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Research Article

Optimization of the effective width of the foundation of a homogeneous earth dam under earthquake using the IWO algorithm

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Abstract

The stability of the earthen dam during an earthquake is important because of the need for safety for the people of that area. Dynamic two-dimensional finite element analysis was performed on a homogeneous earthen dam of Narmab located 5 km south of Minodasht city in Golestan province in Iran. In this study, the effect of theManjil earthquake on the structure of the earthen dam with the water stored in the reservoir has been investigated. In this research, the foundation is assumed to be flexible and not rigid, so the effective width of the foundation in dynamic analysis needs to be considered. The purpose of this research is to determine optimal foundation flank according to the height of the earth dam, which is modeled based on logical assumptions in PLAXIS software. The invasive weed optimization (IWO) algorithm has been used to obtain the effective width of the foundation in the homogeneous earth dam. The result of the algorithm method calculations gives the optimal value of the foundation analysis flanks in terms of dam height equal to 1.81.

Keywords: Dynamic analysis, Homogeneous earth dam, Manjil Earthquake, Foundation analysis flanks, Invasive weed optimization

Introduction

Ambraseys by studying a large number of dams damaged under earthquakes, showed that inertial forces and pore pressure played a significant role in the destruction of these structures [1]. Rampello *et al*, showed that if the water flow passes through the crest of the dam and the slope of the downstream body during an earthquake, it will cause severe damage and erosion of the dam [2]. Terzaghi described various methods which are possible to evaluate the seismic stability of dam using pseudo-static analysis [3]. Newmark et al Displacement-based (New mark or sliding block)methods are also available using dynamic stress-deformation numerical analysis. These analyses provide a suitable solution for the seismic response of earthen dams with homogeneous embankments and important parameters are determined. These parameters included stimulation features (intensity and frequency content), dam geometry (height and embankment in the body), foundation soil conditions, and dam operation stages [4-7].
Studies by De Alba *et al*. and Seed show that earth dams have better seismic performance than concrete dams due to the lack of rigidity[8-9]. The researchers concluded that if a dense earthen dam were built, it could be predicted that with earthquakes having accelerations of 0.2 g or slightly higher the dam would remain stable and undamaged. Chen *et al*. In the evaluation of 670 earthen dams damaged by the earthquake, it was found that cracking in the dams is the most damage caused by the earthquake[10]. Tschuschke *et al.* noted the quality of the construction of tailings dams and the effects of its practical technology, taking into account the natural environmental conditions which should be studied by researchers[11]. Ambraseys *et al.* recorded that previous studies had concluded that if the bed rock is to be found at depth, the rigid foundation should be considered a flexible foundation, although aspects of the interaction were not discussed[12]. Chopra *et al*, considered the dam analysis under the influence of periodic excitations on a semi-infinite environment [13].
In general to investigate the dynamic interaction, the following factors need to be considered: a) properties of foundation materials and dam body; b) The ratio of the elastic modulus of the foundation to the dam body; and c) the dam foundation interaction. Kong et al, considered relative settlement ratios between 0.4% and 1%

as the assessment limits of the dam crest. They analyzed fragility when the dam showed minor to severe failure [14].

Materials and Methods

Figure 1 shows Narmab homogeneous earthen dam under construction: The river bed is 60 meters, the crown length is 807 meters and the effective volume of the reservoir is 115 Mm^3. Narmab Dam was constructed following the request of Golestan Regional Water Company (2003) by the Water and Sustainable Development Consultant for drinking water supply and agricultural land in areas downstream [15].

***Figure 1**. Location of Narmab homogeneous earth dam site*

In this research, the dynamic analysis of the homogeneous earth dam at Narmab (Iran) under the 1990 Manjil earthquake acceleration-time record (peaking at 0.28 g) has been used as input acceleration or dynamic loading in PLAXIS. To determine the effective foundation width, the effect of the interaction of the foundation and the dam body with the reservoir as a complete set, using the Manjil earthquake record, was modeled with PLAXIS software. It should be noted that PLAXIS software is considered reliable and suitable for solving dynamic analysis problems when modeling the dam body, foundation ,and reservoir. The design variables of the earth dam height with values such as 30, 60, and 90 meters and the foundation analysis flanks with values such as 50, 100, and 200 meters were modeled in PLAXIS software. It is a difficult process to determine for which values of the earth dam height and the effective foundation width, the horizontal displacement in the earthen dam crest is minimized. The Invasive Weed Optimization (IWO) algorithm is used with a fixed height of the earth dam and effective width of the foundation based on the minimum horizontal displacement in the crest of the earth dam. Jiriaei Sharahi et al analyzed the cross-section of the Narmab homogeneous earth dam is 60 meters high with diagonal and horizontal drains and stable slopes on both sides of the dam according to Figure 2, where the earthquake record is applied on a rigid foundation [16].

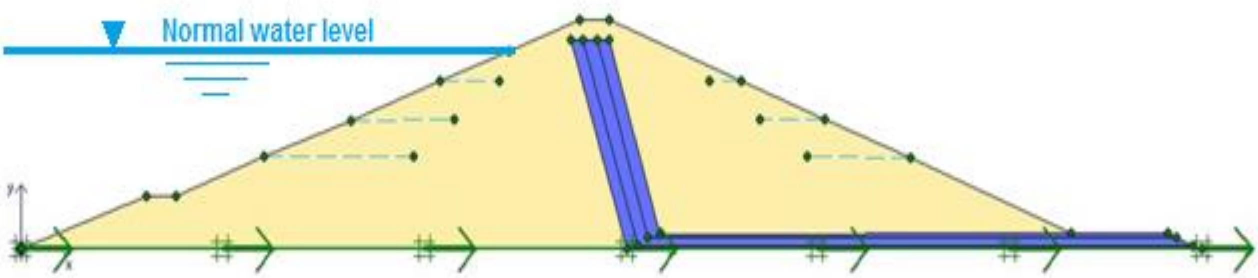


***Figure 2**. Dam cross-section with a rigid foundation*

Figure 3 shows the dam body with a flexible foundation. The distance between the Narmab dam construction site and nearest active fault (at Alborz) is 6 km.

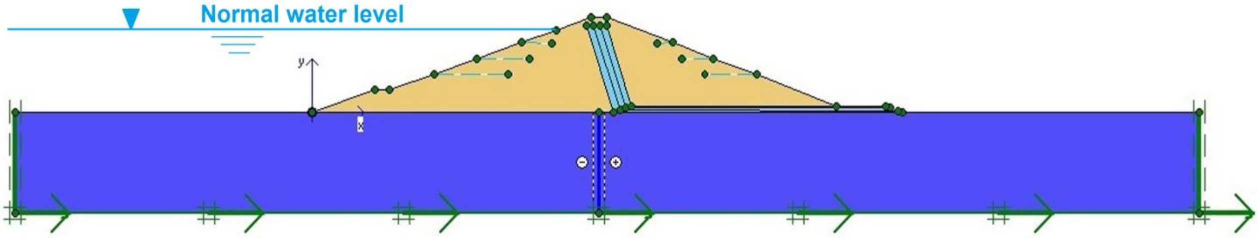


Figure 3. *Interaction of a homogeneous earth dam body with foundation*

It should be noted that numerical modeling of the dynamic analysis using PLAXIS software is performed based on the finite element method. Because the results of the 15-node element are more accurate than the 6-node element, the 15-node element is used in meshing.

Figure 4 shows the cross-sectional network of the Narmab earthen dam with a rigid base.

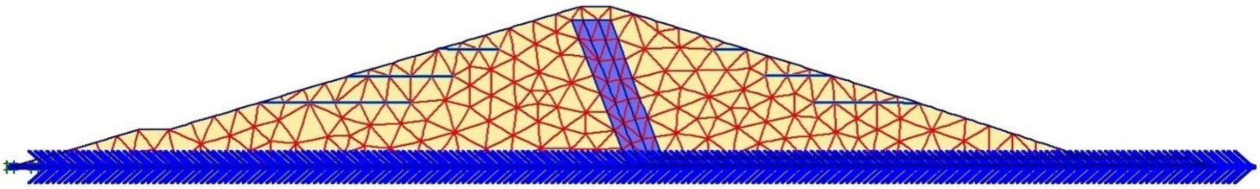


Figure 4. *A modelof the dam with rigid base and its elements*

Figure 5 shows the cross-section interaction of the Narmab earth dam body with a meshed foundation.

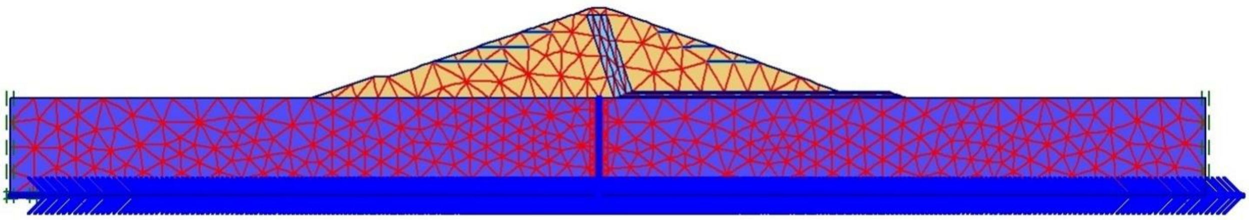


Figure 5*. A model of dam foundation and its elements*

Absorber boundaries are included on the sides of the foundation to absorb additional stresses in the dynamic load. Kohmeier et al, suggest that for an accurate representation of transmitted waves in the Plaxis model, the element size should be as small as possible to meet the following criteria[17]:

$$\lambda \leq \frac{\Delta l}{10}$$

Equation 1

where λ is the wavelength with the highest frequency component that has the highest energy and Δl is the length of the element. By considering these criteria, the size of the component is selected as finely as possible. **Table 1** is from the report "Geotechnical studies of the second phase of Narmab reservoir site" in 2004 was prepared by water consulting engineers and sustainable development[18]. These values were used in the dynamic analysis with the Mohr-Columb model.

Table 1*. Characteristics of homogeneous Narmab Dam earth materials*

Type of material	Material properties	C (kPa)	φ	E (MPa)	γ_{sat}(kN/m^3)	υ	k_x, k_y m/day
Dam body	Cl	27	23	214.6	21	0.3	8.64E-7

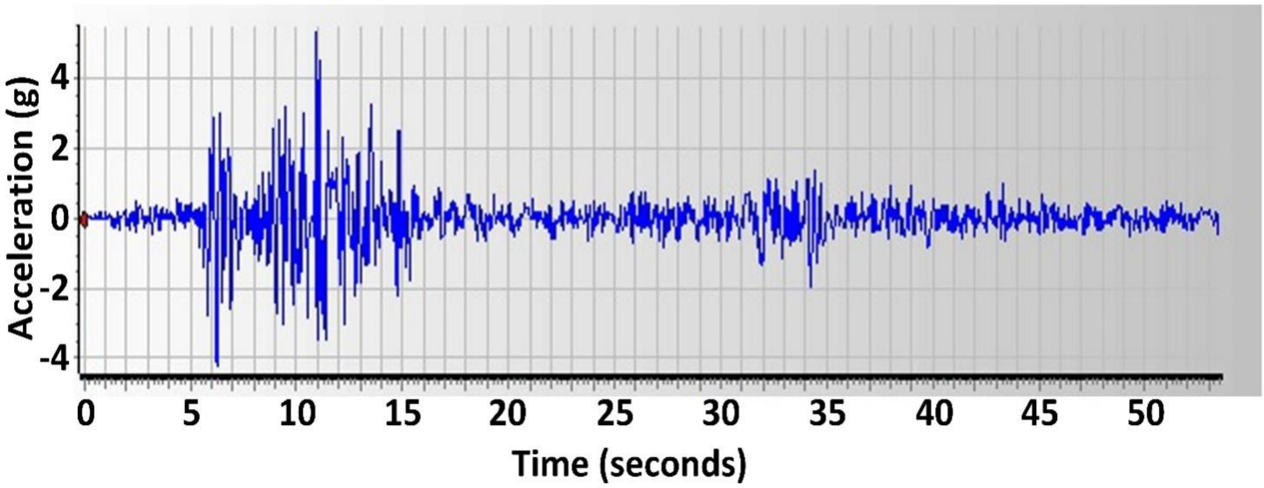
Drain material	Gw	1	42	348	20.7	0.25	86.4
foundation	Gp	1	42	267	21	0.3	0.864

2. DYNAMIC ANALYSIS

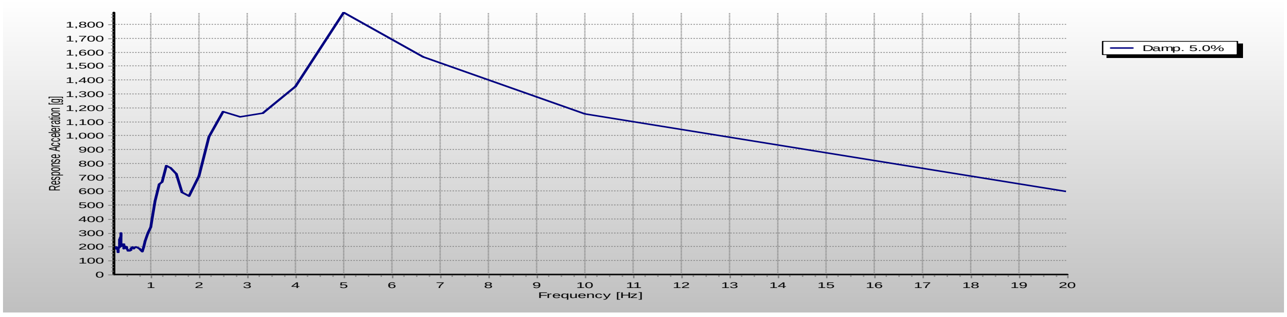
One of the most destructive earthquakes in Alborz region was Manjil earthquake in June 1990 with Mb=7.3 and Ms=7.7. The earthen dam analysis for the Narmab damwas performed in three phases (Jiryaei Sharahi M et al):

1. Completion of the dam construction.
2. Reservoir filling up to normal reservoir level.
3. Dynamic analysis in Manjil earthquake conditions and taking into account the effect of the interaction between the foundation and the body of the dam in the condition of the reservoir being filled up to the normal level[19].

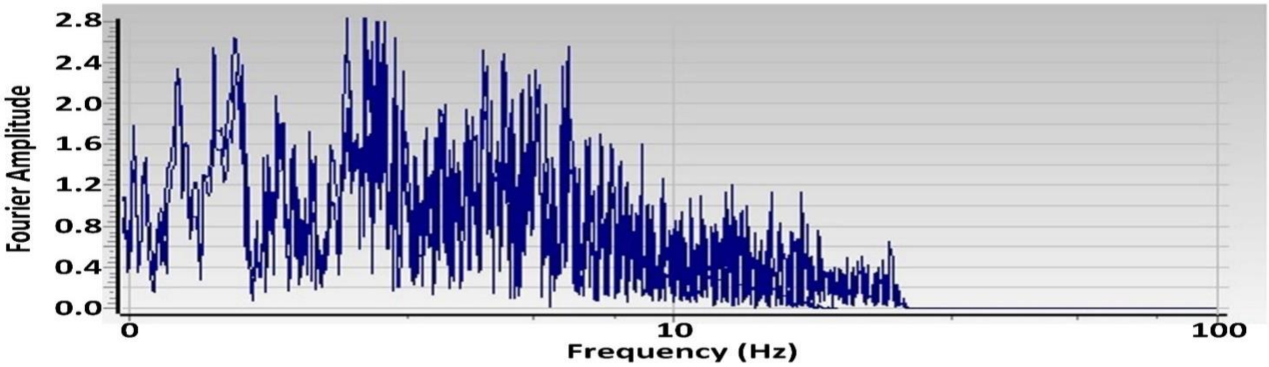
Figure 6 shows the maximum acceleration of 0.28 g related to the normalized acceleration time history of the Manjil earthquake with the SEISMOSIGNAL 2022 software, which is considered under the maximum design level (MDL) and used in the modeling.



a) Acceleration mapping of the first component of the Manjil earthquake



b)The acceleration response spectrum of the first component of the Manjil earthquake(Damping 5%)



c) The Fourier function spectrum of the first component of the Manjil earthquake

***Figure 6**. Acceleration of the Manjil earthquake, response acceleration, Fourier amplitude with SEISMO SIGNAL 2022 software*

The horizontal accelerations, vertical accelerations, and horizontal displacements obtained from the results of Plaxis software were used for the detailed investigation of the Normab dam under the Manjil earthquake, and for this purpose, a point on the crown of the Normab dam was selected as a reference, which is presented in Figures 7-9.

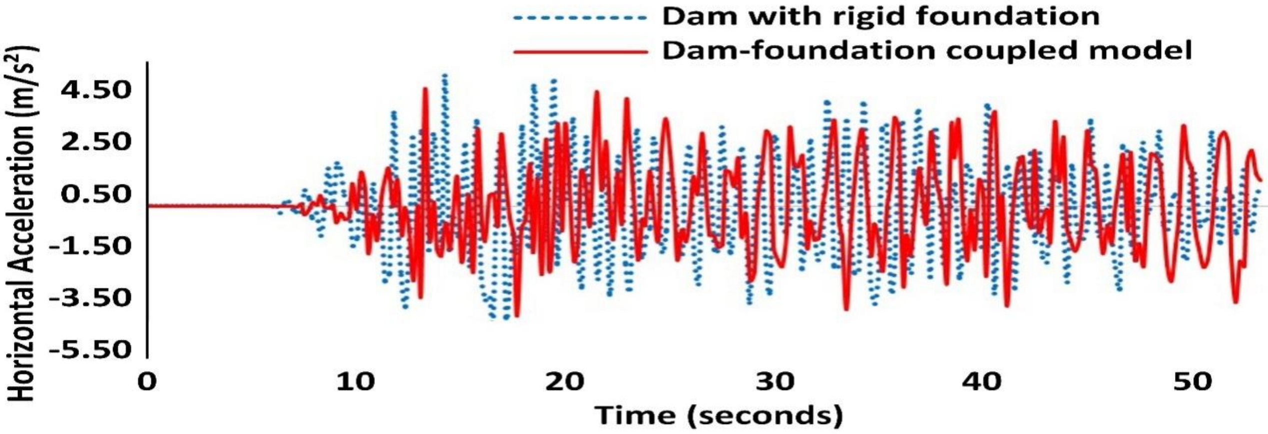


***Figure 7**. Horizontal acceleration at the middle point of the crest of the dam due to the Manjil earthquake*

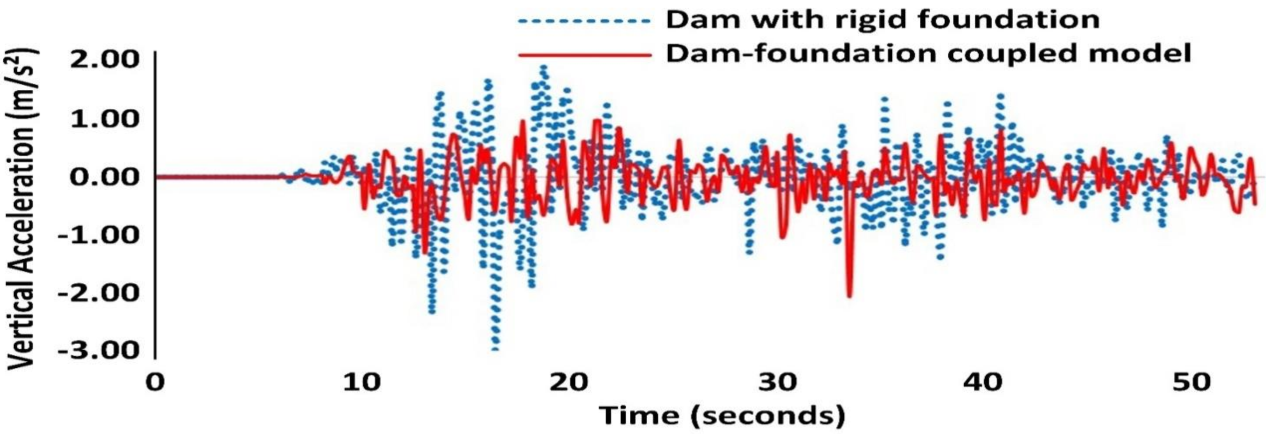


***Figure 8**. History of vertical acceleration at the middle point of the dam crest due to the horizontal component of the Manjil earthquake*

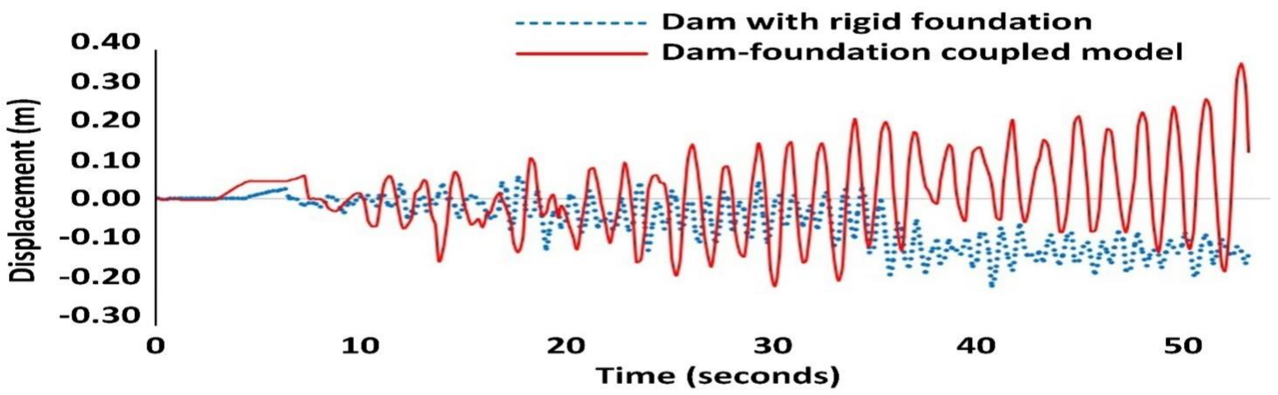
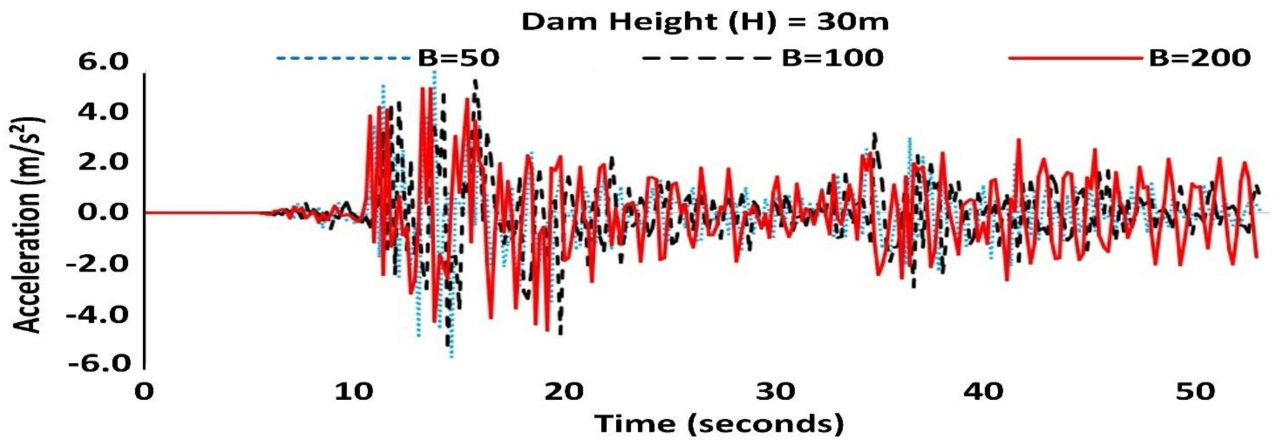
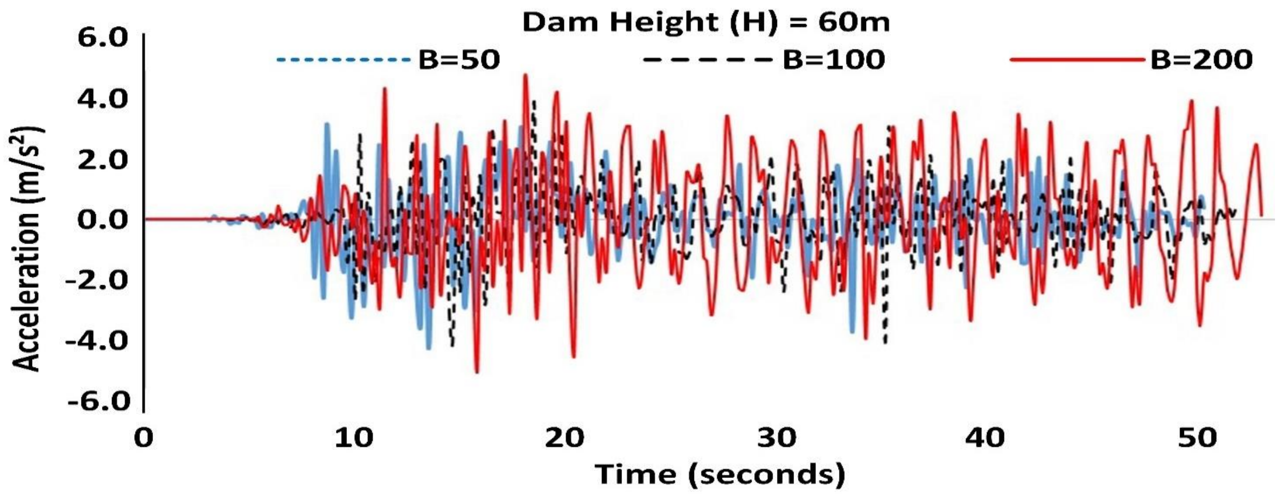


Figure 9. *The history of horizontal displacement in terms of time at the middle point of the crest of the dam under the Manjil earthquake*

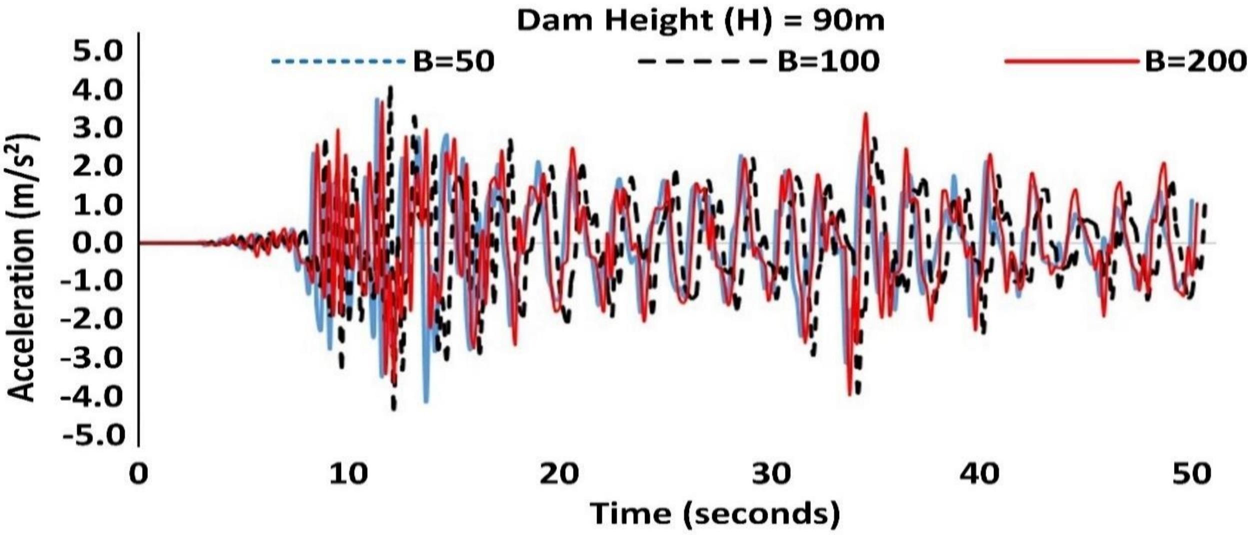
The horizontal acceleration and horizontal displacement from the results of Plaxis software at the middle point of the crest of the Narmab dam due to the Manjil earthquake, are presented in **Figures 10 to 11**.



(a) Horizontal acceleration for dam height 30m

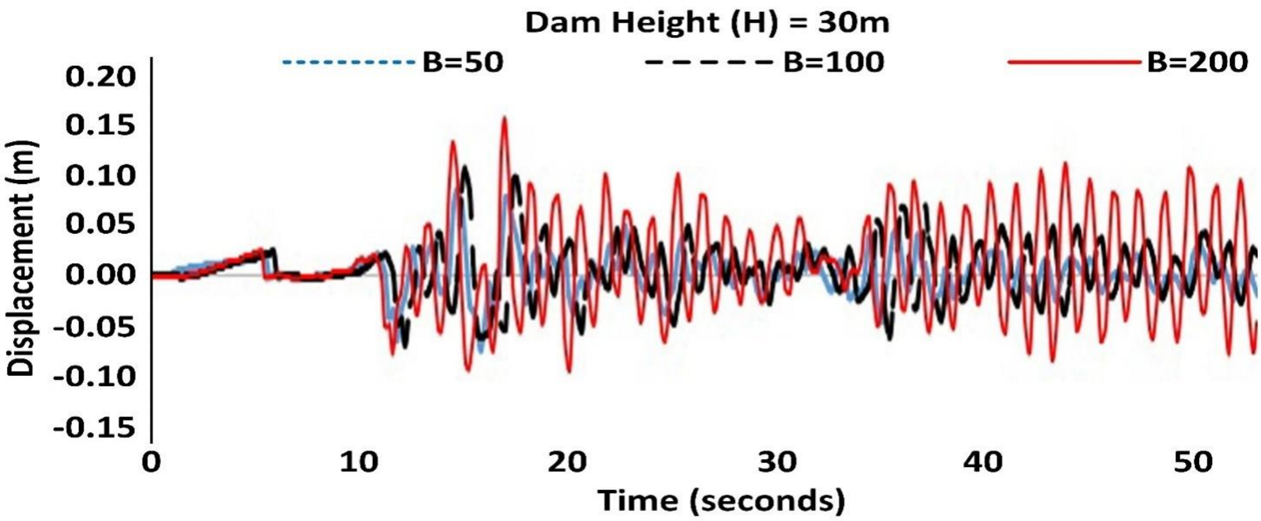


(b) Horizontal acceleration for dam height 60m

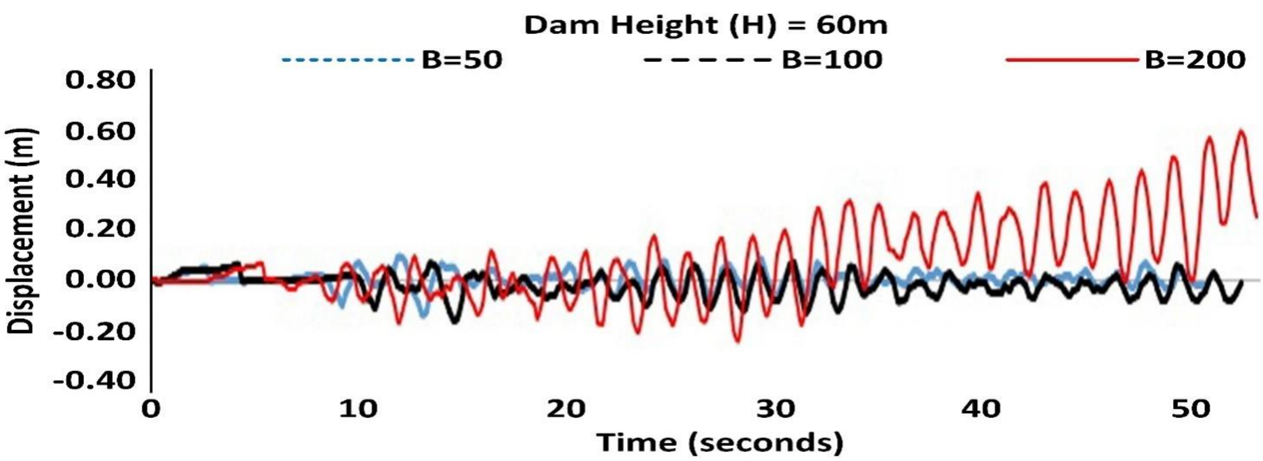


(c) Horizontal acceleration for dam height 90m

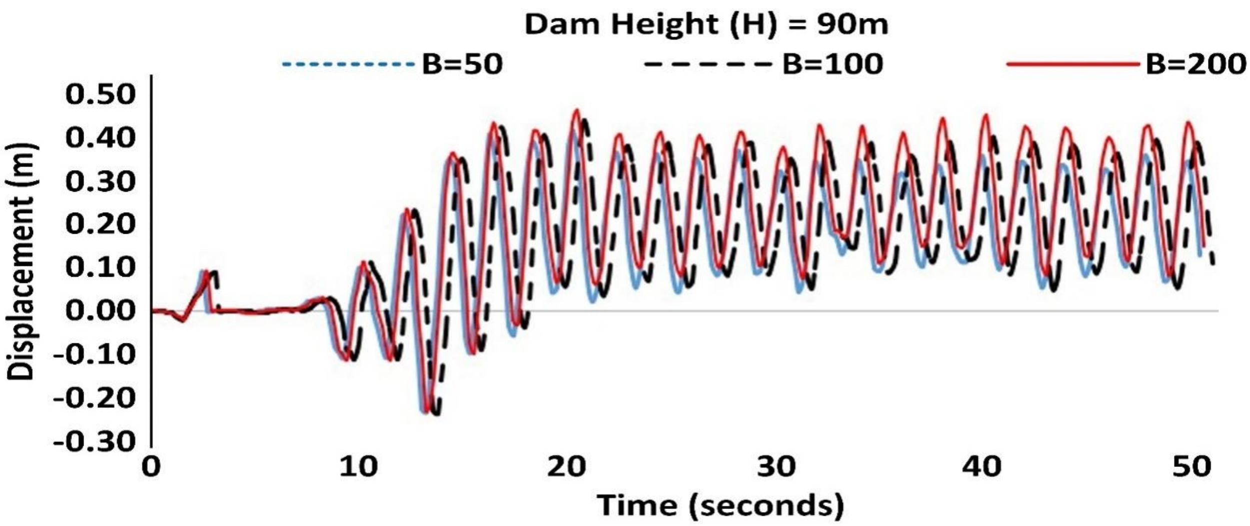
***Figure 10**. Time history of horizontal acceleration at the middle point of the dam crest.*



(a) Horizontal displacement for dam height 30m



(b) Horizontal displacement for dam height 60m



(c) Horizontal displacement for dam height 90m

***Figure 11**. Time history of horizontal displacement at the middle point of the dam crest*

From the results of Plaxis software shown in Figures 10 to 11, it can be concluded that the horizontal elastic displacement in the crest of the dam increases with the increase of the B/H ratio, especially when the foundation flank (B) are more than twice the dam's height (H). Permanent displacements are not sensitive to the choice of foundation flank in the model and did not change. The frequency content of the acceleration response at the earthen dam crest is significantly different when the foundation analysis flanks (B) is more than twice the dam's height (H).

3. THE PROPOSED INVASIVE WEED OPTIMIZATION (IWO)

Determining the height of the earthen dam in terms of the effective width of the foundation to minimize the horizontal movement in the crest of the earthen dam is not easily possible. For this purpose, it is useful to use the invasive weed optimization algorithm (IWO). The weed quickly adapts to the environmental conditions of nature and resists destructive factors. Introducing these characteristics, a powerful optimization algorithm is proposed which is used in this study.

The reasons for paying attention to weeds are the following:

1- The existence of weeds after several thousand years of agriculture
2- The existence of weeds even after using any kind of poison and herbicides
3- The growth of new weeds on a large scale in agricultural lands
4- Changing the behavior of weeds for adaptation to the environment

Weed behavior can be simulated as follows:

1- Spread the seeds in the desired space
2- Seed growth based on desirability (fertility) and ecological dispersion (reduction of environmental distribution over time)
3- Survival of grasses to achieve more utility (competitive elimination)
4- Continue this process to achieve the best desirability of plants.

As a result, the steps of the IWO can be summarized as below:

1- Production of initial random population and evaluation of objective function
2- Reproduction based on fitness and updating standard deviation (environmental dispersion)
3- Competitive elimination
4- Check the status of the completion of the work

In the following, the steps will need to be explained in more detail.

A) The initial population is generated randomly to create a predetermined initial random population of N_{weed}.

B) Reproduction

According to Mehrabian *et al.* each plant can produce seeds based on the minimum and maximum conditions of its colony. The number of sources that each plant can increase production linearly from the minimum potential value to the maximum possible amount (S_{min}, S_{max}). The number of sources planted around each grass is obtained according to the following procedure[20]:

$$Seed_i = Round\left\{S_{min} + \left(S_{max} - S_{min}\right) \times \frac{N_{weed} - rank_i}{N_{weed} - 1}\right\}$$

Equation 2

$Seed_i$: The number of sources planted around the i
S_{min}: The minimum number of seeds that can be produced around each grass
S_{max}: The maximum number of sources that can be planted around each grass
N_{weed}: The number of primary grasses
$Rank_i$: Rank grass i

C) Environmental dispersion

The produced seeds are distributed in the search space with a normal distribution of zero and a predetermined variance. This means that the sources are close to their parents (grasses). The initial and final standard deviations must be specified numerically beforehand to change their value. During the implementation of the algorithm, the initial deal can be reached non-linearly from the initial value. In other words, by approaching to the end of the algorithm, the more grains are generated around the obtained answers, and the less scatter there is. The standard deviation update is performed according to **equation 3**:

$$\delta_{Iter_i} = \frac{\left(\max It - Iter_i\right)^{pow} \times \left(\delta_{initial} - \delta_{final}\right)}{\left(\max It - 1\right)^{pow}} + \delta_{final}$$

Equation 3

δ_{Iter_i}: Deviation of the ith repeat criterion
max It: Maximum number of repetitions
$Iter_i$: Repetition of i
Pow: Nonlinear coefficient

D) Competitive elimination

Every grass needs to be propagated to survive. Therefore, competition between lawns is required to limit the maximum number of properties in a colony. After producing seeds around each grass, we can pass on the specified maximum number of grass (P max) natural grasses and seeds to the next generation. The maximum number of restricted grasses can be equal to the initial population.

Figure 12 shows the performance of the proposed method of weed optimization algorithm as a flowchart:

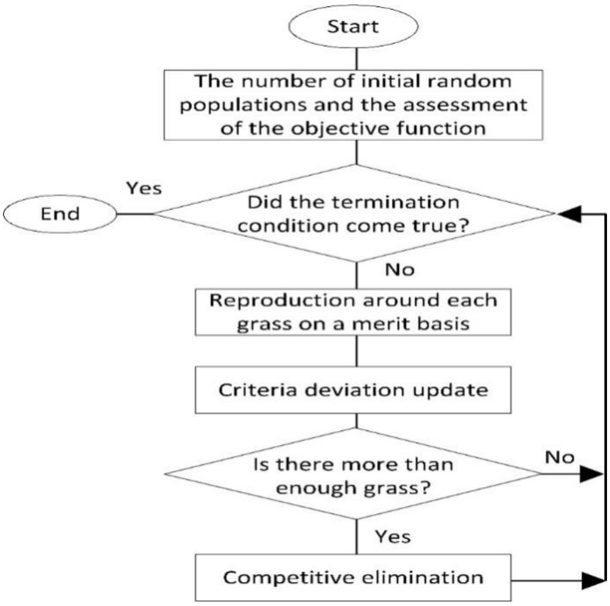


Figure 12. *Flowchart of the weed optimization algorithm.*

4. PROPOSED METHOD

The control of slope stability upstream and downstream of Narmab Dam has been investigated by Atanaz Bahrami et al [21]. Dynamic analysis with design variables to determine the foundation analysis flanks(B) in terms of dam height (H) has been carried out by the finite element method. (Table 2). To determine the optimal effect, the assumptions of the foundation analysis flanks(B) from 50m to 200 m with the height of the homogeneous earth dam (H) in the range of 30m to 90 m have been calculated. **Table 2** shows the height (H) of the dam, the foundation analysis flanks(B), and the sum of the effective lower W widths studied.

Table 2. *Dimensions in dynamic analysis in meters.*

Model number	1	2	3	4	5	6	7	8	9
Height (m)	30(m)			60(m)			90(m)		
Foundation analysis flanks (m)	50	100	200	50	100	200	50	100	200
The sum of the effective lower W widths (m)	297	397	597	474	574	764	651	751	951

In **Figure 13**, the cross-section of a homogeneous earth dam defined in **Table 2** is performed as a complete set in two-dimensional analysis with PLAXIS software. In this paper, the midpoint of the dam crest is considered as the basis and comparison of all horizontal deformations that occurred due to the Manjil acceleration-time record.

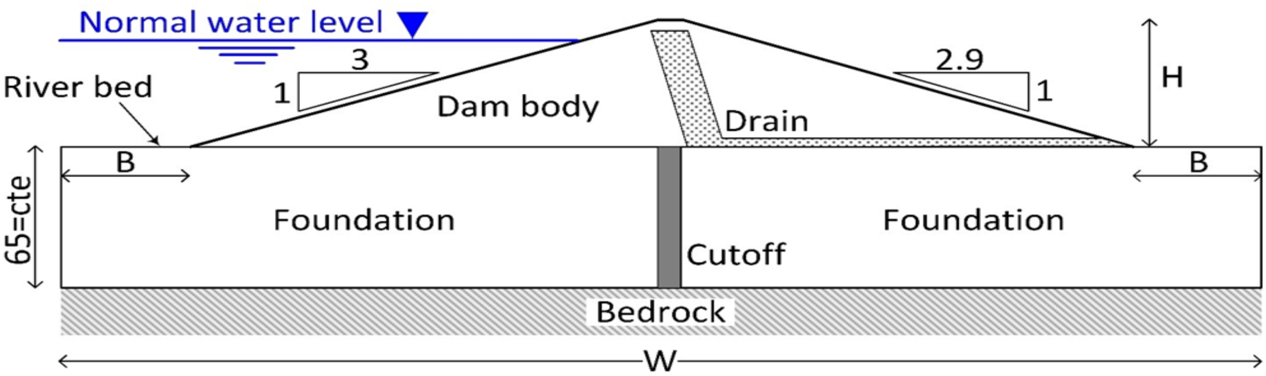


Figure 13. *Cross section of a homogeneous earthen dam according to Table 2*

The fitness function of PLAXIS software output data from the dynamic analysis produces a fitting curve. Since the horizontal deformation in the dam's crest shows the greatest amplitude, it was defined as a comparison criterion. The Z function is the amplitude of the horizontal deformation at the homogeneous dam crest, according to **Table 2**.

$$Z=MY_1^4 + N Y_1^3 + PY_1^2 + Q Y_1 + R$$

Equation 4

Where, Y_1 is the fitness function which is the B/H ratio and M = -2.8, N = 26, P = -51, Q = 32, and R = -15 are coefficients obtained from data analysis in PLAXIS software. The steps for optimizing the B/H ratio using the invasive weed optimization method are shown in **Figure 14** as a flowchart.

1- In the proposed method, design variables (B, H) are first selected.
2- The desired specification of the output including horizontal displacement is evaluated.
3- The stop conditions are checked. If the stop conditions are not met, new solutions will be sought by the IWO.
4- If the stopping conditions are met, the final results will be produced

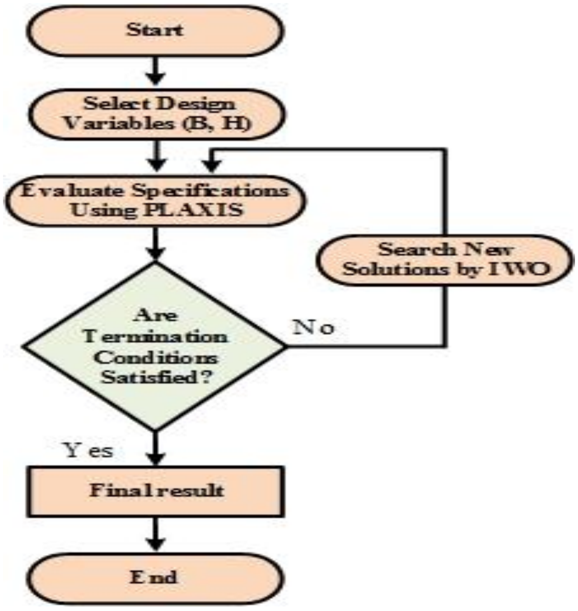


Figure 14. *Flowchart of B/H ratio optimization steps invasive weed optimization method*

SIMULATION

According to Table 2, from the results of dynamic analysis with PLAXIS software, it was predicted that the foundation analysis flanks should be less than twice the dam's height. In this research, to determine the foundation analysis flanks, the basis for obtaining the fitness function based on minimising the horizontal deformation in the dam crest under earthquake response has been defined. The fitting function of the amplitude of horizontal deformations in the crest of a homogeneous dam is considered according to equation (4) in terms of the B/H ratio. For the solution, it is proposed to minimize the cost function using the IWO algorithm. The IWO parameters used for optimization in this research are presented in **Table 3**. These parameters are selected in such a way that there is a compromise between the speed and accuracy of the algorithm.

Table 3. *IWO parameters used for the optimization*

MaxIt=3	Maximum number of Iterations
No=50	Number of initial population
Pmax=100	Maximum number of weed population
Smin=1	Minimum number of Seeds
Smax=10	Maximum number of Seeds
n=3	Nonlinear modulation index

Initial sigma=0.3	Initial value of standard deviation
Final sigma=0.001	The final value of the standard deviation

In this study, IWO parameters with 3, 5, 10, 50 and 100 iterations were used to determine the optimal ratio of the foundation analysis flanks according to the height of the dam. Based on the simulation, the obtained results were 1.808, 1.803, 1.811, 1.8111 and 1.8111 respectively. Figure 15 shows the desired iterations of the algorithm to find suitable answers for this ratio. The diagram of this algorithm show the proposed cost described in equation (4) in terms of iterations. The IWO algorithmis implemented in MATLAB R2019a software. In this study, using the IWO algorithm, the B/H ratio was 1.81. Anisheh, S. R et al. using the IWO algorithm, the optimal B/H ratio was 1.81, which was exactly equal to the results of the cuckoo optimization algorithm (COA)[22-23]. But the computational time of the proposed method based on the IWO algorithm is about 68% of the COA method.

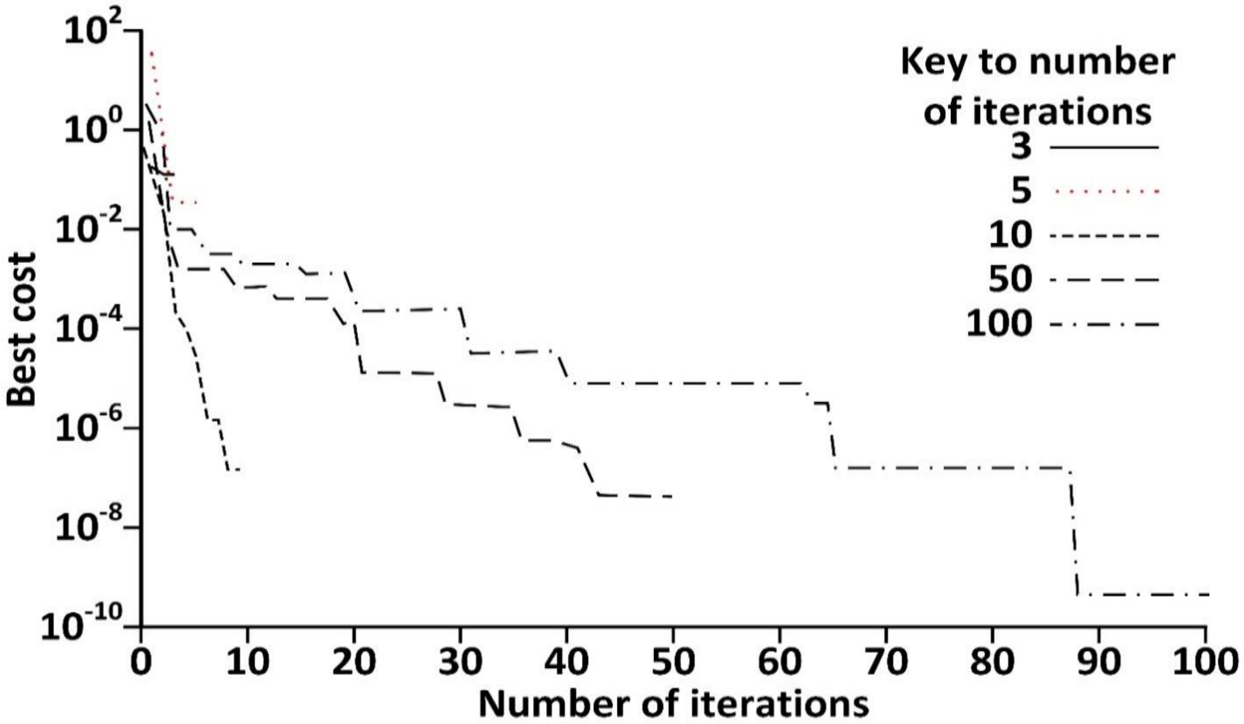


***Figure 15**. IWO parameters with 3, 5, 10, 50 and 100 iterations*

The effective width of the foundation obtained from the algorithm was re-examined in three different cases with B/H equals 1.8.

1)H=30, B=54

In the width B = 50,54 meters and the height of the earthen dam is 30 meters, the changes of acceleration and horizontal displacement of the dam crest have been compared in terms of time and a good match is seen between B=50 and B=54. The optimized horizontal displacement obtained from the IWO algorithm is drawn in the **Figure 16**.

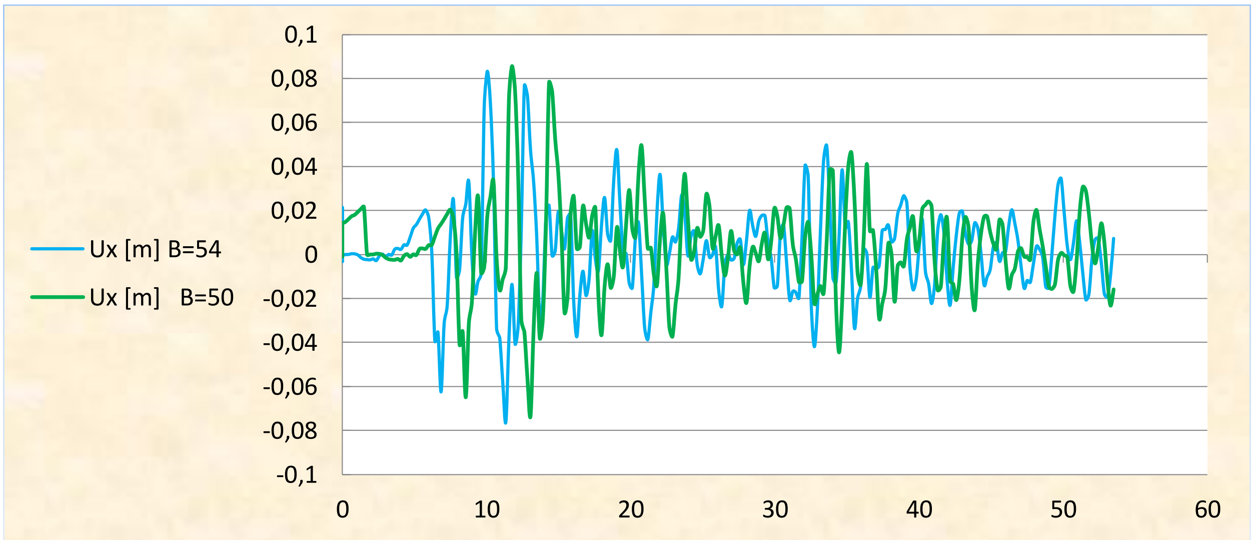


Figure 16. *Horizontal displacement (m) versus time (s).*

2) H=60 ,B=109

In the foundation analysis flanks B=100, 109 meters with the height of the earthen dam of 60 meters, the changes of acceleration and horizontal displacement of the dam crest were compared in terms of time and in this case, a good match was obtained between B=100 and B=109. The optimized horizontal displacement obtained from the IWO algorithm is drawn in the **Figure 17**.

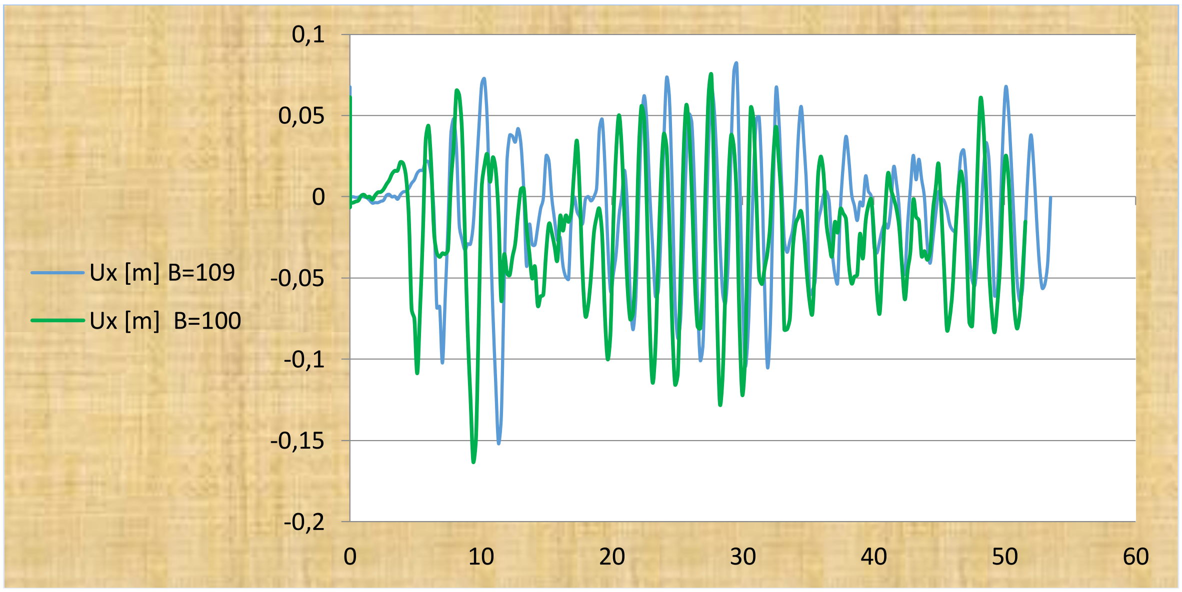


Figure 17. *Horizontal displacement (m) versus time (s).*

3) H=90, B=163

In the foundation analysis flanks B=163, 200 meters with the height of the earthen dam of 90 meters, the changes of acceleration and horizontal displacement of the dam crest were compared in terms of time and in this case, a good match was obtained between B=163 and B=200. The optimized horizontal displacement obtained from the IWO algorithm is drawn in the **Figure 18**.

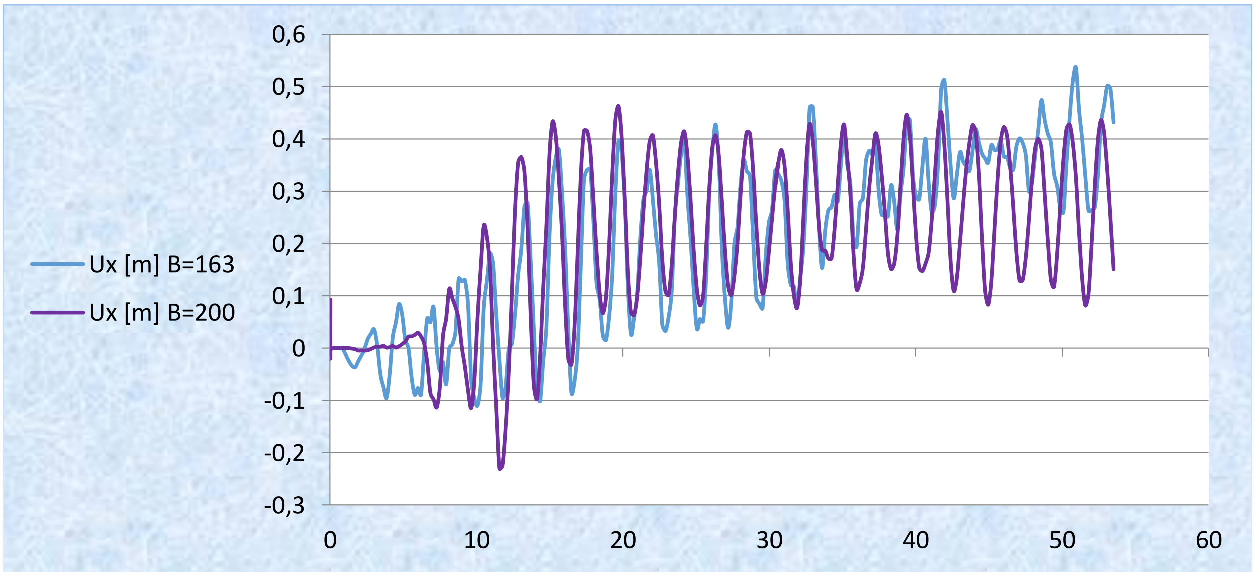


Figure 18. *Horizontal displacement (m) versus time (s).*

Conclusion

In this research the dynamic analysis of a homogeneous earthen dam in Iran was performed under the horizontal component of Manjil earthquake using PLAXIS program. In previous studies, the B/H ratio was approximate. From the obtained results, it can be seen that in the flexible foundation model, the amplitudes of low periods (high frequencies) are reduced or eliminated, and the range of horizontal displacement in the crest of the dam is significantly higher than that of the rigid base model. In the modeling of an earthen dam with a rigid foundation, the vertical acceleration has also been significant. It seems that for dams with rigid foundations, it is necessary to consider the vertical acceleration caused by the earthquake in the horizontal direction. The IWO algorithm was inspired by the behavior of invasive weeds and resulted in a powerful optimization algorithm. By applying the IWO algorithm to the problem of dynamic analysis of the Narmab earth dam, the performance of this algorithm was investigated. In this research, IWO algorithm was used to determine the optimal ratio of the foundation analysis flanks according to the height of the dam.

Acknowledgement

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