*American Journal of Civil Engineering and Architecture, 2014, Vol. 2, No. 5, 167-173*
Available online at http://pubs.sciepub.com/ajcea/2/5/3

DOI:10.12691/ajcea-2-5-3

# The Investigation of Effective Parameters on the Stability of Concrete Gravity Dams with Case Study on Folsom, Blue Stone, and Pine Flat Dams

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*Received September 10, 2014; Revised September 25, 2014; Accepted October 08, 2014*

**Abstract** In this research, the effective parameters in stability of concrete gravity dams in the form of case study on three important dams: Blue stone; Folsom; and Pine Flat, are investigated. Typically, cognition and understanding of effective parameters in stability and knowing the role of each them, in designing new dams, could be very helpful. Concrete gravity dams (which are surveyed in this research) have their strength and stability because of their weight. The shape of their section are triangle and commonly, The base of the triangle is greater than the dam is stable, the more stable dam is. Also, in this investigation we are going to study the horizontal displacement called sliding of dam's bottom, in contact with foundation by ABAQUS software. The sliding displacement has no considerable change in each of the three nodes on heel and toe, and also in middle part of dam, and eventually is equal in each three and all parts of the dam's bottom and foundation. With choosing three nodes on the dam's bottom and similar nodes on the foundation, and with differentiating horizontal displacements of these nodes with each other, the relative displacements of dam are obtained. With using these displacements acquired from ABAQUS software in RS-DAM software, we show them as time series graph and relative displacement. Whenever this graph has a jump with the increase of earthquake PGAs (end of the graph moves away from the starting point of it), dams is considered as unstable.

***Keywords:*** *dam, stability, Pine Flat, Bluestone, Folsom*

**Cite This Article:** Elyas behradimehr, afshin mansouri, babak aminnejad, and mohammad ali barkhordari bafghi, "The Investigation of Effective Parameters on the Stability of Concrete Gravity Dams with Case Study on Folsom, Blue Stone, and Pine Flat Dams." *American Journal of Civil Engineering and Architecture*, vol. 2, no. 5 (2014): 167-173. doi: 10.12691/ajcea-2-5-3.

## 1. Introduction

### 1.1. Utilization as Well as Safety Control

For avoidance of lake incontrollable triggering, 2 main and chief factors must be considered: first, dynamic stability of cracked part which is protect during the earthquake and second, is for the conditions after the earthquake which static stability and foundation are protected respectively against the increase of interaction pressure in the body of dam, and against the decrease of structural strength caused by fracturing or cracking and movement of seams. Inertia forces considerably could increase from the size and amount for beginning the crack of bottom to the value which results in crack in the upper area of dam. For tall dams, when the crack begins in upper area, these cracks tend to extend in brittle form to separate the upper of dam from its bottom. Dynamic stability of asunder upper area is investigated with considering huge overturning and potential sliding displacement from the oscillation nature of earthquake are two inseparable and consistent processes in dams' lifetime. Construction and utilization of mega- structure like dam actually could cause potentially perilous conditions for downstream society, and failure and fracture of dam is an abnormal phenomena which results in flood in downstream and financial and life damages or losses. The amplitude of these damages either in time scale or spatial scale, is very extended and even contributes in the deduction of national credit.

With considering of the information introduced, the safety issue of dam is remarkably important. In fact, because of the high cost of dam's construction, without enough attention to dams' safety could result in misspending of national funds.

## 2. The Purposes of Research Conducting

In this study, the effective parameters in stability control of concrete gravity dams, in form of case study of three important dams: Bluestone; Pine flat; and Folsom, are investigated. It is important to note that our intention and purpose of stability in this study, is mainly instability against sliding which is more important and more probable rather than the other forms of instability and.in this investigation, with the help of CADAM, RSDAM, and ABAQUS software, and after defining the dams inside software and completing modeling, we are identifying more important parameters and specifying their ratio. These parameters could include shear strength parameters like friction, various horizontal and vertical parameters of earthquake, emptiness and fullness of reservoir, material characteristics like elastic module of dam and foundation, and so on. Also, the results of these three software are compared with each other to identify whether there is an obvious relation or not? For example, is there a relation between the relative sliding graph of RSDAM software and ABAQUS? On the most important questions which are exist in this study, is that how elastic or rigid foundation could affect the stability of dam; which means that with more rigid foundation is there any change in stability? The other important point which is the other goals and aims of this investigation, is investigation of the vertical effect of earthquake in compared with vertical parameter. The effect of foundation's weight also is researched in this study. Traditionally, the cognition and understanding of effective parameters in stability and roles of them could considerably help us for the issue of dams designing. Moreover, we are investigating the horizontal displacement of dam in toe, heel, and middle part of the dam.

## 3. Modeling with Using ABAQUS and CADAM Software

First, we are going to introduce and define these under investigated dams in this research which means Bluestone, Pine flat, and Pine. The geometry of these dams and material characteristics of body and foundation are introduced in the beginning of this chapter. The way of modeling in each of them based on it are described. The assumptions done in this study are brought in this chapter

## 4. Blue Stone Dam

This dam was constructed in the late of 1930 on New river near the Hinthen of West Virginia in order to control flood and produce electricity. This dam include rigid blocks which are positioned next to each other and the transition of shear in them is happened with the help of friction between blocks.

### 4.1. Dam Geometry

The length of dam's crest is 629 m which include 241 m spillway, 96 m input basin of power plant, and 292 m support and part which are not spillway. Foundation values in the lowest or deepest point is 415 m and not in the highest point of overflow is 467 m. Eventually, the maximum height of dam is approximately 53 m. The spillway part is controlled with using 21 gates which have 9 m gross and net height. Take to account that the elevation and values of water in upstream spillway in 454 m, it is could be concluded that dam's height in upstream is approximately 40 m. The following Figure shows the general shape of a SARRIZ NASHAVANDEH* block (block number 12).

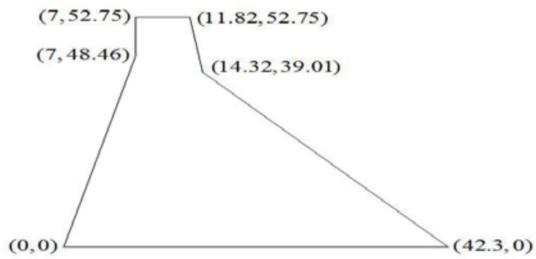


**Figure 1.** Bluestone dam geometry

## 5. Folsom Dam

Folsom dam was constructed between the years of 1948 to 1955 in the north of American River state on Folsom river. This dam is established 25 miles north of the California and in Sacramento City by US army engineers and after the construction USBR is responsible for maintenance and preservation of this dam. The purposes of constructing this dam are flood control, fresh and drink water as well as electricity providing. The cost of construction of this this dam is roughly 81.5 million dollars. Tank's or reservoir's volume of lake is about 1205 million cubic meter.

### 5.1. Dam Geometry

The length of this dam is 427 m. This dam is consisted of 28 blocks with 15.2 width. For analyzing this dam, the highest block which is block number 11 with 82.45 m height, is used. The shape of this block is as follows:

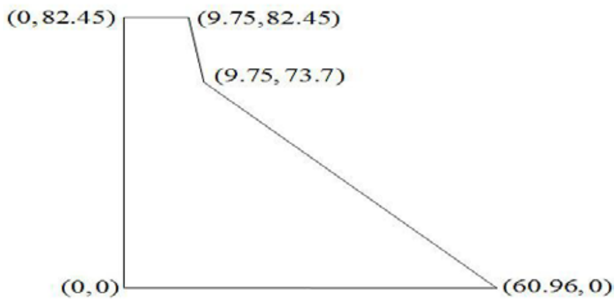


**Figure 2.** Folsom dam geometry

## 6. Pine Flat Dam

This dam is constructed in 1954 at 30 miles east of Fresno on Kings river in order to control flood and provide the water for agriculture and also the lake which is created back of this dam, provides various recreational facilities for tourists.

### 6.1. Dam Geometry

The length of this dam is 560 m. This dam consists 37 blocks with 15.2 width. For analyzing this dam, the highest block with 122 m height is used. The shape of this block is illustrated below

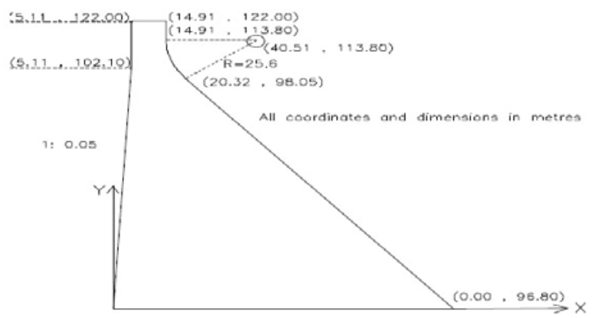


**Figure 3.** Pine flat dam geometry

## 7. Dam's Material Characteristics

**Table 1. Characteristics of materials used in dam**

| Bluestone | | | |
|---|---|---|---|
| Unit | Value | Symbol | characteristic |
| 3kg / m | 2483 | C | Concrete special weight |
| GPa | 33.558 | EC | Concrete elastic module |
| - | 0.255 | C | Concrete poison ratio |
| Folsom | | | |
| Unit | Value | Symbol | characteristic |
| 3kg / m | 2579 | C | Concrete special weight |
| GPa | 40.68 | EC | Concrete elastic module |
| - | 0.19 | C | Concrete poison ratio |
| Pine Flat | | | |
| Unit | Value | Symbol | characteristic |
| 3 kg / m | 2334 | C | Concrete special weight |
| GPa | 29.546 | EC | Concrete elastic module |
| - | 0.232 | C | Concrete poison ratio |

## 8. Foundation's Material Characteristics

**Table 2. Material characteristics which are used in dam's foundation**

| Bluestone | | | |
|---|---|---|---|
| Unit | Value | Symbol | characteristic |
| GPa | 27.25 | $E_f$ | Rock elastic module |
| - | 0.165 | f | Rock poison ratio |
| Folsom | | | |
| Unit | Value | Symbol | characteristic |
| GPa | 54.24 | E f | Rock elastic module |
| - | 0.3 | f | Rock poison ratio |
| Pine Flat | | | |
| Unit | Value | Symbol | characteristic |
| GPa | 27.25 | $E_f$ | Rock elastic module |
| - | 0.165 | f | Rock poison ratio |

In dam vibrated loading, the horizontal parameter of earthquake, Coalinga, is used

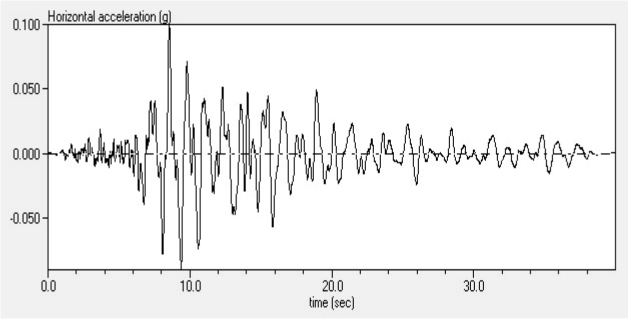


**Figure 4.** Acceleration-time graph of Coalinga earthquake

## 9. Drawing the Model

With using Part module we are going to draw the geometry of dam, foundation, and reservoir.

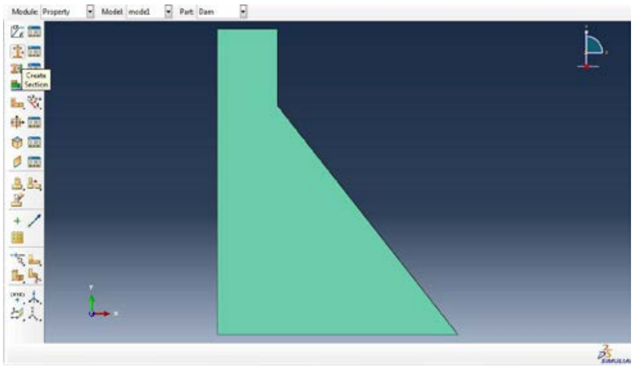

**Figure 5.** Dam geometry drawing in ABAQUS

## 10. Analysis and Conclusion of Analysis

In this paper, the results of dam analysis in CADAM and RSDAM software are presented and these results compared with each other. The effect of horizontal and vertical earthquake in dam stability is also investigated. Then, the results of ABAQUS software are presented and compared with previous software. In this case, the effect of vertical parameter of earthquake, foundation elasticity and its weight are also studied. At the end of this paper, proposal and suggests for further research are expressed.

## 11. The Results of RSDAM and CADAM Software

In this section, the three dam considered in this study are modeled in RSDAM and CADAM based on rigid method. In this case, with increasing PGA, the differences of sliding safety factor was investigated. The results is as following table and because of the page limitation of paper, we bring part of them as an example.

| Eq component | Friction | Reservoir | Software | Dam |
|---|---|---|---|---|
| H | 0.7 | Empty | Cadam And Rsdam | Blue Stone |
| SSF | | | PGA / g | |
| >100 | | | 0 | |
| 7 | | | 0.1 | |
| 3.5 | | | 0.2 | |
| 2.3 | | | 0.3 | |
| 1.7 | | | 0.4 | |
| 1.4 | | | 0.5 | |
| 1.2 | | | 0.6 | |
| 1 | | | 0.7 | |
| | | | 0.8 | |
| | | | 0.9 | |
| | | | 1 | |

| Eq component | Friction | Reservoir | Software | Dam |
|---|---|---|---|---|
| H | 0.7 | Empty | Cadam And Rsdam | Pine Flat |
| SSF | | | PGA / g | |
| >100 | | | 0 | |
| 7 | | | 0.1 | |
| 3.5 | | | 0.2 | |
| 2.3 | | | 0.3 | |
| 1.7 | | | 0.4 | |
| 1.4 | | | 0.5 | |
| 1.2 | | | 0.6 | |
| 1 | | | 0.7 | |
| | | | 0.8 | |
| | | | 0.9 | |
| | | | 1 | |
| | | | | |

| Eq component | Friction | Reservoir | Software | Dam |
|---|---|---|---|---|
| H | 0.7 | Empty | Cadam And Rsdam | Folsom |
| SSF | | | PGA / g | |
| >100 | | | 0 | |
| 7 | | | 0.1 | |
| 3.5 | | | 0.2 | |
| 2.3 | | | 0.3 | |
| 1.7 | | | 0.4 | |
| 1.4 | | | 0.5 | |
| 1.1 | | | 0.6 | |
| 1 | | | 0.7 | |
| | | | 0.8 | |
| | | | 0.9 | |
| | | | 1 | |

With respect to the above tables we can obtain the following results:

11.1.1. The most important result of this part is that the value of safety factor in one particular PGA in CADAM software is same and equal to the minimum safety factor of on earthquake record with the same PGA in RSDAM software.

11.1.2. Friction coefficient 0.7 in almost every dams cause the instability of dam in minor and small earthquake (PGAs are decreased) which that means in friction angle of 35 the probability of instability is very high.

11.1.3. Vertical earthquake has no effect on sliding instability when the reservoir is empty and just increase the tensions.

| Eq component | Friction | Reservoir | Software | Dam |
|---|---|---|---|---|
| H | .7 | Empty | Cadam And Rsdam | Blue Stone |
| SSF | | | PGA / g | |
| >100 | | | 0 | |
| >100 | | | 0.1 | |
| >100 | | | 0.2 | |
| >100 | | | 0.3 | |
| >100 | | | 0.4 | |
| >100 | | | 0.5 | |
| >100 | | | 0.6 | |
| >100 | | | 0.7 | |
| >100 | | | 0.8 | |
| >100 | | | 0.9 | |
| >100 | | | 1 | |

11.1.4. With comparison the results of vertical and horizontal earthquake we can go to a conclusion that the effect of horizontal earthquake is more critical than vertical earthquake.

11.1.5. The other important result is that in some case which the reservoir is empty, sliding safety factor is much bigger than when the reservoir is full. For example we have for one of these cases:

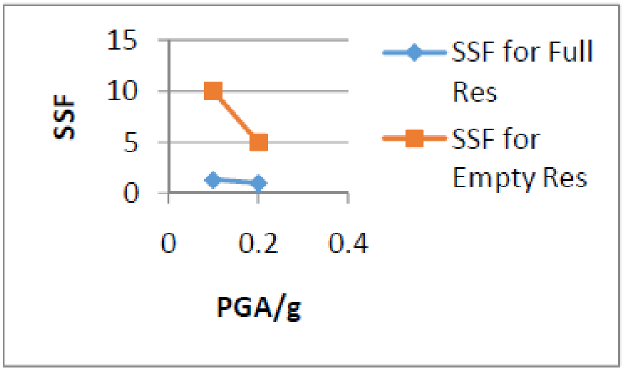


**Figure 6.** The graph from software

11.1.6. Considering the foundation with no weight, increase the responses, because in this case the attenuation due to weight of foundation is disappeared.

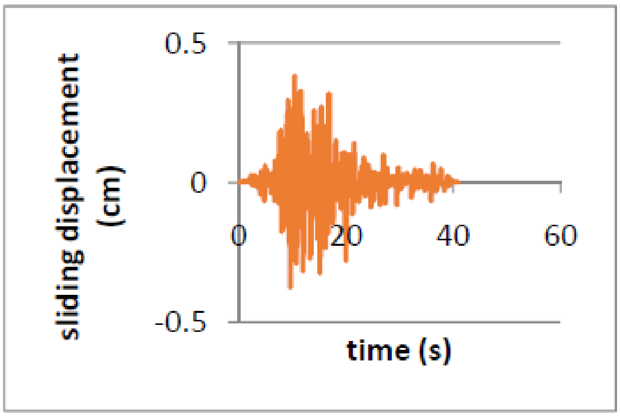


**Figure 7.** Without considering foundation weight

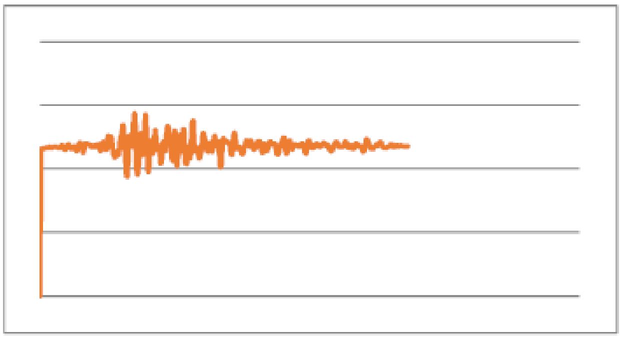

**Figure 8.** With considering foundation weight

11.1.7. The effect of vertical earthquake respects to horizontal earthquake

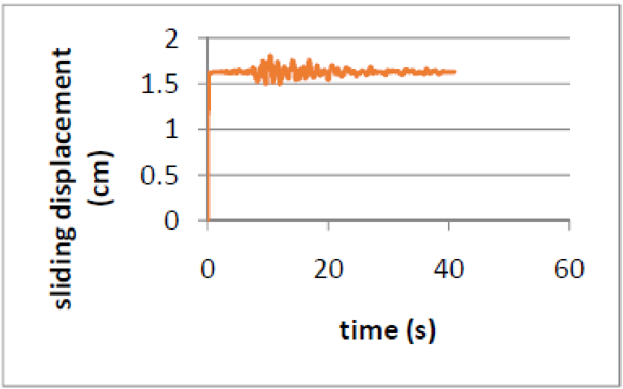


**Figure 9.** Vertical earthquake

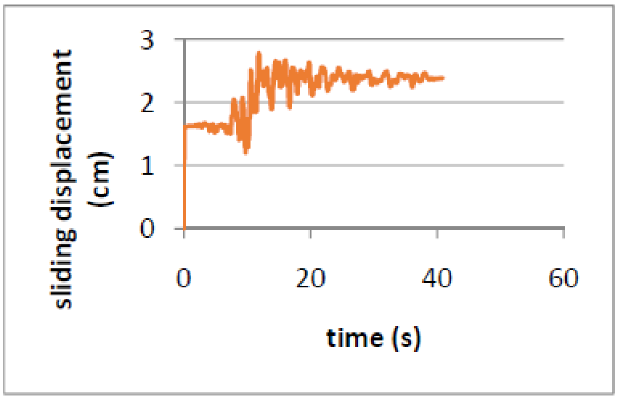


**Figure 10.** Horizontal earthquake

With respect to the previous sample graphs, it could be see that the effect of horizontal earthquake in sliding, almost in most of the times of earthquake is bigger and more than vertical earthquake. But we must pay attention that the movement of vertical earthquake in case and issue of stability (particularly when the reservoir is full) cannot be neglected and is very important.

11.1.8. The effect of $\frac{E_f}{E_c}$ in stability With the analysis done, we conclude that with increasing the $\frac{E_f}{E_c}$ ratio (foundation becomes rigid in respect to dam), sliding displacement reduced, which means that the dam is becomes more stable.

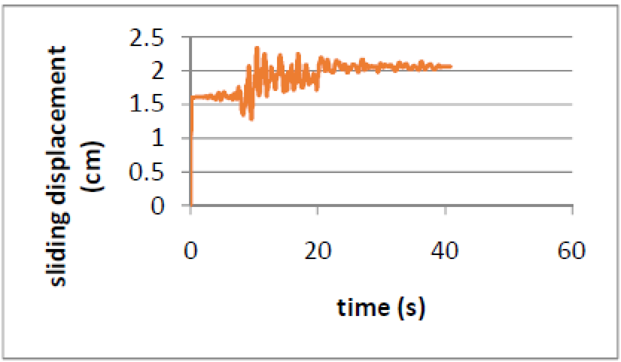


**Figure 11.** Reduction of $\frac{E_f}{E_c}$

With comparing the result of ABAQUS with two RSDAM and CADAM software it could be suggest that in most of the times, instability point in ABAQUS software is happened and positioned in bigger PGA rather than the two others.

## 12. Modeling in ABAQUS

Drawing the model With using the Part module we are going to draw dam, foundation, and reservoir geometry It should be noted here that in this investigation, the dam is considered in two cases: one case without water (like load combination number 4 of US military engineers), and on time full of water (like load combination number 6 of US military engineers). In type of full reservoir, without considering free board respect to the dam height, we consider the height of the water inside the dam is equal to the height of dam and also we assume that there is no water in downstream. The length of lake in considered equal to 5 times of dam height (h). The depth of foundation is also considered as 2 h and from

The Figure below illustrates the geometry of dam, reservoir, and foundation.

Then, with choosing three nodes on dam's bottom and also three analogous nodes on foundation and differentiating the horizontal displacement of these nodes with each other, the relative displacement of dam is acquired. With using these obtained displacement form ABAQUS in RS-DARM, we show them as time series and relative displacement graph. Whenever this graph faces a jump with increase of PGA (end of the graph moves respect to the beginning of it), the dam is considered as unstable.

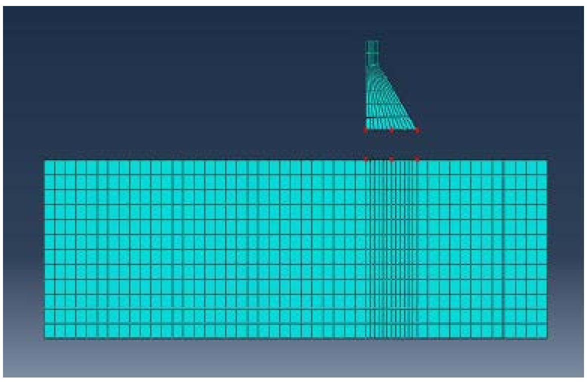

**Figure 12.** The location of nodes in ABAQUS software

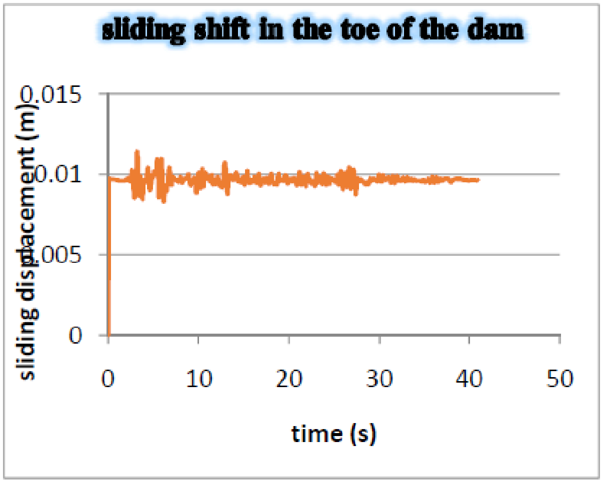


**Figure 13.** Sliding displacement graph in dam toe in RS-DAM software

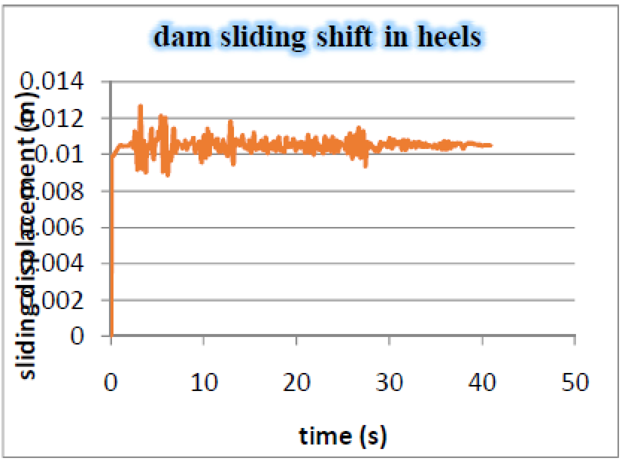


**Figure 14.** Sliding displacement graph in dam heel in RS-DAM software

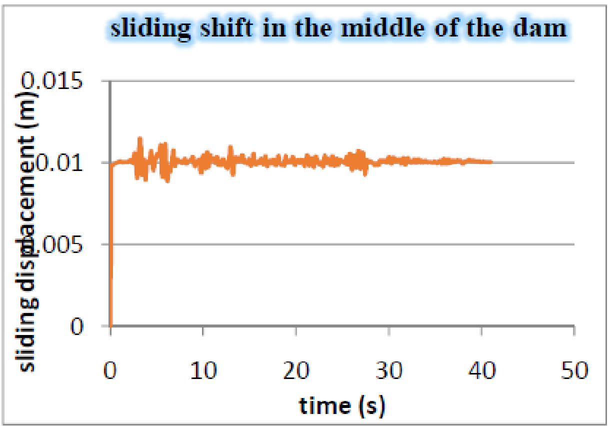


**Figure 15.** Sliding displacement graph in dam middle part in RS-DAM software

As we see in Figure 13, Figure 14, and Figure 15, sliding displacement in all three nodes in heel, toe, and also in middle part of dam has no significant different and change. As a result, displacement in all three nodes is equal and has the same scenario in all parts of dam bottom and foundation.

## 13. Conclusion

1. The safety factor value in one particular PGA in CADAM software equals to the minimum safety factor due to one earthquake record with the same PGA in RSDAM software.
2. Friction coefficient 0.7 in the most of dams leads to instability in minor and small earthquake which means that in roughly 35 degree friction angle the probability of instability of dam is high.
3. Vertical earthquake in some situations which the dam reservoir is empty does nothing and has no effect on sliding instability and just increases the tensions.
4. With comparing the results from horizontal earthquake could be conclude that the effect of horizontal earthquake is more significant and critical than vertical earthquake.
5. The other important result is that in some cases which the reservoir is empty, the sliding safety factor is much bigger rather than the reservoir is full. For example, for on mode and case we also have:
6. Considering foundation without weight leads to increase in responses, because in this case attenuation due to weight of foundation is disappeared. In respect to the analysis done on dam, we come to a result that with the increase in Ef ratio (foundation becomes more rigid EC respect to dam), sliding displacement is decreased which means that the dam in more stable.
7. About comparing the results of ABAQUS with CADAM and RSDAM software, we could also suggest that in almost every case, the instability point in ABAQUS software, is happened at higher PGA in contrast to two others software.
8. Sliding displacement in all three nodes in heel, toe, and middle part of dam has no significant differences which means that is equal in all three nodes and all parts of dam bottom and foundation.

## 14. Suggestions and Proposals for Further Research

1. Considering concrete non-linear behavior in stability analysis.
2. Investigate and considering the adherence effect between dam and foundation in ABAQUS software.
3. Studying the effects of foundation non-linear behavior in stability of concrete gravity dams.
4. The comparison between dams stability and maximum applied tensions in them.
5. Investigate the collapse of concrete gravity dams with finite element method.

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