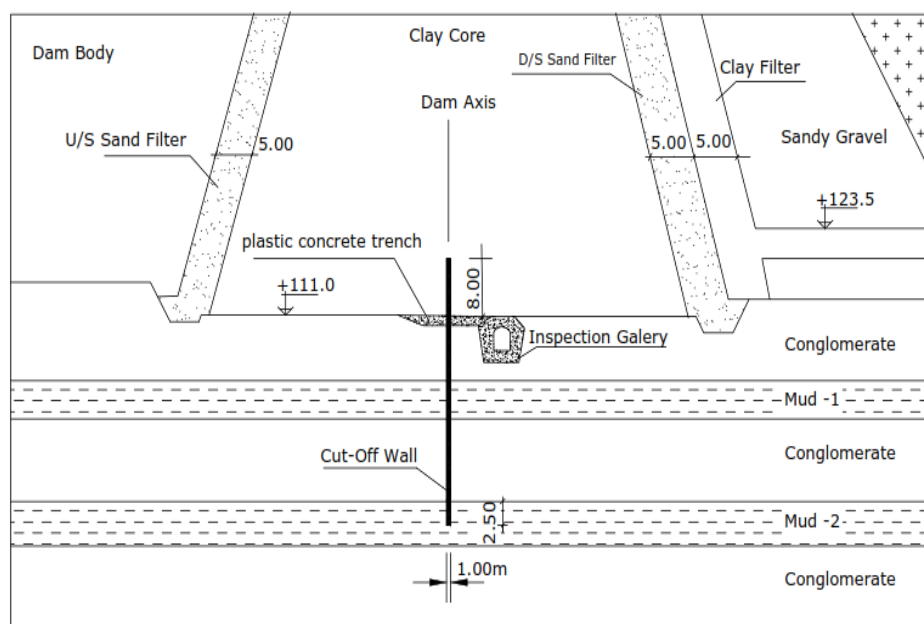


Figure 1. The dam section in the region of cut-off wall.

Conglomerate layers permeability is affected by how their cementation process is, and varies between 10^{-6} to 10^{-1} cm/s. The structure of lichen layers between argillite and sandstone are variables and their permeability are between 10^{-8} and 10^{-5} cm/s [12]. In Table 1, the engineering properties used for modeling of various dam materials are presented. Dam model in FLAC, including its upstream and downstream berms, is shown in Figure 2.

The width of foundation, “B” is equal to 1400 m, its depth, D_f , is 80 m below the level of core, and overall height of dam, “H”, is about 207 m. As it is seen in this model, the core region and close to the axis of dam has a finer mesh.

In FLAC, 2-dimensional planet-strain model has been developed. In model 4-node elements has been used. Also for a better model and to have result as much as possible to real values, interface elements at the contact surface of cutoff-wall and foundation or clayey core have been used. Using these elements allows shear deformation because of slipping of wall relative to its surrounding environment. For cut-off wall in model, structural beam element has been used. The properties of cutoff-wall have been assigned to these beam elements. To define the beam element in FLAC, the modulus of elasticity (E), moments of inertia (I), cross-sectional area (A), as well as the damping parameters are input data (FLAC User’s Manual, 2002 [13]). The dam elements sizes are about a few meters. However, due to use of a finer mesh, in the region close to the dam axis, the width of these elements is close to 1 meter. Ghaderi [16], Yu [15], and Khan [14] studied the behavior of plastic model vs elastic model. They showed that a plastic model is more reliable than an elastic model in describing the mechanical behavior of the concrete cut-off wall.

Table 1. Dam material properties used for modeling

Material	E (kPa) $\times 10^4$	ν	ϕ°	C (kPa)
Core, at the end of construction (first impoundment)	2.5	0.4	12	50
Core, service time	1.5	0.3	22	20
Surface	9	0.25	38-40	0
Plastic concrete	400	0.25	25	1300
Conglomerate above lichen layer (mud-1)	80	0.23	39.4	85
Lichen layer (mud-1)	12	0.3	22	70
Conglomerate below lichen layer (mud-1)	100	0.23	39.4	85
Lichen layer (mud-2)	12	0.3	22	70
Conglomerate below lichen layer (mud-2)	100	0.23	39.4	85

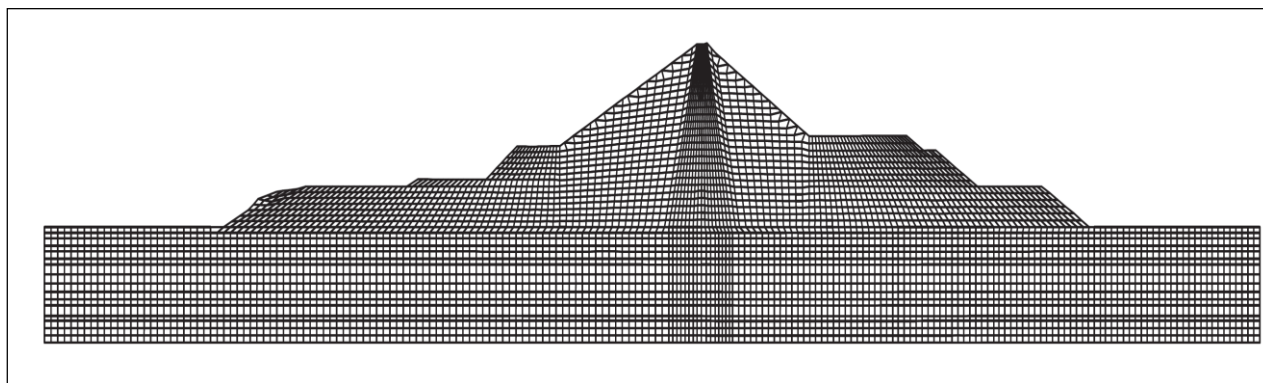


Figure 2. Model geometry in FLAC

In order to simplify the calculation, in this study a linear elastic model was assumed. However, an appropriate plastic model should be applied in further study using behavior of plastic concrete in exposure to stress range obtained from this study.

The reason that in this research beam elements have been used for cutoff-wall is that if 4-node elements have been used, the wall with a 1 meter cross section width is modeled by only one element. While in this analysis, it is expected that the wall behavior is similar to that of a beam, and even having tension stress on one side of the wall and compression stress on the other side are unlikely. With such a view, it is impossible to model the width of a wall with a single element, on the other hand, using elements of length from 10 to 20 cm, the number of elements is increased, and thus the volume of calculations is very high. Using the Beam element in the model eliminates this problem.

3. Research Methodology

As the dam is lengthy with nearly same section through its length, a 2D modeling with plane strain elements would be a rational assumption. The section chosen for this study is in KM: 1+200 which is considered as a critical section. The wide of dam at basement of this section is 1000 m and consequently 1400m wide has been modeled for foundation to place the borders far enough to eliminate its effects on results. The height of the dam is 127m in this section and 80m of the foundation modeled. The size of elements gradually decreases to 1m closing to the center of the dam where the cut-off wall is located. For the connection between the wall and its surroundings an Interface Element is used to allow and monitor sliding between wall and soil due to friction. Meanwhile all the properties of materials assigned to the elements.

In order to perform the analysis of the end of construction, at first the cofferdam layer is activated, then the body of dam is divided into 26 horizontal layers. Consequently, through 26 steps, one of these 26 layers in each step is activated respectively and added to below structure then the vertical displacement of last surface is set to zero in order to model actual Layer Analysis. For the seepage analysis, the corresponding pore pressure of water head assigned to upstream surface of dam and then let the computer analyze the seepage.

To avoid reflection of seismic waves from borders, free-field and Quiet Boundary used in horizontal and vertical borders of the model. In the case of having a quiet boundary, the dynamic load should be applied to the model in the form of stress. As the formulation to convert seismic loading into stress is based on velocity history, the velocity history derived from the available acceleration history. SeismoSignal software used to do this and also to make baseline correction and filtering on the acceleration history. The acceleration history filtered for the frequencies above 25Hz because the size of elements were not appropriate for above frequencies as to avoid numerical errors in wave propagation, the elements' size must be smaller than $\frac{1}{8}$ to $\frac{1}{10}$ of the wave length (λ).

4. Static Analysis

The static analysis of the whole system, including foundation, dam body, and cut-off wall has been done in effective stress state. In this analysis pore water pressure has been considered in core and by applying hydrostatic force on core, foundation, and cut-off wall a boundary condition analysis has been carried out. Static analysis includes two steps, which are:

1. Analysis at end of construction
2. Analysis during seepage

Since it is assumed that during earthquake the pore water pressure due to impoundment has been dissipated, therefore it is concluded that only seepage analysis is adequate and there is no need for impoundment analysis. The piezometer results also shows that the excess pore pressure of construction has been dissipated. In Figure 4, pore water pressure at the time of stabilized seepage is shown. In Figure 5, the horizontal displacement of the cut-off wall for different penetration length of wall into dame core after seepage is shown. As it is seen, the internal deformations of the wall are approximately constant, but after the wall has penetrated into the core region, the horizontal displacement of the wall increases with a considerable slope, which may have attributed to the difference of the foundation material stiffness and that of core material.

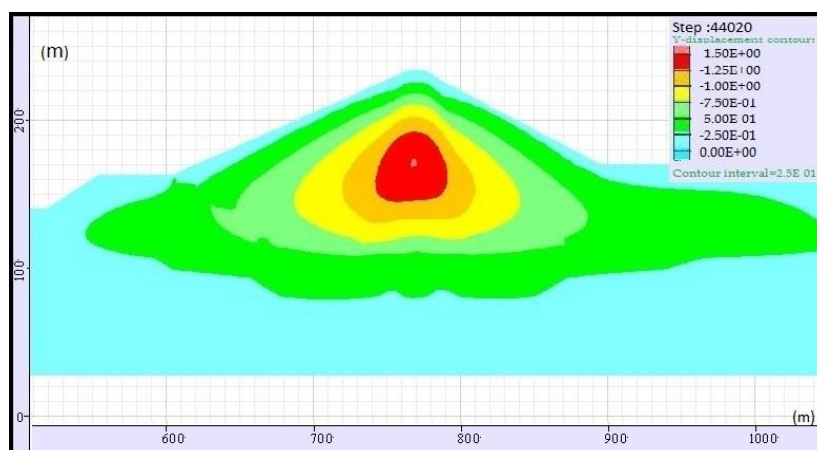


Figure 3. Vertical deformation contour in layered condition analysis

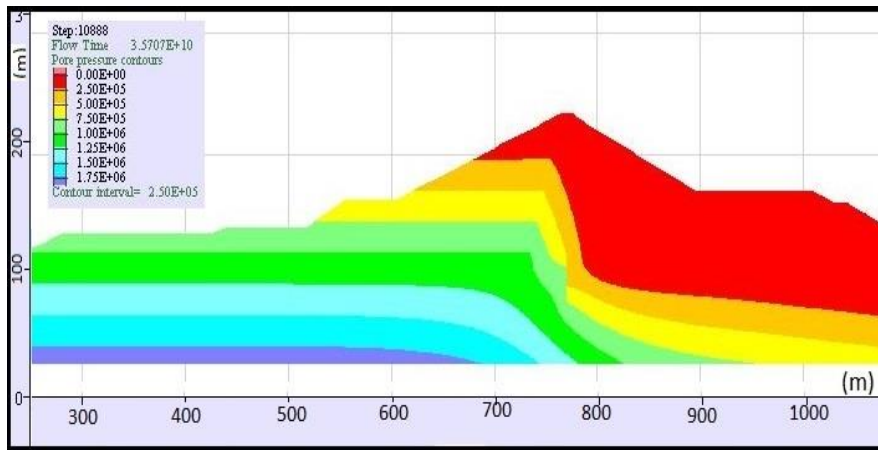


Figure 4. Pore water pressure, stabilized seepage

Since the differential horizontal displacement in the wall is about 30 cm and the height of the wall in this region is 20 m, the angular strain of cut-off wall is obtained by using Equation 1.

$$\gamma = \frac{30}{20 \times 100} = 1.5\% \tag{1}$$

Where “ γ ” is the angular strain. Up to this step, calculated strain is less than the allowable strain of Karkheh dam, which is about 2% (Kazemian [5]). Therefore, it may be concluded that dam is safe during construction and seepage stage. In Table 2, the maximum axial force in cutoff-wall is presented.

Table 2. Maximum axial force in cut-off wall

Maximum axial force (N) $\times 10^6$	Penetration length of wall (m)
3.35	0
3.66	5
4.60	10
6.07	15
7.30	20

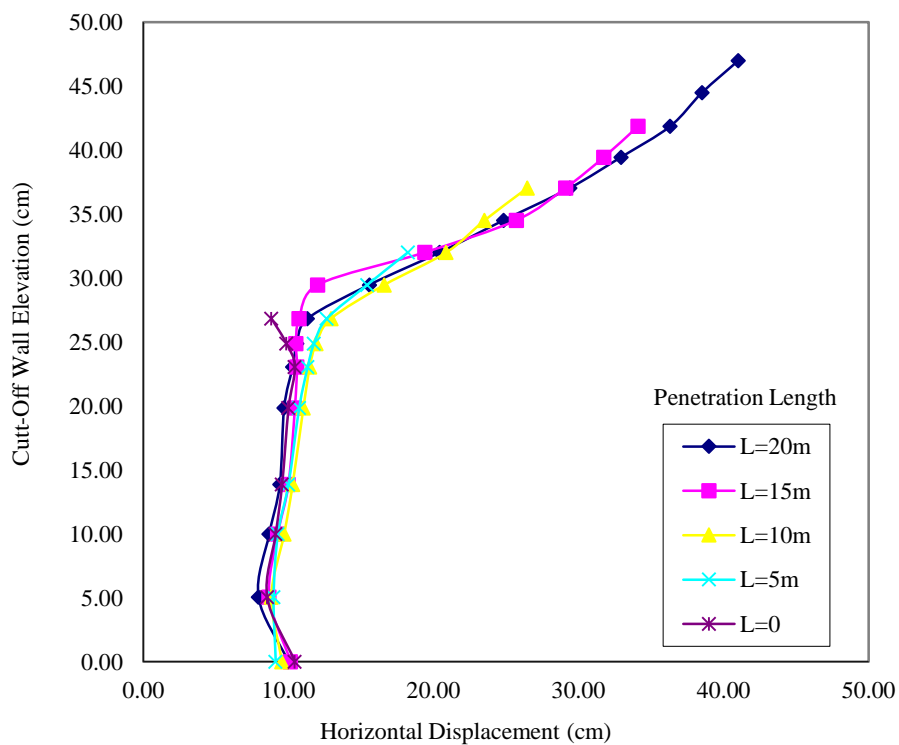


Figure 5. Horizontal displacement of cut-off wall for different penetration length of wall into the core, after seepage analysis

5. Dynamic Analysis

According to design report of Karkheh [12], the seismic studies carried out in the Karkheh dam site, showed that the maximum possible seismicity at the MCE level has the following characteristics: Maximum horizontal acceleration of 0.4 g, Maximum vertical acceleration of 0.3g, return period of 1000 years, magnitude of 6.8 on a Richter scale. Based on these information, the dynamic analysis in this study was carried out using the 25 seconds of Manjil earthquake [17] acceleration record, which was calibrated based on the maximum horizontal acceleration equal to $PGA = 0.4g$.

In this paper for Karkheh Dam model, due to use of quiet boundary in the lower one, earthquake force has been applied to the model in the form of stress. Because of the complexity of damping phenomenon and lack of precise knowledge of the damping characteristics of Karkheh dam, the damping coefficient of 5% was considered empirically for the model. In Figure 6, the horizontal displacement of the cut-off wall for different penetration length of wall into dam core due to applied earthquake. As it seen from Figure 6, angular strain for all penetration lengths is almost the same. Considering that the horizontal differential displacement of the wall with a penetration length of 20 m due to earthquake and static and seepage analysis are 12 cm and 30 cm respectively, the angular strain in cut-off wall may be calculated by Equation 2.

$$\gamma = \frac{12 + 30}{20 \times 100} = 2.1\% \tag{2}$$

In order to calculate the stresses in the cut-off wall, at first the applied bending moment should be found. Then by using beam equations the maximum and minimum stresses due to bending moment is calculated. Result then is added to stress due to axial force in the cut-off wall.

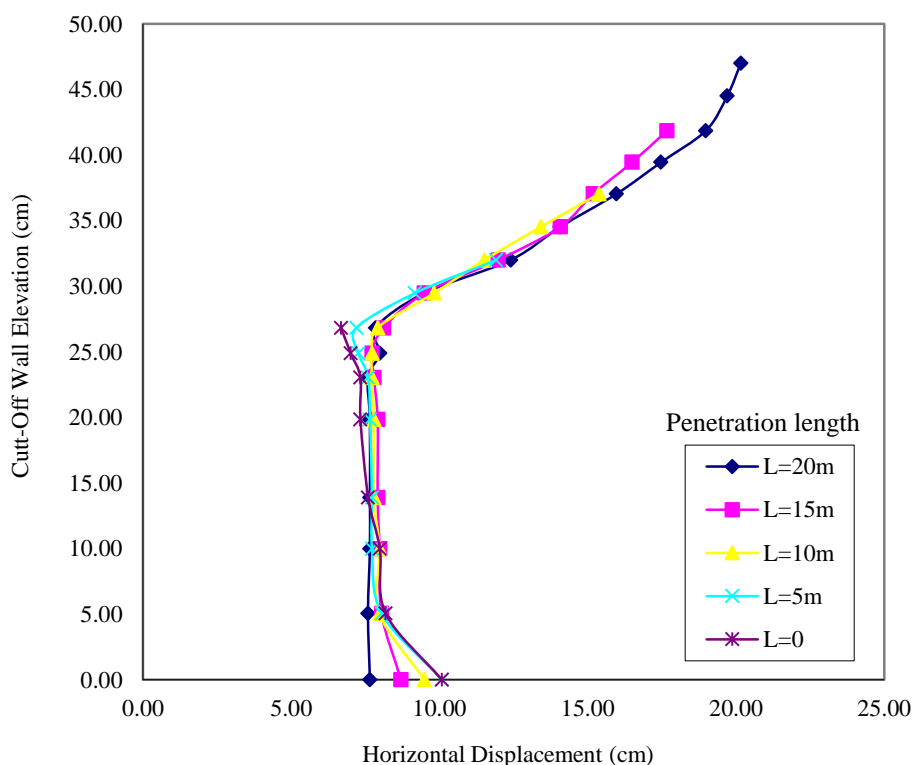


Figure 6. Horizontal displacement of cut-off wall for different penetration length of wall into the core, due to earthquake

Figure 7 shows the bending moment for a penetration length of 20 m. As it can be seen, the maximum bending moment has occurred at the boundary between the clayey core and the dam foundation. Stresses in cut-off wall are calculated using Equations 3 and 4.

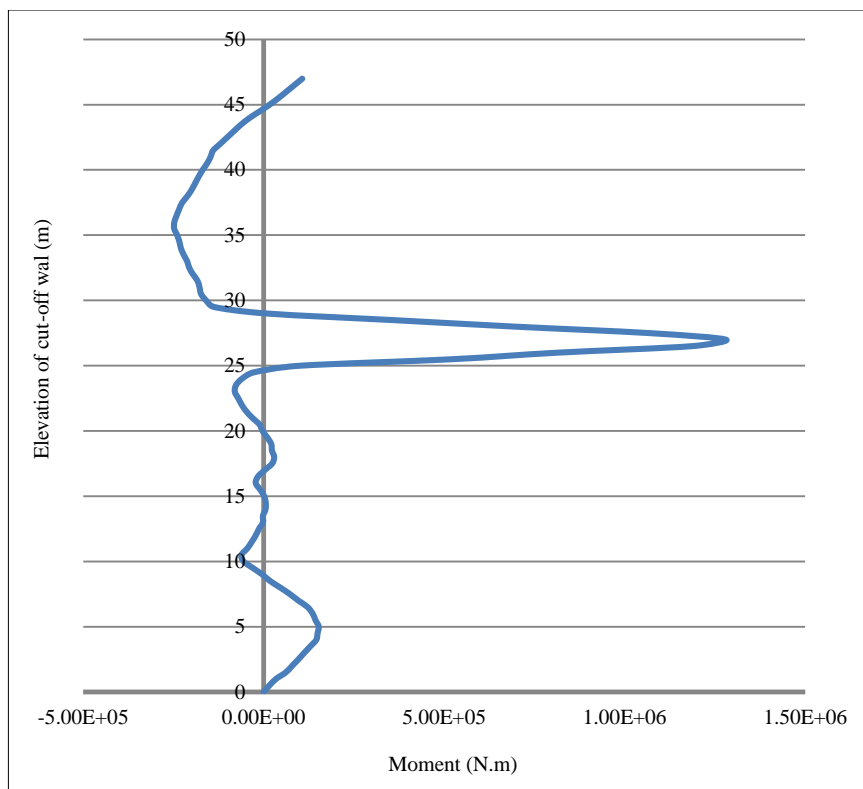


Figure 7. Bending moment for penetration length of 20 m.

$$\sigma = \frac{P}{A} \pm \frac{MC}{I} \tag{3}$$

$$\frac{C}{I} = \frac{0.5}{\frac{1}{1 \times 1^3}} = \frac{1}{2} \Rightarrow \sigma = P \pm 6 M \tag{4}$$

Where “M” is the bending moment, “I/C” is the cross sectional modulus of the cutoff-wall, “P” is the axial force, and “A” is the area of the cross-section per unit length of cut-off wall, which is equal to 1 (A = 1).

By calculating the maximum bending moment for each penetration length, and using equations 3 and 4, stresses for each penetration length are obtained, which are presented in Table 3.

Table 3. Maximum bending moment and corresponding stress for different penetration length

Penetration length (m)	Maximum axial force (N)	Maximum bending moment (N-m)	Maximum stress, (N/m ²)	Minimum stress (N/m)
0	3.35×10 ⁶	2.43×10 ⁵	4.81×10 ⁶	1.89×10 ⁶
5	3.66×10 ⁶	3.37×10 ⁵	5.68×10 ⁶	1.64×10 ⁶
10	4.60×10 ⁶	8.03×10 ⁵	9.42×10 ⁶	-0.22×10 ⁶
15	6.07×10 ⁶	16.7×10 ⁵	16.1×10 ⁶	-3.95×10 ⁶
20	7.30×10 ⁶	12.8×10 ⁵	15.0×10 ⁶	-0.38×10 ⁶

6. Conclusions

Following conclusions were obtained from this study:

- The horizontal displacement of the cut-off wall just after penetrating into core, considerably increases, which is due to smaller stiffness of core material to that of foundation
- As the penetration length of wall into core increases, maximum displacement of cut-off wall is also increases; and the longer the wall penetrates the more displacement we see. It seems that the wall actually obey the deformation of the dam core and cannot have impact on the huge mass which is going to move through seismic displacement.

- The location of the maximum bending moment on the cut-off wall is near the boundary of cut-off wall and dam foundation/dam core. The axial forces produced in the wall is also maximized in this region simultaneously.
- The maximum moment has an increasing trend up to penetration length of 15 m, but for penetration length of more than 15 m, it has a decreasing trend. That is because the upper part of the core has less displacement and the end of the wall slightly being fixed in that region resulting the wall not act just like a cantilever beam.
- Stress calculations on the cut-off wall and based on the stress produced by the bending moment and axial force indicates that in some regions, the plastic concrete wall is under tension. Consequently, tension cracks may be developed in cut-off wall.
- With respect to about 12 cm of horizontal differential displacement of cutoff-wall in dynamic analysis, and its 30 cm displacement in static analysis and seepage analysis, obtained angular strain is equal to 2.1%, which is close to the failure strain of plastic concrete of Karkheh dam (i.e. 2%).

7. Conflicts of Interest

The author declares no conflicts of interest.

8. References

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