



Research Article

## Effect of Inclination and Stiffness of Asphalt Concrete Core on Analysis of Rockfill Dams

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### Abstract

This study investigates the influence of the geometric placement of asphalt concrete cores on the performance of rockfill dams, comparing vertical and inclined configurations under both construction and steady-state conditions. Although traditional clay cores are widely available and exhibit low permeability, their limitations—such as low shear resistance, prolonged construction time, and high material volume—have led to a growing preference for asphalt concrete cores. Using GeoStudio 2021 for numerical modelling, this research conducts static and dynamic analyses to assess the effects of core stiffness and geometric positioning. The findings reveal that an inclined asphalt core experiences less settlement by the end of construction compared to a vertical core. However, due to its placement in the upper section of the dam, the inclined core exhibits greater horizontal displacement. This study highlights the critical role of core geometry in dam stability and deformation behaviour, providing key insights for optimizing the design of asphalt concrete cores in rockfill dams.

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## Introduction

For an extended period, clay cores have commonly been utilized in embankment dams to serve as a sealing component within the dam structure. Dams with asphalt concrete core are one of the important options in designing embankment and rockfill dams, especially in areas that suffer from lack of fine grain materials with good quality and appropriate quantity for constructing clay core dams (ICOLD, 1982). Advantages of this kind of dam are lack of cracks and appropriate impermeability, not being sensitive to different climate conditions, sluicing during construction, self-repairing capacity of core material, flexibility and deformability, durability and resistance against continuous seepage, relative resistance against earthquake and high security in war conditions (Hoeg, 1998). Good contact also exists between the asphalt concrete core and the material of the embankment (ICOLD, 1992).

Several cases of this type of dam have been constructed over the world. Lefebvre and Duncan (1974) studied some of the factors leading to transverse cracking in low-embankment dams using finite element analysis. The factors studied were the analysis procedure, gravity turn-on or construction sequence, the magnitude and time of occurrence of the settlement of the dam, the stress-strain characteristics of the dam material, and the shape of the abutment profile. Chugh (1983) conducted one-dimensional wave propagation method for earthquake response analysis of horizontally-layered sites of infinite lateral extent is adapted to account for the finite cross-sectional dimensions of an embankment dam overlying a foundation deposit which may be considered infinite in its lateral extent. A two-dimensional dynamic finite element analysis was also performed for that case. The comparisons of computed and observed responses support the modified use of the simple numerical procedure. Zhao et al. (1993) carried out a systematic investigation into the effect of both the type of impervious members and the reservoir bottom sediment on the dynamic response of embankment dams using the finite and infinite element coupled method. Tancev and Kokalanov (1995) developed an incremental, nonlinear finite element procedure,

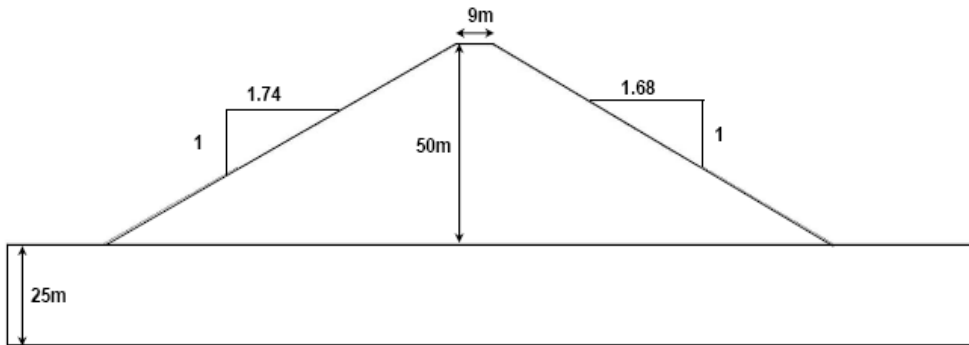
suitable for deformation, stress and stability analysis of embankment dams with waterproof elements other than earth. The procedure was applied for analysis of hypothetical rock-fill dams with asphaltic facing and an internal asphaltic core -vertical and inclined. Studies were carried out to understand the prototype behavior of these types of rock-fill dams. Both rock-fill and asphalt behavior were modeled by using hyperbolic relations. Akkose et al. (2007) studied the stochastic seismic response of a rock-fill dam by the finite element method. The Keban dam constructed in Elazig, Turkey was chosen as a numerical example. The interaction of the rock-fill dam with the reservoir was neglected, but not the foundation rock. Tanaka (2007) studied the elastoplastic and viscoelastic constitutive relations with the kinematic strain hardening-softening model. A generalized return-mapping algorithm was applied to solution methods of the problems. The dynamic relaxation method for static problems and the dynamic analysis for earthquake responses were solved based on finite element methods. Moayed and Ramazanpour (2008) studied the dynamic behavior of a zoned core earth-fill dam which due to lack of suitable clay materials, the dam was designed as the zoned core that was composed of three vertical zones including a Central Lean (CL) clay core and two-sided clayey Gravel Layers (GC). The seismic behavior of the dam was analyzed in two cases including a homogenous clayey core and a zoned core by the finite element method. The results showed that the displacements, accelerations and spectral response in the simple core are more than zoned core. Tsompanakis et al. (2009) focused on the simulation of the seismic response of a typical embankment using artificial neural networks. The dynamic response of the embankment was evaluated utilizing the finite-element method, where the nonlinear behavior of the geo-materials can be taken into account by an equivalent-linear procedure.

Despite these advancements, no study to date has systematically investigated the influence of the geometric positioning (e.g., vertical vs. inclined) of an asphalt concrete core on dam performance under both static and dynamic conditions. Addressing this gap, the present study evaluates the behavior of vertical and inclined asphalt cores

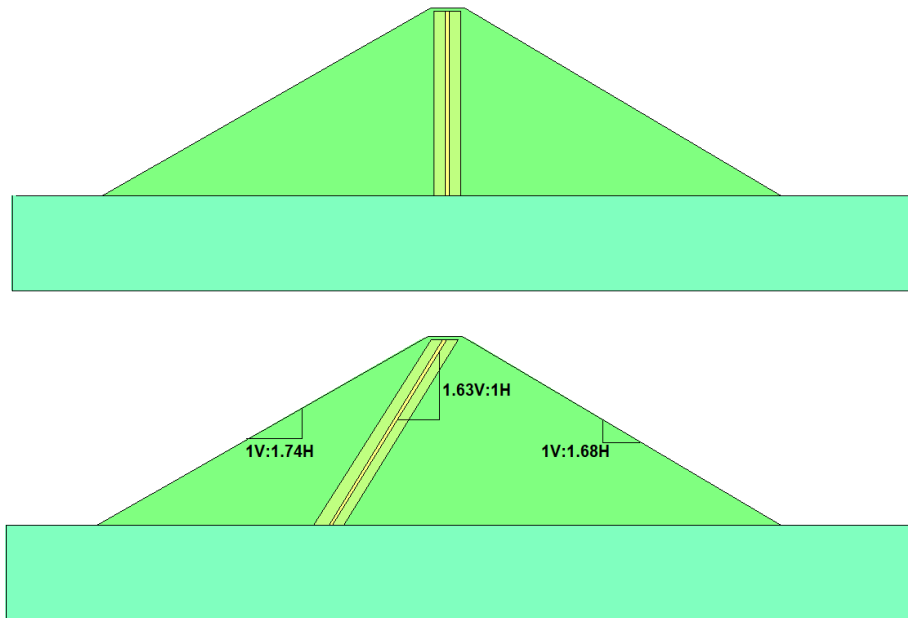
in rockfill dams during construction and steady-state operation using GeoStudio 2021. The software’s integrated capabilities in slope stability, groundwater flow, and stress-deformation analysis are leveraged to assess core stiffness effects, providing new insights into optimal core configurations for enhanced dam safety and longevity.

**Specifications of the rockfill dam with an asphalt core**

For the analysis of the asphalt core dam, Abolfares Dam has been selected as a case study. Abolfares Dam is located on the Abolfares River, 30 km from Ramhormoz city in Khuzestan province of Iran. The overall section of the dam is the same for both vertical and inclined asphalt core dams (Figure 1). The cross-section of the dam with a vertical and inclined core is shown in Figure 2. The dam's height is 50 meters, and the asphalt core extends one meter below the dam crest.



**Figure 1:** The overall Cross-section of Abolfares dam



**Figure 2:** Cross-section of the dam with the vertical and inclined asphalt core

The upper shell slope is considered as 1V:1.74H and the lower shell slope is considered as 1V:1.68H. A 1-meter-thick asphalt core is planned, with two 3-meter-thick filters on each

side covering the entire core. The same conditions apply to rockfill dams with inclined asphalt cores. The core and filters in this type of dam have a slope of 1.63V:1H. According to geological

studies, a layer of almost 25 meters of claystone is located under the body of the dam. The water level of the dam reservoir is 40 meters in steady state condition.

The specifications of the dam materials have been selected based on the evaluation of several dams under similar conditions to Abolfars Dam conditions (Adikari et al., 1988; Hoeg, 1998; Zhao et al., 1993). The static analysis was carried out using Duncan and Chang's behavioral model (Duncan and Chang, 1970). Duncan and Chang's nonlinear stress-strain curve is hyperbolic in shear stress space in terms of axial strain, which produces three types of modules according to the stress state and stress path. These three modules include the initial elastic modulus (Ei), tangential (Et), and loading-reloading modulus (Eur) which are shown in Figure 3.

Ei (Initial Tangent Modulus) is the initial stiffness of the soil at very small strains (slope of the stress-strain curve at the origin) Calculated Based on the following formula:

$$E_i = K.P_a \left( \frac{\sigma_3}{P_a} \right)^n \tag{1}$$

Where, K: modulus number (dimensionless), n: modulus exponent (dimensionless), Pa: atmospheric pressure (reference pressure, ~100 kPa).

Eur (Unloading-Reloading Modulus) is the stiffness of the soil during unloading and reloading cycles (usually higher than Ei) Calculated Based

on the following formula:

$$E_i = Kur.P_a \left( \frac{\sigma_3}{P_a} \right)^n \tag{2}$$

Where, Kur: unloading-reloading modulus number, strength parameters include the following parameters:

c (Cohesion): shear strength intercept at zero normal stress (from Mohr-Coulomb failure criterion), φ (Friction Angle): angle of internal friction (deg), determining shear strength increase with confining pressure, Rf (Failure Ratio): ratio of asymptotic shear strength to actual shear strength as following:

$$Rf = Kur.P_a \left( \frac{[\sigma_1 - \sigma_3]_f}{[\sigma_1 - \sigma_3]_{ult}} \right)^n \tag{3}$$

Where,  $[\sigma_1 - \sigma_3]_f$  (Deviatoric Stress at Failure): actual peak shear stress from Mohr-Coulomb and  $[\sigma_1 - \sigma_3]_{ult}$  (Ultimate Deviatoric Stress): theoretical maximum stress difference at infinite strain.

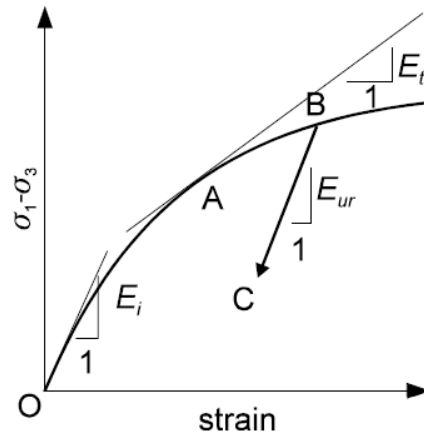
Pressure-Dependent Parameters include the following parameters:

m (Modulus Exponent for Et): controls how stiffness changes with confining pressure (σ3) and

Kb (Bulk Modulus Number): for volumetric response in some advanced versions.

**Table 1:** Parameters of Duncan and Chang model

Model	Parameters of Asphaltic core dam			
	asphalt core	filter	shell	foundation
	Nonlinear-Elastic	Nonlinear-Elastic	Nonlinear-Elastic	Linear-Elastic
Soil Unit Weight(kN/m <sup>3</sup> )	24	21	20.5	22
K(dimensionless)	1110	235	800	
v	0	0	0	0.4
n(dimensionless)	0.10	0.25	0.40	
Cohesion(kPa)	360	0	40	350
Phi(Degree)	28	47	43	35
R <sub>t</sub> (dimensionless)	0.90	0.90	0.90	
Phi B(Degree)	0.5	0.5	0.5	
E <sub>i</sub> (kPa)	0	0	0	2E+05
K <sub>ur</sub> (dimensionless)	1400	1000	950	
K <sub>b</sub> (dimensionless)	3600	1300	600	
m(dimensionless)	0.28	0.40	0.70	

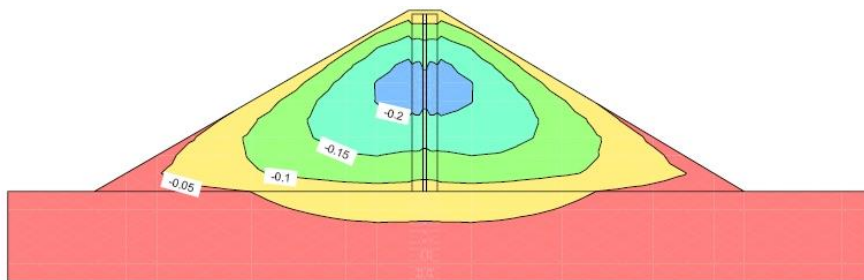


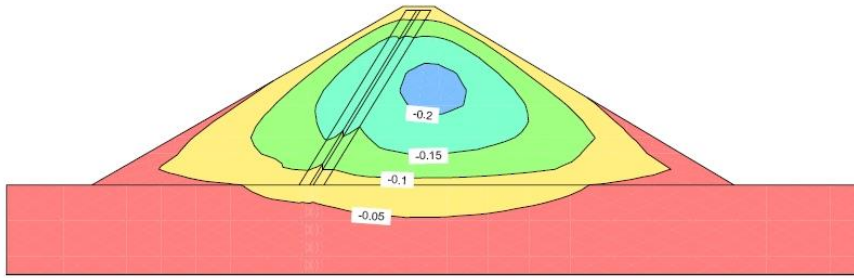
**Figure 3.** Duncan and Chang's nonlinear stress-strain curve (Duncan and Chang, 1970)

### Results of static analysis at the end of construction conditions

To examine the vertical and horizontal displacements at the end of construction, stress-strain analysis was performed on the specified model using SIGMA software in GeoStudio. At this stage, to create construction end conditions, it was assumed that the dam was constructed in 10 stages. Considering the construction stages in a detailed analysis of vertical displacements at the end of construction is very effective. It is necessary to mention that if the construction stages of the dam are not considered, the value of vertical displacements at the end of construction will be much greater than reality. Figure 4 shows the changes in vertical displacement at the end of construction in the dam body, while Figure 5 compares the vertical displacement in the constructed height. Figure 6 illustrates the changes in horizontal displacements at the end of

construction in the dam body. Based on Figure 4, the maximum vertical displacement in a dam with a vertical asphalt core is at one-third of the core's height, decreasing as it moves toward the shell. Conversely, for a dam with an inclined core, maximum vertical displacement occurs in the middle third of the dam's height, under the crest (not in the core). As we can see in Figures 4 and 6, the horizontal and vertical displacements at the end of the construction in the dam with a vertical asphalt core have a symmetry to the core, which is not observed in the dam with an inclined core. The maximum vertical deformation obtained is 22 centimeters for a dam with a vertical asphalt core and 21 centimeters for a dam with an inclined asphalt core. According to the USBR (U.S. Bureau of Reclamation), the allowable total settlement for embankment dams during or after construction is typically limited to 0.5–1% of the dam height (e.g., 25–50 cm for a 50 m-high dam).

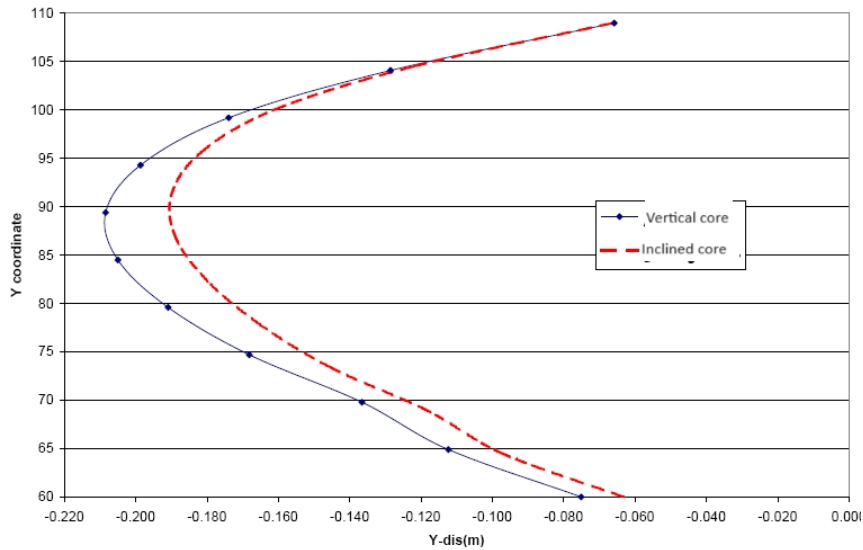




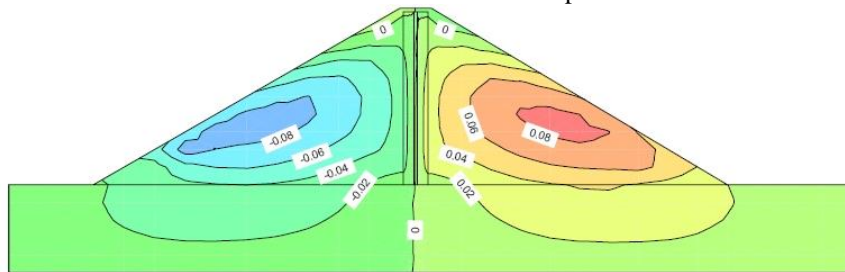
**Figure 4:** Comparison of vertical displacement at the end of the construction in the dam body with inclined and vertical asphalt core (m)

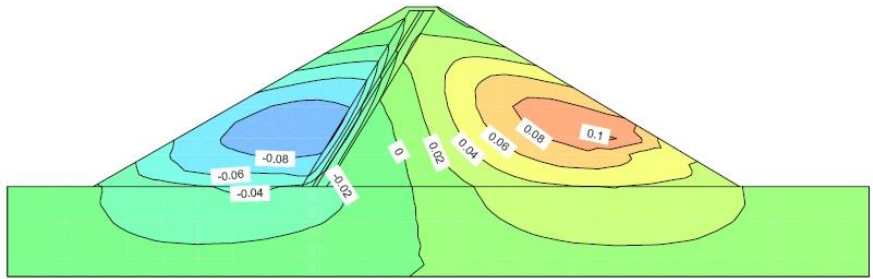
The negative sign in the numbers on the Figures indicates displacement downwards. According to Figure 6 for the dam with a vertical asphalt core, the maximum horizontal displacement has occurred in the upper and lower flanks of the shell, which decreases in intensity as it approaches the core and approximately reaches zero in the core. While in the dam with an inclined core, due to the

positioning of the core in the lower part, the horizontal displacement reaches points of the core, even up to 5.5 centimeters. The negative sign in the numbers on the figure indicates displacement towards the upper part of the dam, and positive numbers indicate displacement towards the lower part of the dam.



**Figure 5:** Comparison of the amount of vertical movement in the height of the core at the end of the construction between the inclined and vertical asphalt core



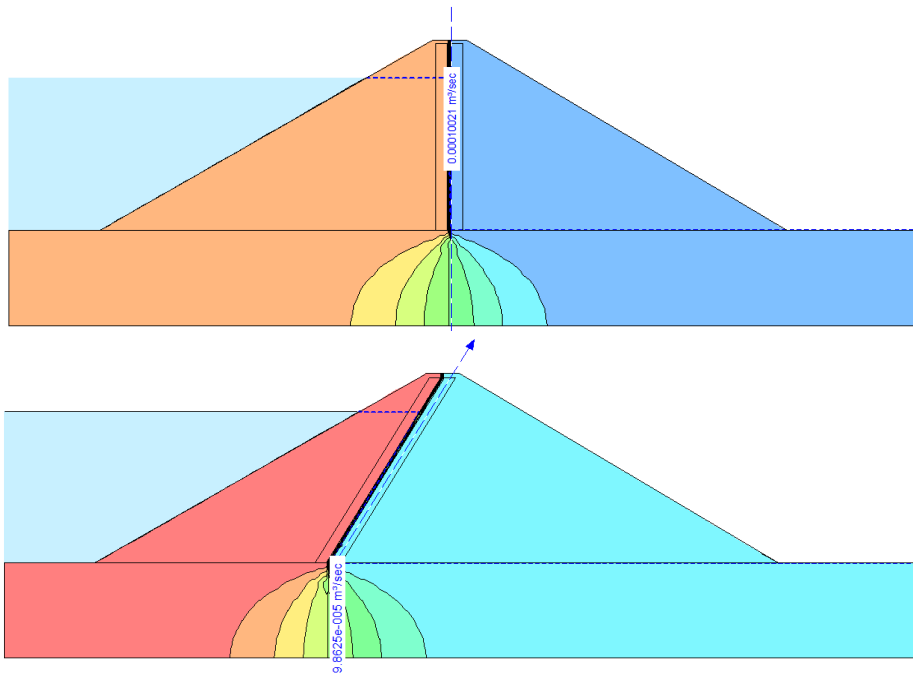


**Figure 6:** Comparison of horizontal displacement at the end of construction in the dam body with inclined and vertical asphalt core (meters).

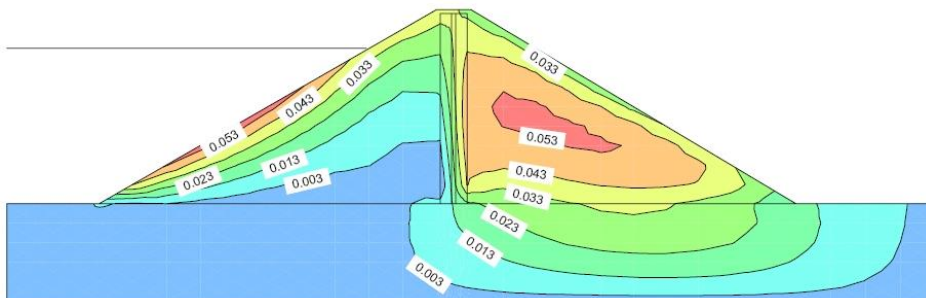
The result of static analysis in steady state condition

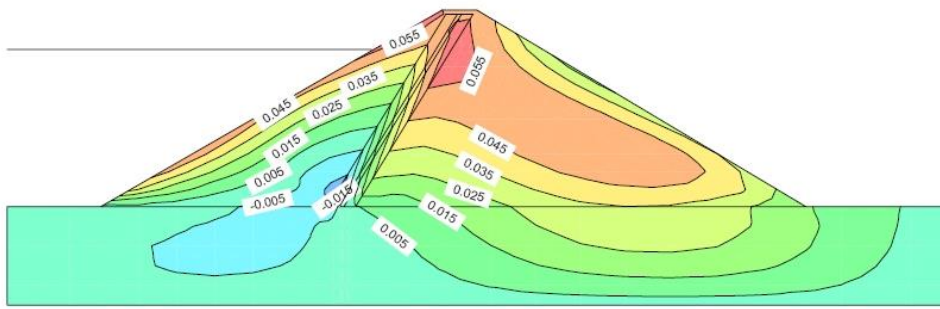
To evaluate the steady state condition, it is essential to conduct a seepage analysis on the dam body using SEEP software in GeoStudio. The results of the seepage analysis are presented in Figure 7. The output flow rate from the dam body

for the vertical asphalt core dam is  $1 \times [10]^{-4}$  cubic meters per second, and for an inclined asphalt core dam is  $9.86 \times [10]^{-5}$ . Using the seepage analysis results, stress and strain analysis were performed in a steady state condition, and the results are shown in Figures 8 to 11.



**Figure 7:** Total head contours of seepage results from the dam body with an inclined and vertical asphalt core

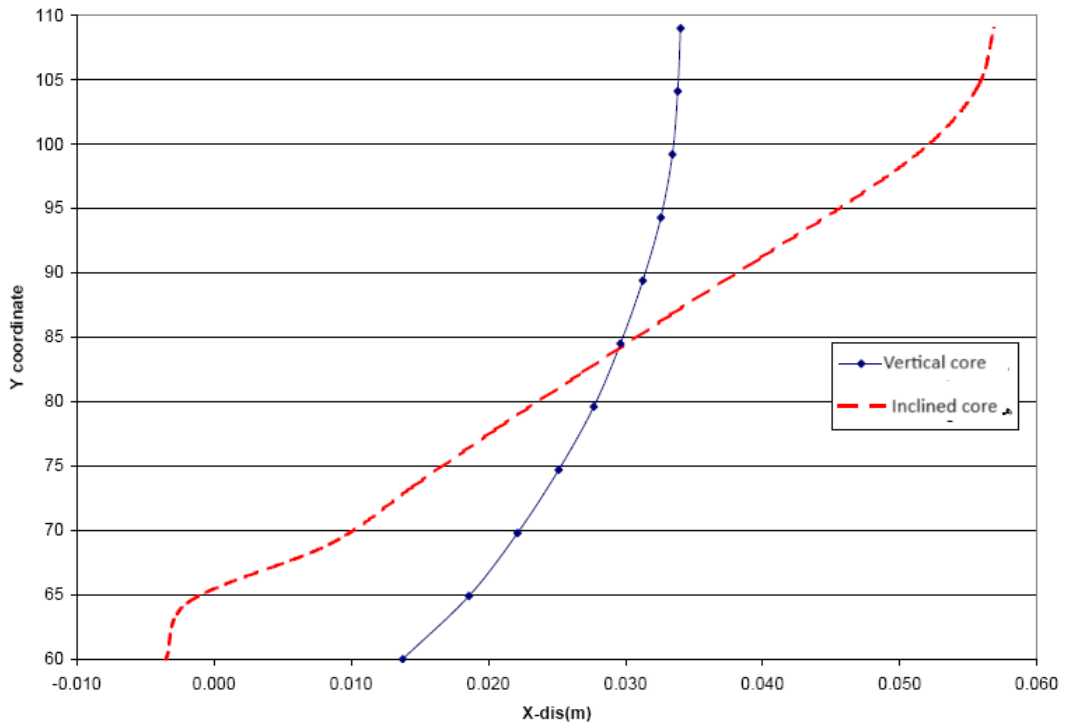




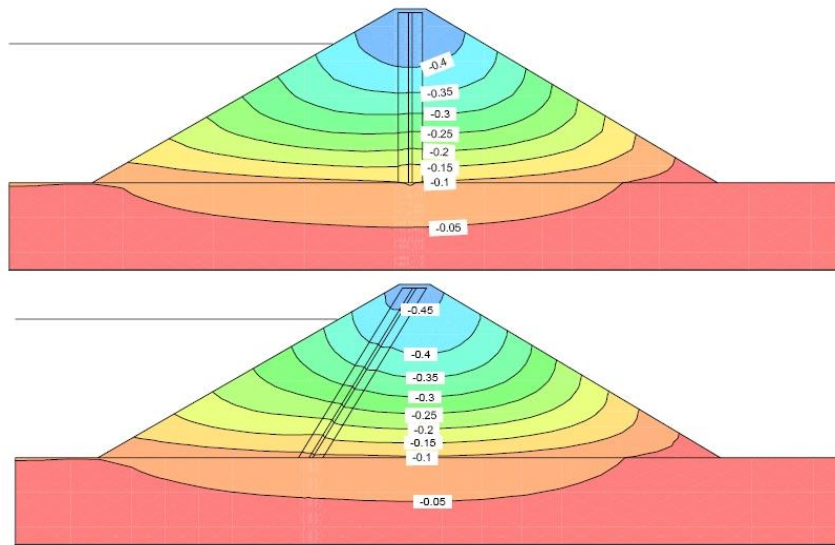
**Figure 8:** Comparison of horizontal displacement in steady state condition between dam with inclined and vertical asphalt core

The result in Figure 8 indicates that the horizontal deformation of the dam is in a steady state, it is noted that the maximum horizontal displacement for a vertical asphalt core dam is 5.3 cm at the upper slope near the reservoir bottom and in the central part of the downstream side, whereas, for an inclined asphalt core dam, this displacement is 5.5 cm and occurred in the upper part of the core and filter in an upward slope. The result in Figure 9 shows that the maximum x-displacement in the

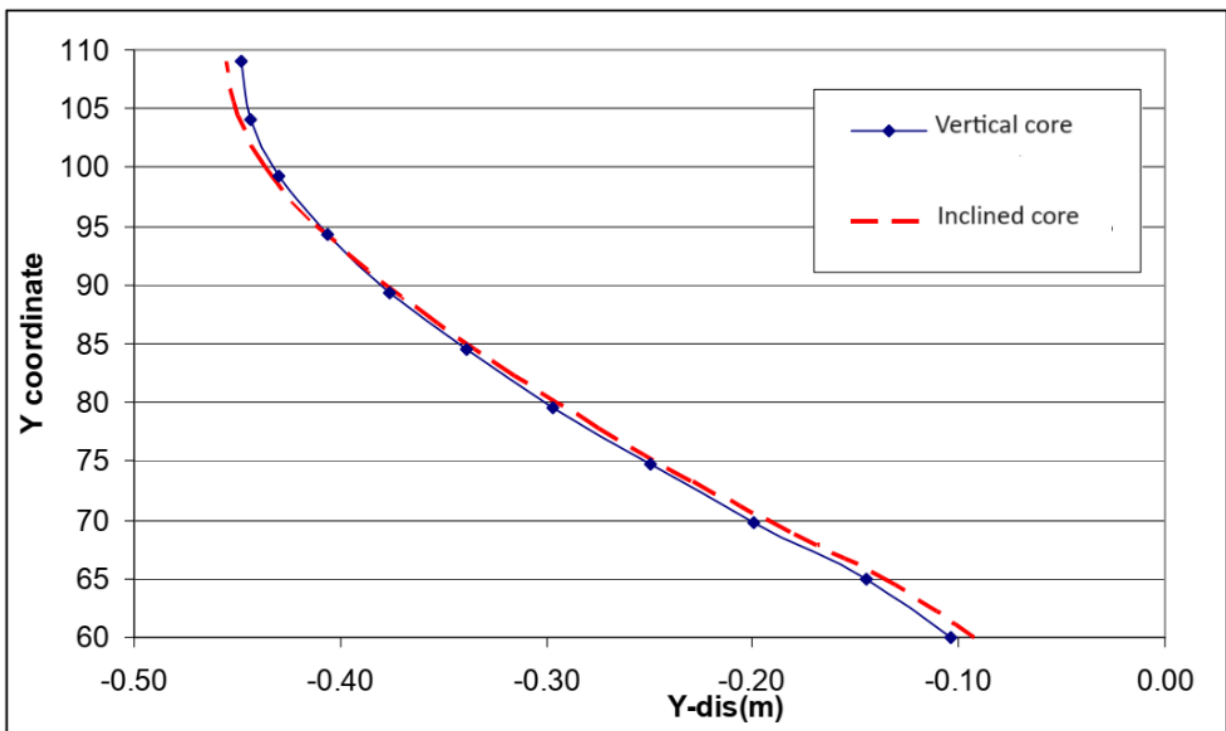
height of the inclined core is almost 6 cm while this value for the vertical core is 3 cm. Additionally, based on Figure 10, the greatest vertical displacement for a vertical asphalt core dam is 45 centimeters at the one-third upper part of the dam body's center, and for an inclined asphalt core dam is 46 centimeters. Furthermore, Figure 11 shows that the vertical displacement in steady state condition has not changed with the inclination of the asphalt core.



**Figure 9:** Comparison of horizontal displacement in the height of the core at steady state conditions between inclined and vertical asphalt core



**Figure 10:** Comparison of vertical displacement in steady state condition between dam with vertical and inclined asphalt core



**Figure 11:** Comparison of vertical displacement in the height of the core in steady state condition between inclined and vertical asphalt core

**Sensitivity Analysis**  
**Effect of the asphalt core stiffness on Static analysis**

To investigate the effect of asphalt core stiffness on the results of static analysis in the end

of construction and steady state condition, six different values are considered for the modulus of elasticity. These values are equal to 1e+5, 2e+5, 5e+5, 1e+6, 2e+6, 5e+6 kilopascals. The wide range of modulus of elasticity (E) for asphalt concrete core (from 1×10<sup>5</sup> kPa to 5×10<sup>6</sup> kPa) is

justified by the material's viscoelastic behavior, which is highly influenced by temperature, loading rate, aging, and mix composition. At high temperatures (40–60°C), asphalt softens, exhibiting a lower modulus ( $E \approx 1 \times 10^5$  to  $5 \times 10^5$  kPa), while at intermediate temperatures (20–30°C), it reaches  $E \approx 5 \times 10^5$  to  $2 \times 10^6$  kPa, and at low temperatures ( $< 0^\circ\text{C}$ ), it behaves nearly elastically with  $E \approx 1 \times 10^6$  to  $5 \times 10^6$  kPa. Loading rate also plays a critical role, where fast dynamic loads result in higher stiffness ( $E \approx 1 \times 10^6$  to  $5 \times 10^6$  kPa), whereas slow or sustained loading (e.g., creep) reduces stiffness ( $E \approx 1 \times 10^5$  to  $1 \times 10^6$  kPa). Additionally,

aging hardens the binder, increasing stiffness ( $E > 2 \times 10^6$  kPa), while mix composition variations—such as soft binders and high air voids—lower stiffness ( $E \approx 1 \times 10^5$  to  $1 \times 10^6$  kPa), and polymer-modified or dense-graded mixes enhance it ( $E \approx 1 \times 10^6$  to  $5 \times 10^6$  kPa). This broad range ensures realistic representation across different environmental and loading condition (Nie et al. 2022). The results of this study are presented in Figure 12 for vertical displacement in the end of construction state and in Figures 13 and 14 for horizontal and vertical displacements in the steady state condition.

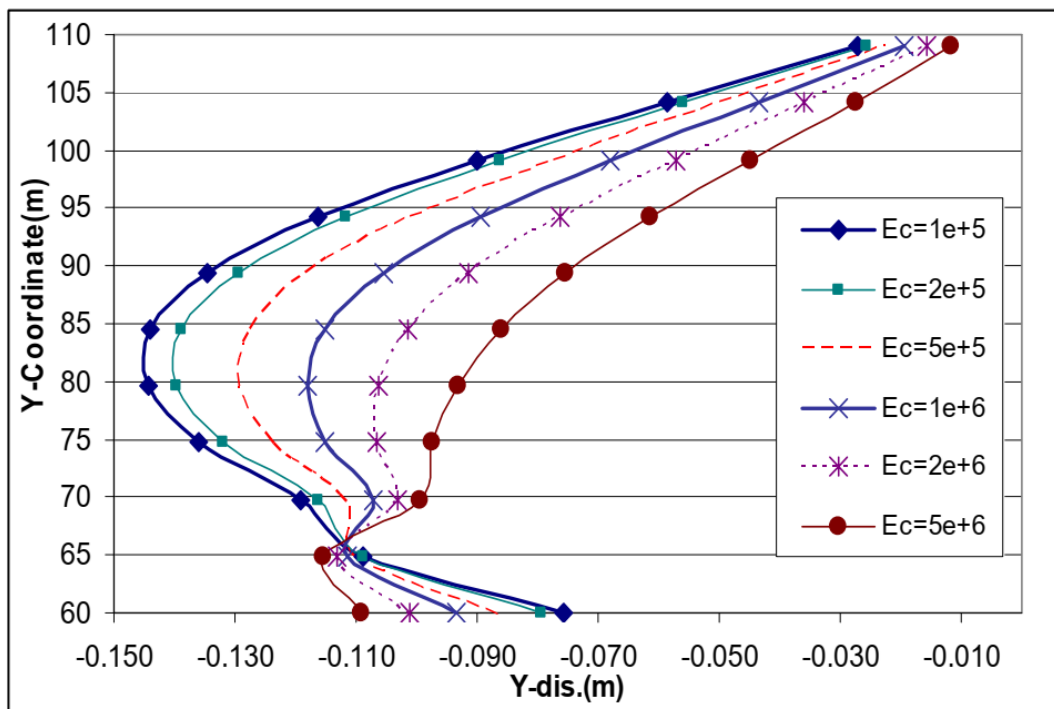


Figure 12: The effect of core stiffness on vertical displacement at the end of construction

As observed in Figure 12, for the end of construction state, an increase in the core stiffness reduces the vertical settlement of the core. For instance, the maximum vertical displacement for a core stiffness of  $1e+5$  kPa is approximately 14.4 centimeters and occurs around the middle of the

core height. With an increase in core stiffness, the location of maximum vertical displacement shifts approximately 10% lower along the core height, so for a stiffness of  $5e+6$  kPa, this value has decreased to 11.5 centimeters.

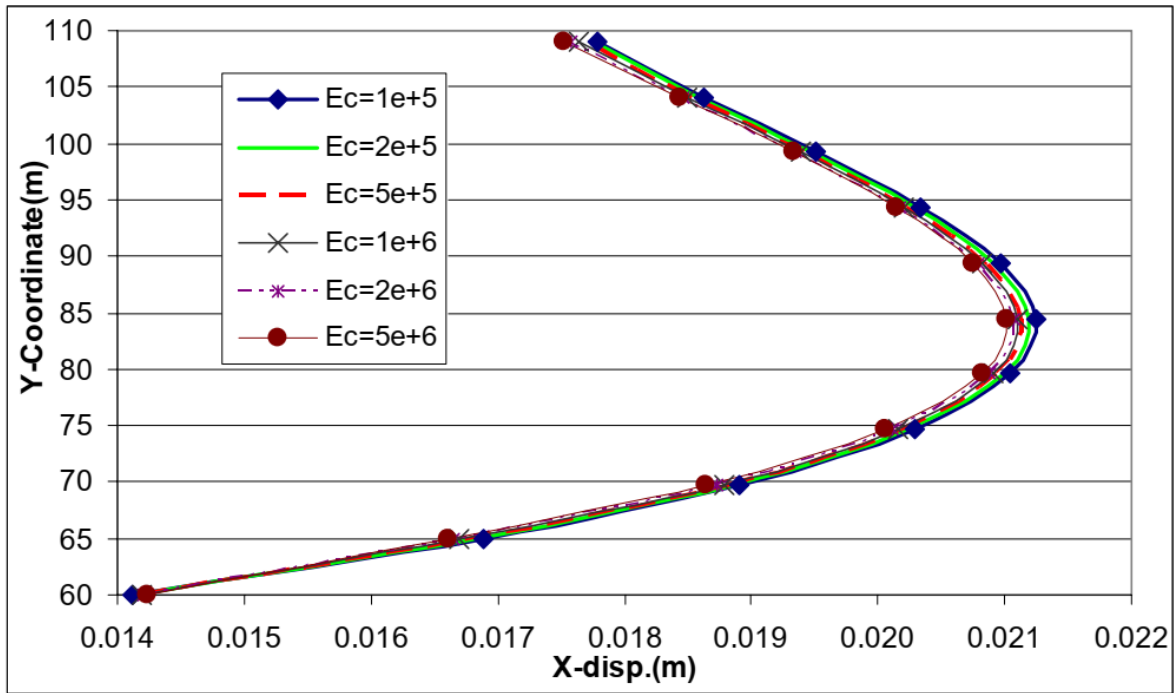


Figure 13: The effect of core stiffness on horizontal displacement in steady-state conditions

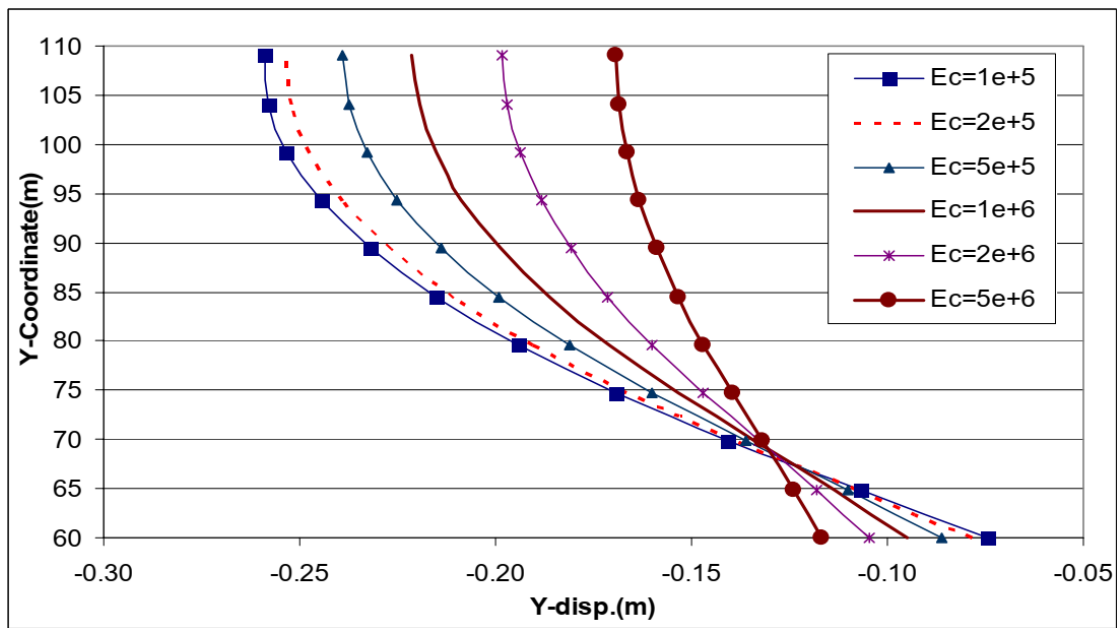


Figure 14: The effect of core stiffness on vertical displacement in steady-state conditions

In a steady seepage state, the effect of the core stiffness on horizontal displacement is not significant (Figure 13). The maximum horizontal displacement for the core stiffness of  $1e+5$  kPa is 2.12 cm, and for the core stiffness of  $5e+6$  kPa is 2.1 cm. However, its effect on vertical displacement is more prominent, with the maximum vertical displacement for core stiffness of  $1e+5$  kPa being 25.9 cm, and for core stiffness

of  $5e+6$  kPa being 16.9 cm (Figure 14). Overall, increasing core stiffness has reduced both vertical and horizontal displacements of the core in a steady state condition.

### Effect of the Foundation stiffness on Static analysis

To investigate the effect of Foundation stiffness on the results of static analysis in the end of

construction and steady state condition, six different values are considered for the modulus of elasticity. These values are equal to  $1e+5$ ,  $2e+5$ ,  $5e+5$ ,  $1e+6$ ,  $2e+6$ ,  $5e+6$  kilopascals. The results of this study are presented in Figure 15 for vertical displacement in the end of construction state and in Figures 16 and 17 for horizontal and vertical displacements in the steady state condition. As

observed in Figure 15, for the end of the construction state, an increase in the Foundation stiffness reduces the vertical settlement of the core especially at the junction of the foundation and the body of dam. On the other hand, the results show that by increasing the stiffness of the foundation from the value of  $5e+6$ , little to no change is observed in the vertical displacement profile.

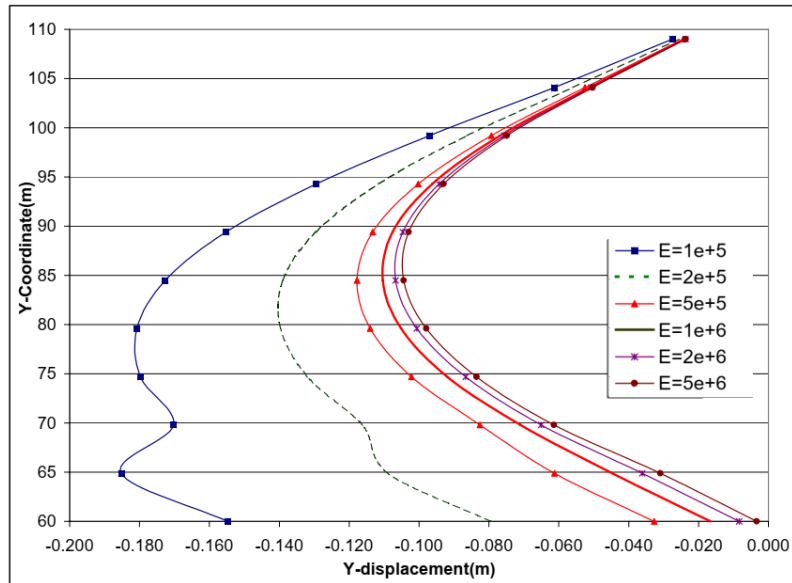


Figure 15: The effect of Foundation stiffness on vertical displacement at the end of construction

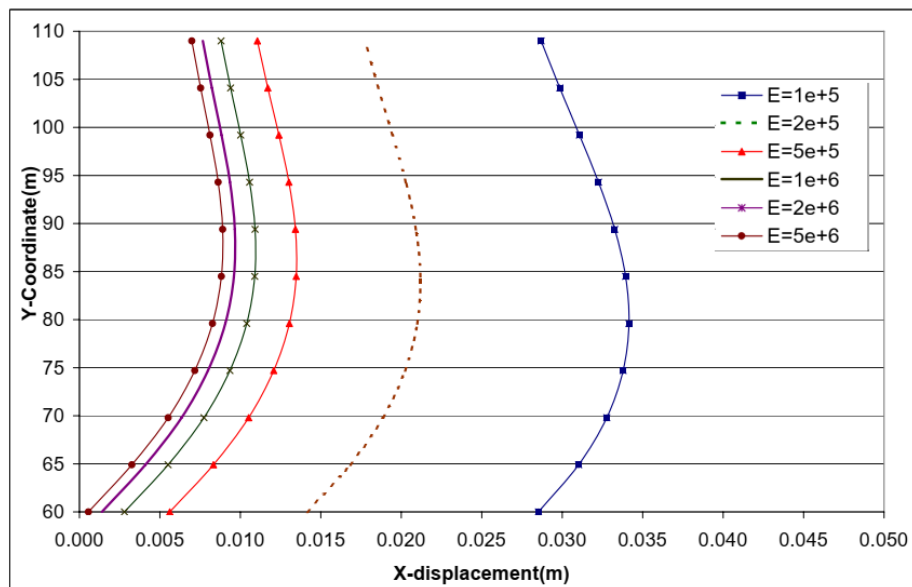


Figure 16: The effect of Foundation stiffness on Horizontal displacement in steady-state conditions

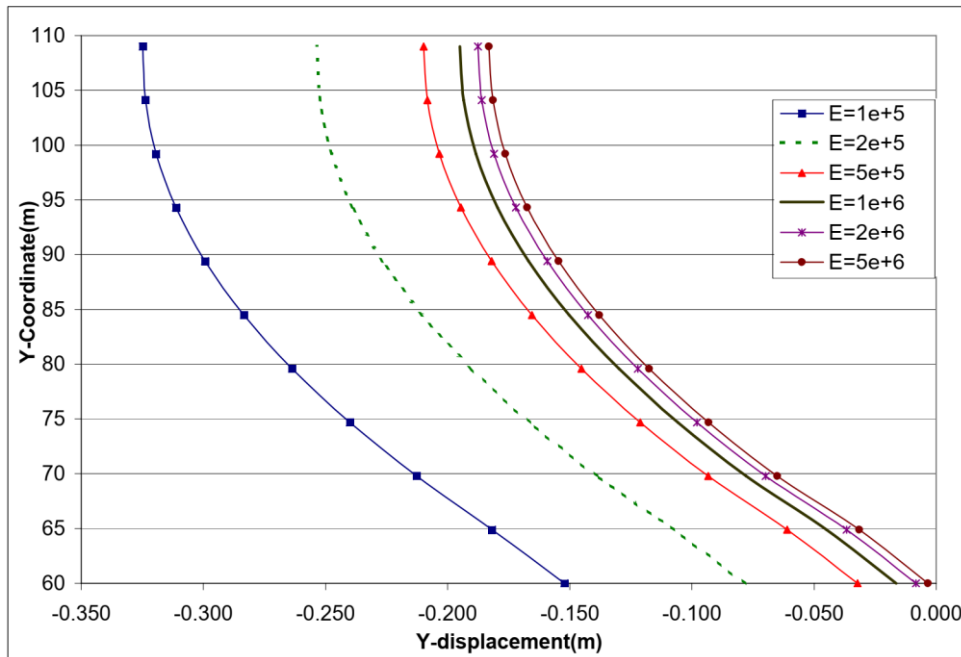


Figure 17: The effect of Foundation stiffness on vertical displacement in steady-state conditions

The vertical and horizontal displacement results in Figures 16 and 17 also show that when the foundation stiffness value is greater than  $5e+5$ , the diagram of vertical and horizontal displacements of the dam core remains almost unchanged.

### Effect of the asphalt core stiffness on Dynamic analysis

For the dynamic analysis, we used the earthquake spectrum of El Centro, which is given in Figure 18, with the maximum horizontal acceleration of  $0.25g$ . Due to the lack of detailed

site-specific earthquake spectral data, this research was carried out using the El Centro earthquake spectrum available in the software. The earthquake spectrum has been applied only in the horizontal direction of the dam. The number of time steps to perform the analysis The dynamic range is 200 and the time step length is 0.05 second. For The dynamic analysis, we used QUAKE software in GeoStudio based on the results of the steady-state and linear equivalent behavioral model for dam materials based on Table 2.

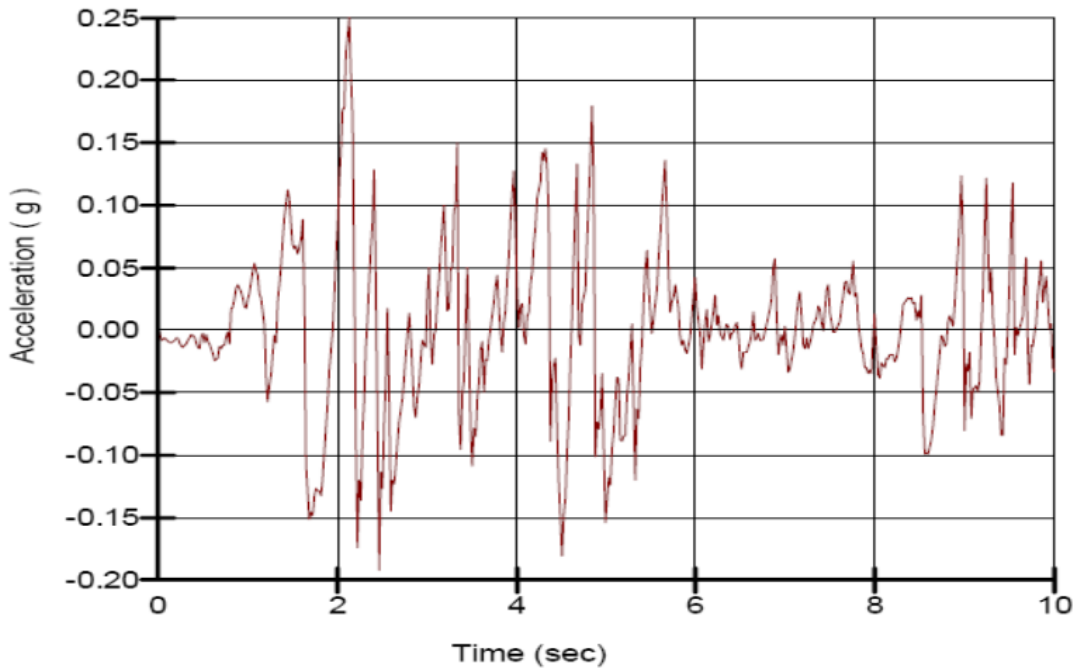


Figure 18: Earthquake spectrum used in dynamic analysis

Table 2: parameters of the linear equivalent model for dynamic analysis

Material	Asphalt core	Filter	Shell	Foundation
Model	Equ. Linear	Equ. Linear	Equ. Linear	Equ. Linear
E	2.0E+05	8.5E+04	1.0E+05	2E+05
$\nu$	0.45	0.3	0.25	0.4

The results of dynamic analysis are presented in Figures 19 to 22. Considering the thinness of the asphalt core and its thickness of about one meter, its stiffness has a very insignificant effect on the dynamic analysis results. The analysis results show

that a change in the core stiffness does not have much influence on the spectrum of acceleration, and horizontal and vertical displacements, and its effect on the magnification factor of acceleration is negligible.

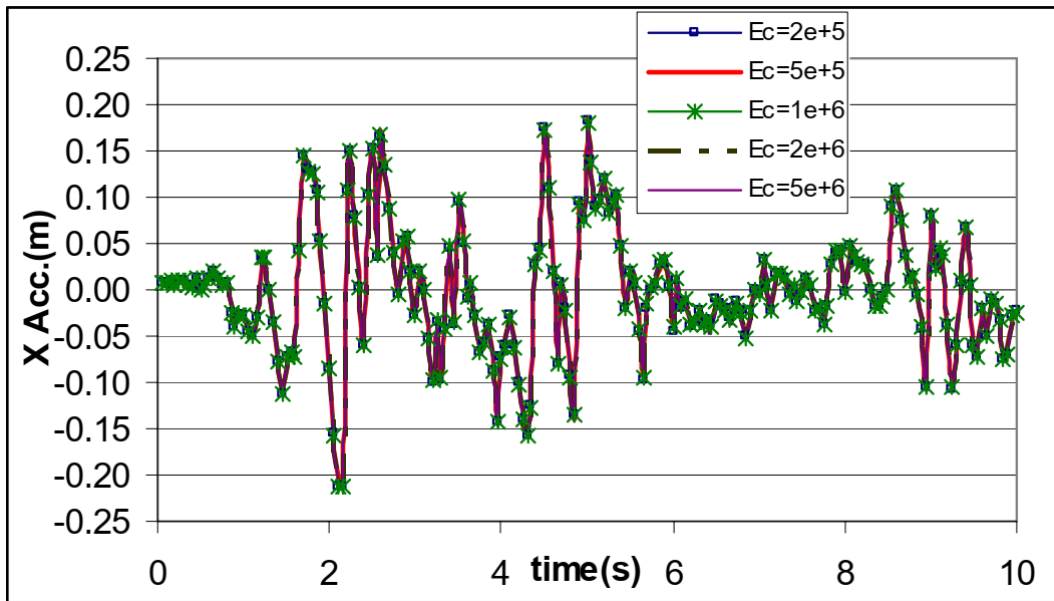


Figure 19: The effect of core stiffness on the spectrum of horizontal acceleration in dynamic analysis

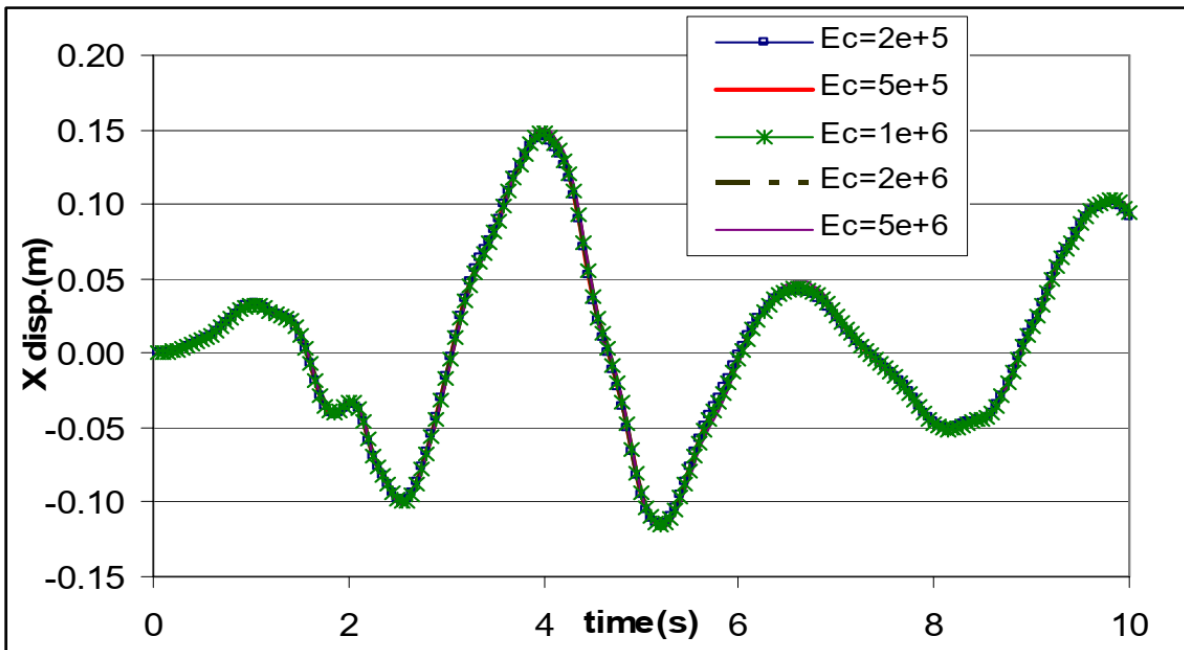


Figure 20: The effect of core stiffness on the spectrum of horizontal displacement in dynamic analysis

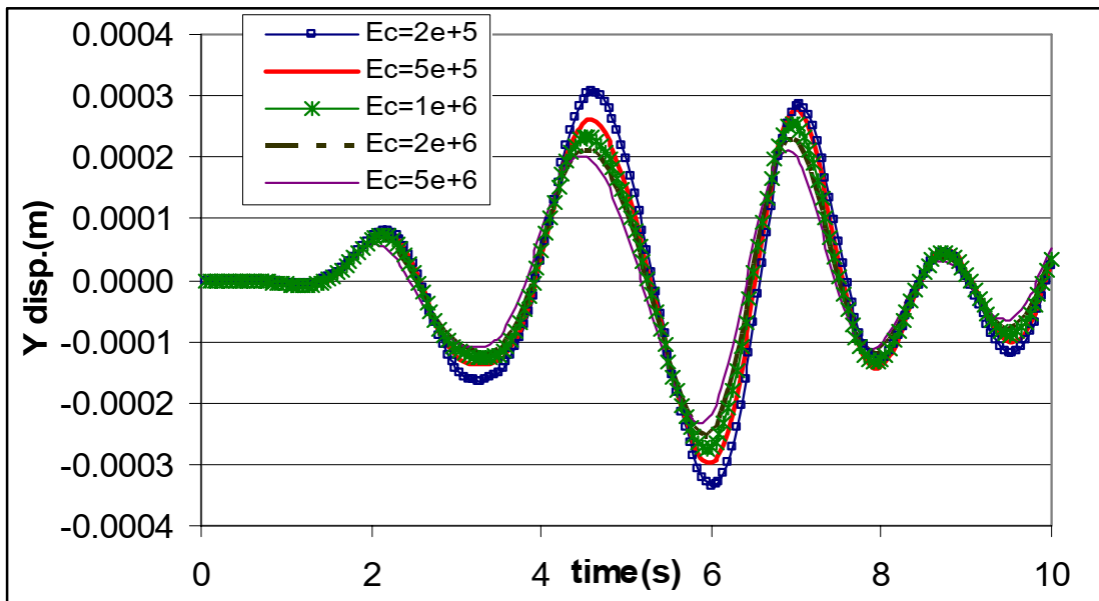


Figure 21: The effect of core stiffness on the spectrum of horizontal displacement in dynamic analysis

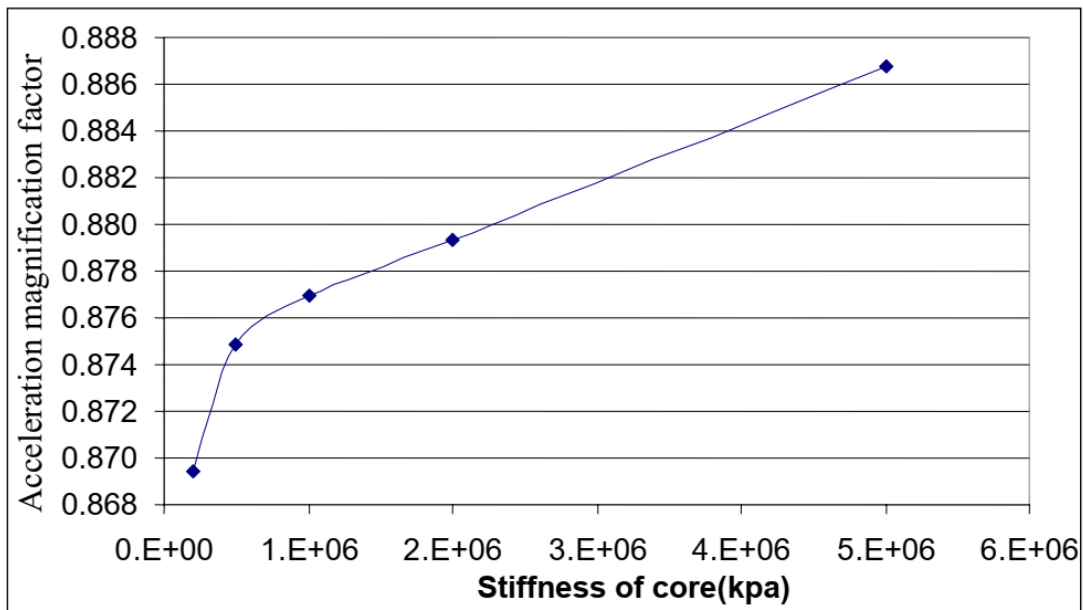


Figure 22: The effect of core stiffness on the value of acceleration magnification factor in dynamic analysis

**Conclusion**

In this study, the comparison of the dam with vertical and inclined asphalt core and the results of static and dynamic analysis at the end of construction and steady state were discussed. Also, the sensitivity analysis of the results for the hardness of the asphalt core and the foundation of the dam was investigated. Based on the conducted analyses, the following results can be inferred:

1. The inclined core experiences less settlement compared to the vertical core at the end of construction in static analysis. However, its

horizontal displacement is greater due to being located in the upper shell.

2. The inclination of the core does not have much effect on the seepage flow rate from the dam.

3. Examining the vertical and horizontal displacements in steady seepage conditions indicates that the core inclination has very little influence on the displacements in this scenario.

4. Dynamic analysis results suggest that the core inclination less than 5% change the dynamic analysis response, and the dynamic analysis results for the inclined core are very similar to those of the

vertical asphalt core.

5- Increasing the core stiffness leads to a reduction in the vertical displacement of the core in the end of construction.

6- In the steady state, the core stiffness has little effect on horizontal displacement but results in a decrease in vertical displacement.

7- The impact of core stiffness on dynamic analysis results is minimal due to the core's thin thickness. This indicates that the function of This indicates that the asphalt concrete core primarily functions as a water barrier diaphragm the asphalt concrete core acts as a water barrier diaphragm influencing dam behavior rather than its resistance and elasticity properties.

8. The vertical and horizontal displacement results show that when the foundation stiffness value is greater than  $5e+5$ , the diagram of vertical and horizontal displacements of the dam core remains almost unchanged.

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## Declaration of competing interest

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