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Numerical Evaluation of Anti-Liquefaction Performance of Deep Soil Mixing Method under Embankment Dams

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ABSTRACT

Liquefaction-induced failure in structures like embankment dams is recognized as one of the most destructive outcomes resulting from earthquakes. When the foundation experiences liquefaction, excess pore water pressure (EPWP) is generated in the liquefied area and spreads within and underlying the structures. Addressing this issue requires the development of appropriate measures to counteract liquefaction. This numerical study examined the effectiveness of the deep soil mixing (DSM) method beneath embankment dams using Flac3D. The model results have been compared to the centrifuge experiments conducted as part of the VELACS (VErification of Liquefaction Analysis by Centrifuge Studies) project to validate the model. Based on the validated model, the anti-liquefaction performance of DSM columns installed beneath embankment dams in reducing EPWP was assessed. The findings indicate that DSM columns can effectively mitigate the detrimental effects of liquefaction beneath embankment dams by considering proper column diameter and a spacing-to-diameter ratio. These results have practical implications in engineering applications and offer valuable insights into the anti-liquefaction capabilities of the DSM method, specifically when applied to embankment dams.

I.INTRODUCTION

The United States relies on over 75,000 dams for crucial purposes such as water management [1]. The failure of a dam can have far-reaching consequences, impacting the lives of thousands of people and incurring significant financial costs. Consequently, ensuring the safety of these structures is of paramount importance. Geo-structures like embankment dams, river dikes, and highway embankments have experienced substantial damage in past major earthquakes [1-3]. Extensive studies have shown that the most severe damages occur when the underlying saturated granular soils undergo liquefaction, leading to embankment cracking, settlement, lateral spreading, and slumping. Notable failures in U.S. Dam Engineering history include the Sheffield Dam failure during the 1925 Santa Barbara earthquake and the Lower San Fernando Dam failure during the February 1971 earthquake [1–2]. Therefore, it is crucial to thoroughly investigate the potential impact of foundation liquefaction on earth embankments. Developing a deeper understanding of the dynamic response and deformations of embankment dams due to liquefaction would greatly enhance our ability to assess liquefaction risks, determine the need for mitigation measures, and design more effective and cost-efficient remedial procedures. These advancements could save hundreds of millions of dollars by preventing or mitigating dam failures.

Several techniques have been developed and implemented to address the remediation of liquefiable soils beneath embankment dams. These techniques include densification [1], the use of stone columns, and grouting. Among these methods, deep soil mixing (DSM) has emerged as a relatively new approach for improving the seismic stability of embankment dams. DSM involves the in-situ mechanical cutting and mixing of soil combined with low-pressure injection of cement slurry, resulting in the creation of uniform-diameter columns that match the dimensions of the mixing auger [4]. The effectiveness of DSM in mitigating liquefaction has been demonstrated at various geotechnical sites. While the reconstruction of Jackson Lake Dam in Wyoming during the late 1980s marked a significant application of DSM for dam construction in the United States, its specific application for mitigating liquefaction under embankment dams has not received sufficient attention [4]. This research aims to address this gap. In this paper, the effectiveness of the DSM method in mitigating liquefaction under embankment dams is evaluated numerically in FLAC^{3D}. This study focuses on the application of group DSM columns beneath embankment dams and assesses their performance in terms of excess pore water pressure (EPWP) generation, a key indicator of liquefaction.

II.NUMERICAL MODELING

This research involves two main components in its 3D dynamic modeling. The initial part focuses on modeling and verifying soil liquefaction, while the second part involves modeling an embankment dam over a liquefiable soil improved by installing DSM columns.

1) Soil Liquefaction Modeling and Verification

The accuracy and capability of a 3D dynamic finite difference model developed in FLAC^{3D} to examine liquefaction in loose sandy soil were validated through a comparison of the simulation results with data obtained from Test No.1 of the Verification of Liquefaction Analysis by Centrifuge Studies (VELACS) project, confirming its ability to predict EPWP during liquefaction. To simulate the behavior of liquefiable loose sandy soils in FLAC^{3D}, the Finn constitutive model was utilized. The laminar box in Test No.1 of the VELACS project consisted of a horizontal layer of uniform Nevada No. 120 sand (properties are given in Table 1). This experimental setup aimed to simulate a 10 m soil layer in the prototype. The numerical model was selected to have dimensions of 12×16 m at a depth of 10 m and the boundary conditions in the numerical model were fixed on all four sides and rigid at the bottom to avoid seismic waves reflection.

TABLE 1. NEVADA SAND PROPERTIES [5]

Characteristics	Dry Density	Void ratio	Permeability	Poisson ratio	Shear Modulus	Friction Angle	Cohesion	$(N_1)_{60}$
Unit	kg/m^3	-	m/s	-	MPa	Degree	kPa	Blows
Nevada Sand	1500	0.73	6×10^{-5}	0.3	3.85	30	0	7

The acceleration time history applied at the base of the box, illustrated in Figure 1, comprised 20 cycles of a sinusoidal input with a frequency of 100 Hz [5]. For the dynamic loading in the model, an acceleration time history was applied at the lowest point with a frequency of 2 Hz and an acceleration of 0.235 g.

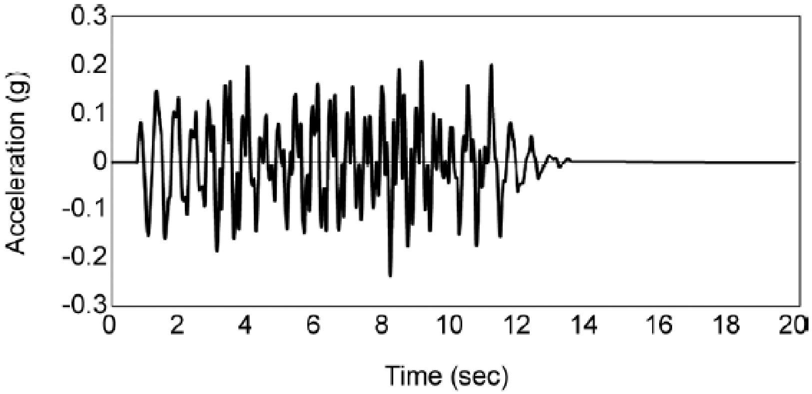

Figure 1. Horizontal acceleration time history for VELACS project (The graph source: [5])

In order to analyze the generation of dynamic EPWP, the Finn constitutive model [6] is incorporated into FLAC^{3D}. This model, which connects equations (1) and (2) to the plastic Mohr-Coulomb model [6-8], considers specific boundary conditions and coefficients to accurately determine the changes in fluid pressure within a porous medium. The Finn constitutive model is capable of conducting the coupled dynamic-groundwater flow calculations and simulating the effects of liquefaction.

$$\Delta\varepsilon_{vd} = C_1.(\gamma - C_2.\varepsilon_{vd}) + \frac{C_3.\varepsilon_{vd}^2}{\gamma + C_4.\varepsilon_{vd}} \tag{1}$$

$$\frac{\Delta\varepsilon_{vd}}{\gamma} = C_1.exp\left(-C_2.\frac{\varepsilon_{vd}}{\gamma}\right) \tag{2}$$

Where C_1, C_2 , C_3 , and C_4 denote constants that are linked as follows: $C_1C_2C_4 = C_3$. $\Delta\varepsilon_{vd}$ shows the soil volume decrease, γ denotes the size of periodic shear strains, and ε_{vd} denotes the accumulated volumetric strain from previous cycles in percent. The amount of C_1 coefficient depends on the sand relative density and C_2 is also a constant fraction of C_1 and can be expressed as $C_2 = \frac{0.4}{C_1}$. Considering Rayleigh damping, the natural frequency of the model is 2 Hz in this study and the damping coefficient applied was 5% of critical damping [9-11].

The comparison between EPWP at a depth of 1.25 m for numerical modeling and the centrifuge test No. 1 in the VELACS project in Figure 2 reveals a relatively good agreement between the numerical results and the results of the model test No. 1 in the VELACS project. liquefaction occurs when excess pore water pressure increases due to cyclic loading during seismic activity, leading to a decrease in effective stress (Liquefaction likely occurs when EPWP > effective stress). The reduction in effective stress weakens the soil, causing it to behave like a liquid and lose its shear strength. A similar agreement was also obtained at depth of 2.5 and 3.5 m. Similar approaches and results in the comparison of numerical results and the results of the model test No. 1 in the VELACS project have been successfully achieved by the author in the previous studies on soil liquefaction, such as [9-11].

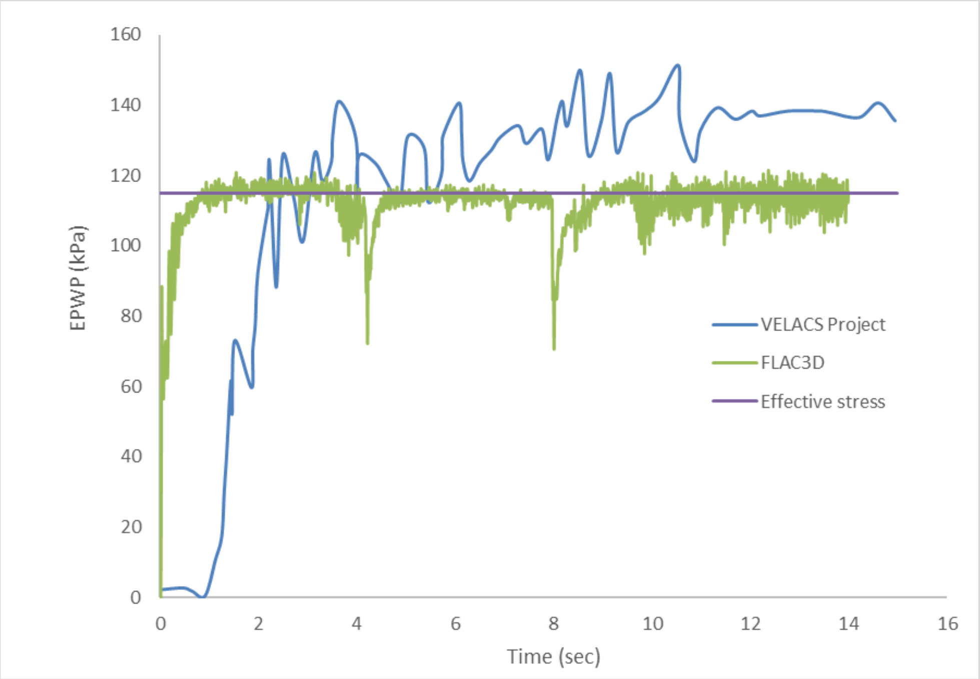

Figure 2. EPWP values at a depth of 1.25 m with finite difference model and test No. 1 of VELACS project

2) *Modeling and verification of an Embankment Dam on the group column type of DSM columns*

Once the validation of the liquefaction simulation model was completed, a 3D dynamic finite difference model was created to represent an embankment dam supported by a square pattern of group columns using the DSM method. The model considered a 10-meter thick liquefiable layer composed of loose sandy soil beneath the embankment dam, with properties similar to Nevada No. 120 sand. The characteristics of the DSM columns utilized in this numerical study are presented in Table 2.

TABLE 2. DSM COLUMNS PROPERTIES [12]

Characteristics	Dry Density	Void ratio	Permeability	Poisson ratio	Shear Modulus	Friction Angle	Cohesion	Bulk Modulus	Young Modulus
Unit	kg/m^3	-	m/s	-	MPa	Degree	kPa	MPa	MPa
DSM Columns	2100	0.45	10^{-1}	0.3	173	33	2800	375	450

In this study, a typical embankment dam with a 34-meter (m) height constructed on 20 m of alluvium which includes a 10-m thick loose sandy soil susceptible to liquefaction over a 10-m thick clay layer. In this study, for simplicity, the weight of the embankment dam has been applied on a square shape pattern over group type DSM columns. The weight of an embankment dam depends on various factors, including its dimensions, geometry, and the materials used for construction. Embankment dams are typically constructed using compacted earth materials. The specific gravity and moisture content of the materials also influence the weight of the dam. To estimate the weight of an embankment dam, the cross-sectional area of the dam and the average unit weight of the materials used were considered. In Table 3, the geotechnical characteristics of a typical embankment dam used in the U.S and other countries and adopted herein for the numerical modeling have been presented.

TABLE 3. CHARACTERISTICS OF AN EMBANKMENT DAM [13]

Characteristics	Wet Density	Saturated Density	Permeability	Bulk Modulus	Shear Modulus	Friction Angle	Cohesion	$(N_1)_{60}$
Unit	kN/m^3	kN/m^3	cm/s	MPa	MPa	Degree	kPa	Blows
Dam Core	20.5	21.5	10^{-6}	600	120	25	39.2	-
Dam Shell	22	23	10^{-3}	450	210	38	9.8	50

The seismogram recorded by University of California – Santa Barbara (UCSB) during the 1978 Santa Barbara earthquake is shown in Figure 3. The seismogram was been used as an input for horizontal input motion at the bottom of the model. This seismogram shows the acceleration of the ground during the earthquake as a percentage of gravity. Figure 4 depicts the finite difference model for the embankment dam load applied over group type DSM columns in Flac^{3D}. The finite difference model shown in Figure 4, used for simulating DSM column behavior, has been previously employed by the author to study soil liquefaction beneath shallow foundations [9-11].

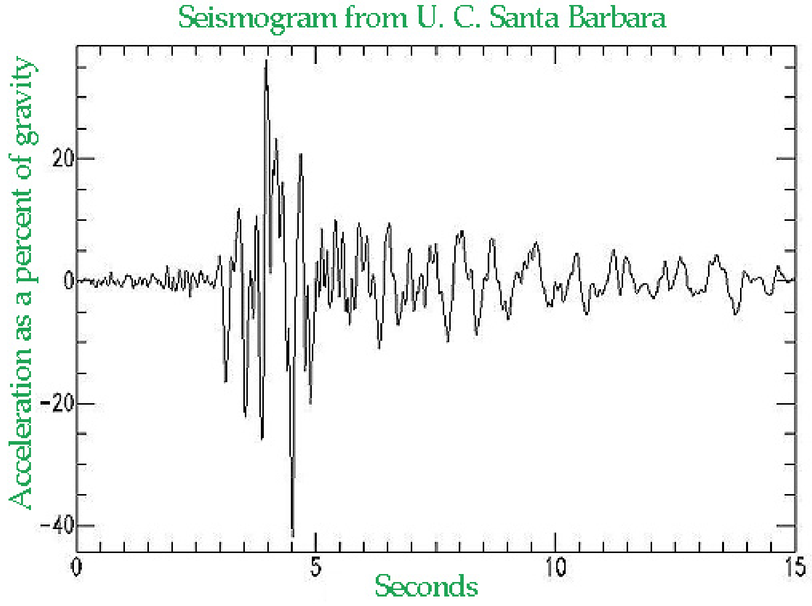

Figure 3. Seismogram from UCSB recorded during the 1978 earthquake (The graph source: [14])

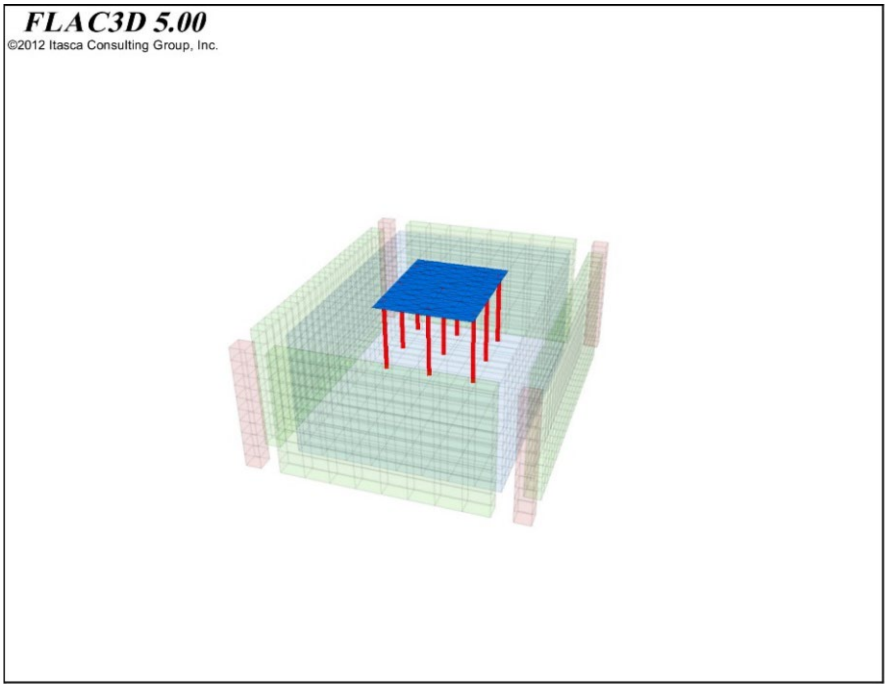

Figure 4. Finite difference model for the embankment dam load applying over group type of DSM columns

III.RESULTS AND DISCUSSION

The numerical findings are presented for a square pattern of DSM columns, which are commonly used in geotechnical projects, with diameters of 100 centimeters (cm), 120 cm, and 150 cm. These columns are subjected to the load of an embankment dam, and the spacing between the columns is determined by the ratio of column spacing to diameter $\left(\frac{s}{d}=2,3,4\right)$. Figures 5-7 illustrate the results of the dynamic analysis, specifically focusing on the changes in EPWP for the group DSM at a depth of 10 meters. Models with $\left(\frac{s}{d}=5\ or\ greater\right)$are not shown in the graphs as they all experienced complete liquefaction. The EPWP values increase when the spacing between the DSM columns is increased regardless of their column diameters. The findings indicate that as the diameter of DSM columns increases, excess pore water pressure decreases and the risk of liquefaction decreases. In addition, DSM columns with a diameter of 120 and 150 cm showed satisfactory results in mitigating liquefaction. The DSM columns for s/d=2 with a diameter of 150 cm showed the best performance. The results depicted in Figures 5-7 demonstrate that, regardless of the column diameter, an increase in the spacing between the DSM columns leads to higher EPWP values. This indicates that larger column spacing may result in reduced effectiveness in mitigating liquefaction. The results suggest that implementing a group DSM configuration with larger column diameters and reduced spacing can significantly improve the resistance of embankment dams to liquefaction.

According to Figure 5, for the square pattern of group-type DSM columns with diameters of 100 cm, as EPWP is greater than the effective stress, liquefaction will be anticipated for that column diameter. According to the results presented in Figures 6-7, the performance of the square pattern of group-type DSM columns with diameters of 120 cm, and 150 cm demonstrates its effectiveness in mitigating liquefaction for a duration of approximately up to 5 seconds. During this critical time frame, the DSM columns successfully reduce the EPWP generated by liquefaction, thus enhancing the stability and resilience of the embankment dams. The significance of this observation lies in the fact that the initial moments following an earthquake are often the most critical for the structural integrity of earth structures. Within this 5-second duration, the group DSM configuration effectively controls and reduces the EPWP, minimizing the potential for liquefaction-induced failure and its devastating consequences.

These findings contribute to the understanding of the time-dependent behavior of the DSM method under seismic loading. By identifying the optimal performance window, engineers and geotechnical professionals can design and implement the appropriate group DSM configurations to effectively counteract liquefaction within this critical timeframe. It is important to note that the specific duration of 5 seconds mentioned here may vary depending on the seismic characteristics and soil conditions of the site. Although, according to the results presented in Figures

6-7, the performance of the square pattern of group-type DSM columns with diameters of 120 cm and 150 cm demonstrates its effectiveness in mitigating liquefaction for durations exceeding 5 seconds (as EPWP is less than the effective stress), further research and analysis are needed to investigate the behavior of group DSM configurations over extended time periods and under various seismic scenarios. Nonetheless, the results presented in this study offer valuable insights into the performance of DSM columns within the initial seconds of seismic activity, providing a foundation for further investigations and practical applications in earthquake-resistant design.

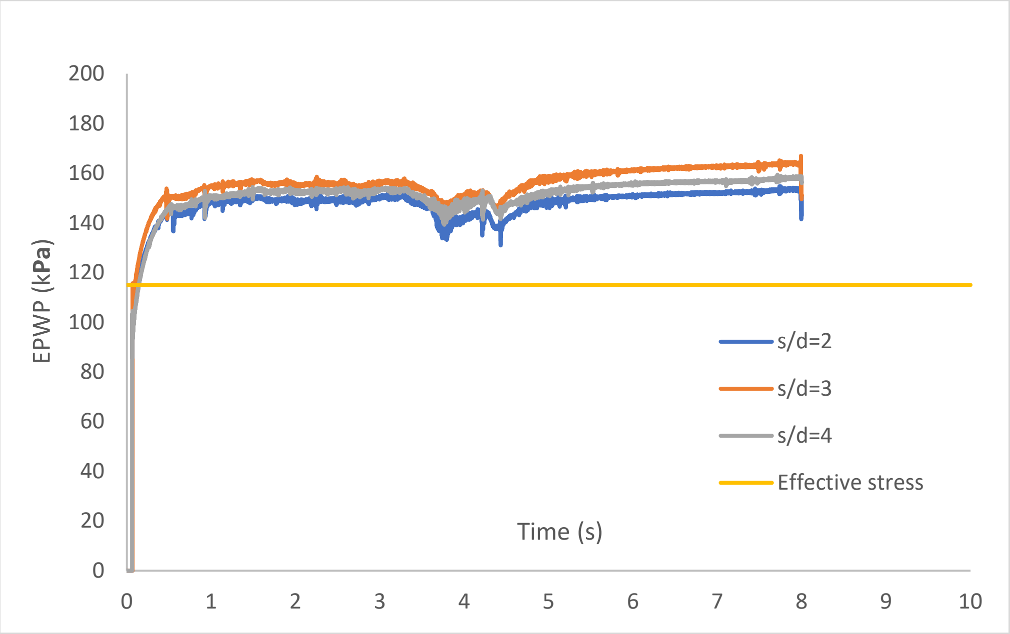

Figure 5. EPWP variation beneath the embankment dam for a diameter of 100 cm DSM columns and a ratio of $\left(\frac{s}{d} = 2,3,4\right)$

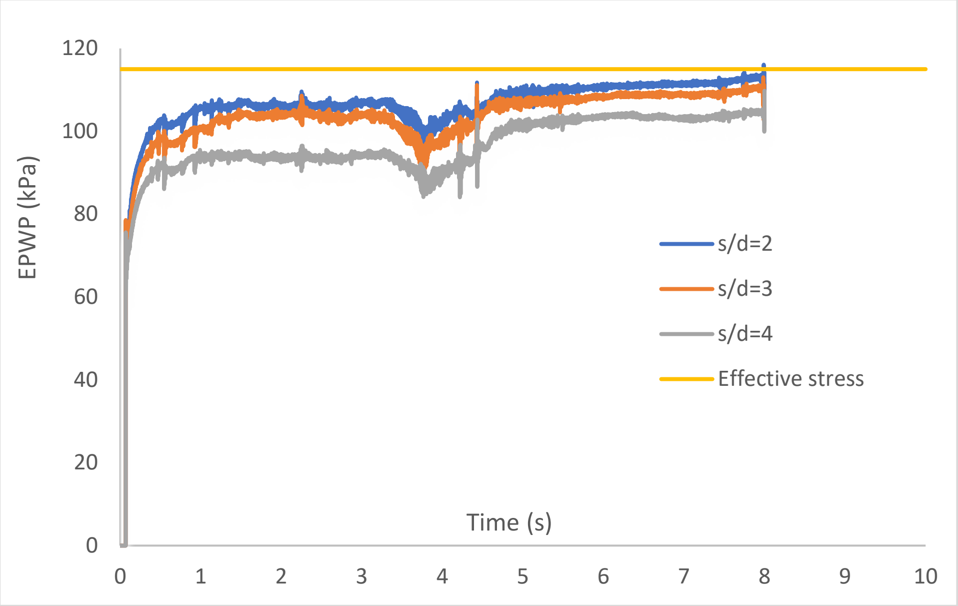

Figure 6. EPWP variation beneath the embankment dam for a diameter of 120 cm DSM columns and a ratio of $\left(\frac{s}{d} = 2,3,4\right)$

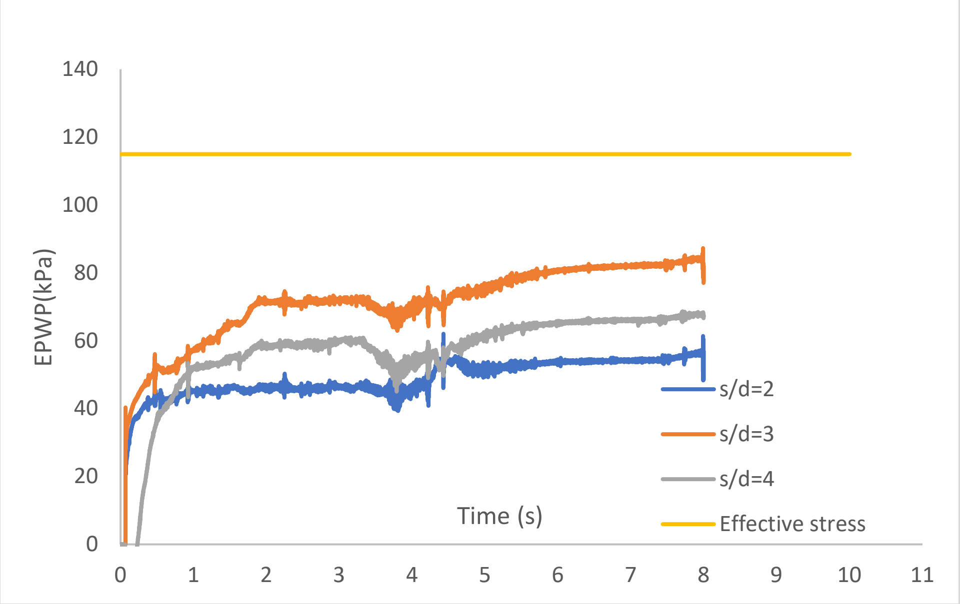

Figure 7. EPWP variation beneath the embankment dam for a diameter of 150 cm DSM columns and a ratio of $\left(\frac{s}{d} = 2,3,4\right)$

IV.CONCLUSIONS

This paper investigated the influence of using DSM columns for liquefaction mitigation for an embankment dam founded on liquefiable soils. The main findings of this study are as follows:

- The application of the group column DSM method has been identified as an effective approach for mitigating liquefaction caused by earthquakes beneath embankment dams.
- The results highlight the importance of column spacing and diameter in mitigating liquefaction-induced failure of embankment dams. The findings demonstrate that increasing the spacing between DSM columns leads to higher EPWP values, indicating reduced effectiveness in mitigating liquefaction. Conversely, increasing the diameter of DSM columns decreases the risk of liquefaction, with DSM columns of 120 cm and 150 cm diameters exhibiting satisfactory performance in reducing liquefaction effects.
- Among the group type DSM columns evaluated at a depth of 10 m with different s/d and diameter, the DSM columns with a diameter of 150 cm and a s/d ratio of 2 demonstrated the most effective performance in mitigating the risk of liquefaction beneath the embankment dam.
- The observed performance of the DSM method is much more effective for a duration of approximately up to 5 seconds. Further research is necessary to investigate its behavior over longer durations and under different seismic scenarios, accounting for site-specific soil conditions and seismic characteristics.
- The developed model and results can be used in the design and implementation of effective group DSM configurations, reducing the vulnerability of embankment dams to liquefaction-induced failure during seismic events.

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