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EFFECT OF SAND SHELL IMPROVEMENT USING POLYPROPYLENE FIBER AND CEMENT ON THE SEISMIC RESPONSE OF SMALL-SCALE ZONED EARTH DAM MODELS

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SUMMARY

The application of sand as shell materials in zoned earth dams is common due to its availability and economic factors. Nevertheless, it is necessary to analyze the performance of such materials under the simultaneous effect of seepage and earthquake loads, especially when the core of the structure is formed from low permeable materials. The present work evaluates the influence of polypropylene fiber and cement additions on the seismic performance of sand-shell zoned earth dams. Three small-scale physical models with equal geometry and silty clay cores were prepared and tested using a shaking table in a laboratory. The physical models involved an unreinforced Sand–Silty clay dam, polypropylene fiber-reinforced sand-shell dam containing 0.5% fibers based on dry weight, and a cement-strengthened sand-shell dam with 3% cement content. The steady state seepage analysis was carried out at first; subsequently, the seismic test with the El Centro earthquake was carried out with the PGA values of 0.1, 0.2, 0.3, 0.4, and 0.5 g. The seepage discharge was relatively constant at values between 2.41×10^{-7} and 2.75×10^{-7} m³/s/m, confirming the dominant control of the silty clay core on the seepage process. For the applied earthquake load, the acceleration magnification, deformation, increase of pore-water pressure, and damages were highest in the untreated model. Under the acceleration of 0.5 g, the settlement on the dam's crest was 26 mm, 18 mm, and 5 mm in the untreated model, the fiber-reinforced model, and the cement-treated model, corresponding to reductions by 31% and 81%, respectively. In addition, the maximum width of cracks decreased from approximately 125 mm in the untreated model to 15 mm and 5 mm in the fiber-reinforced model and the cement-treated model, respectively. The effectiveness of stresses and factors of safety was higher for the cement-treated model than other models through the entire loading sequence. Although both improvement techniques increased the seismic resistance of the embankment, the latter had a larger decrease in deformation and damage while retaining higher stability under simultaneous effects of seepage and earthquakes.

Key words: *zoned earth dam, seismic response, shaking table test, sand shell improvement, polypropylene fiber, cement-treated sand, pore-water pressure.*

INTRODUCTION

Earth dams have been favored in many construction projects because embankments for these structures are often built with materials that can be obtained within close proximity to the construction site. The very same reason, however, makes the safety of the earth dam highly dependent on the hydraulic and mechanical properties of the material used for its construction. An earthquake following seepage within the embankment. Crest deformation, cracking, excess pore-water pressure, loss of effective stress, and slope instability may interact during the same loading event. Therefore, seismic assessment of earth dams should account for the existing seepage condition as well as the cyclic resistance and deformation characteristics of the embankment materials [1][2].

The core and shell of a zoned earth dam perform different but interdependent roles. The core limits seepage while the shells provide stability, drainage and resistance to deformation. Consequently, the core properties alone cannot be used to assess the seismic behaviour of a zoned dam. The way acceleration is transmitted during shaking, the accumulation of deformation, and the development of pore-water pressure can be influenced by the cyclic response, permeability, and shell stiffness. Past studies using experimental and numerical methods found that the crest displacement, pore-water pressure generation and slope stability under seismic loading are significantly affected by embankment zoning, seepage condition and material properties [3][4]. The shell's hydraulic role is important because a change in permeability or seepage path can shift the phreatic line and change the degree of downstream saturation [6].

From a construction standpoint, suitable shell material may not always be available, especially when borrow areas are limited or hauling distances are long. An alternative to complete material replacement could be to improve local sand. When used with a low-permeability core and subjected to earthquake loading, an untreated sand shell can experience excessive cyclic deformation, although sand can provide drainage. Polypropylene fibers and cement are two options for improving sandy soils, but it does not act in the same way. Randomly distributed fibers in the sand matrix can restrain particle movement and improve cyclic resistance through a tensile-bridging mechanism [7][9]. Cement treatment improves sand mainly through interparticle bonding, which increases strength and stiffness, but the same cementation process can also reduce permeability [7].

Although several studies have examined improved sands or strengthened embankment zones, direct comparisons between fiber-reinforced and cement-treated sand shells under the same zoned-dam configuration remain limited. Such a comparison is needed because shell improvement affects two coupled aspects of performance: the mechanical resistance of the shell during shaking and its hydraulic role in controlling drainage near the downstream side. An additive that increases strength may not necessarily improve seepage conditions, and this trade-off can influence the overall seismic response of a zoned dam. Recent research on small earth dams has also emphasized that the benefit of improvement depends on where the treated zone is placed and what function it serves within the embankment.

The present study investigates a Sand–Silty clay zoned earth dam model in which the shell consists of sand and the core consists of silty clay. The untreated model was used as the reference case, and only the sand shell was modified using two improvement methods, namely polypropylene fiber reinforcement and cement treatment. To isolate the effect of shell treatment, the silty clay core and the model geometry were kept constant in all tests. The models were first tested under steady-state seepage and then under shaking-table excitation. The assessment included seepage discharge, phreatic-line position, crest acceleration, relative displacement, permanent settlement, pore-water pressure, minimum effective stress, slope stability, and crack development. The main objective is to clarify the influence of different shell-improvement methods on the coupled hydraulic and seismic response of the Sand–Silty clay zoned dam model.

This paper is divided into several sections. In Section II, the literature review has been demonstrated and in Section III, material and methods, experimental set-up, construction of dam model, instrumentation, test procedure, and numerical calibration technique have been explained. Section IV has discussed the results of seepage and seismic behavior of the dam model such as deformation, pore water pressure,

effective stress, stability, and cracking behavior. Finally, in Section V, conclusions have been drawn from the study.

LITERATURE SURVEY

Many studies carried out in recent times emphasize the significance of assessing the effects of seepage and seismic loads on the performance of earth dams together. Full scale shake table tests carried out in this context revealed that zoning and internal reinforcement had positive influences on crest displacement and improved seismic stability of the earth dams [3]. Likewise, another study carried out through centrifuge modeling indicated that seepage played an important role in seismic behavior of the embankment dams [4]. The effect of excess pore water pressure on effective stress was recognized as one of the most significant parameters determining the stability of the dam during earthquake. It was observed that excess pore water pressure could greatly decrease the effective stress resulting in increased deformation of zoned earth dams during seismic loads [5]. This is in line with the results of the current research, which show that unimproved sand shells had higher pore pressure build-up and reduced effective stress. Recently, research in soil improvement methods has emphasized the improvement of cyclic resistance of sandy soils [18][19]. The result indicated that randomly distributed polypropylene fibers decreased the production of pore water pressure and delayed cyclic failure of the sand. Similarly, this study found that fiber reinforced dense sand showed better resistance against deformations and particle movement under cyclic loads [9]. Also, cement stabilization is another well-known technique for soil improvement [20]. This study showed that cement-stabilized soil possessed high stiffness and strength because of bonding between particles [10]. Later, this study examined the improvement of small earth dams and found that significant reductions in settlement and cracking occurred during earthquake loading [11]. Further evidence in the form of shaking table tests proved that soil improvement helped in increasing seismic stability and minimizing damage accumulations [13][14].

Despite past investigations into the use of polypropylene fibers as well as cement stabilization, comparative assessments between these two techniques in the context of an identical zoned earth dam have not been widely conducted before. This current research aims to address this issue, as it presents a direct comparison between plain, polypropylene-fiber-reinforced, and cement-stabilized sand shells subjected to similar levels of seepage and seismic forces.

MATERIALS AND METHODS

Figure 1 illustrates the entire methodological approach employed in this study. This figure shows the development of the three models of zoned earth dams with varying conditions of sand shell, together with their respective seepage and seismic shaking table tests, conducted at an incrementally increasing value of PGA. Their hydraulics and dynamics behaviors were then analyzed and compared with those from numerical analysis conducted through SEEP/W, QUAKE/W, and SLOPE/W software.

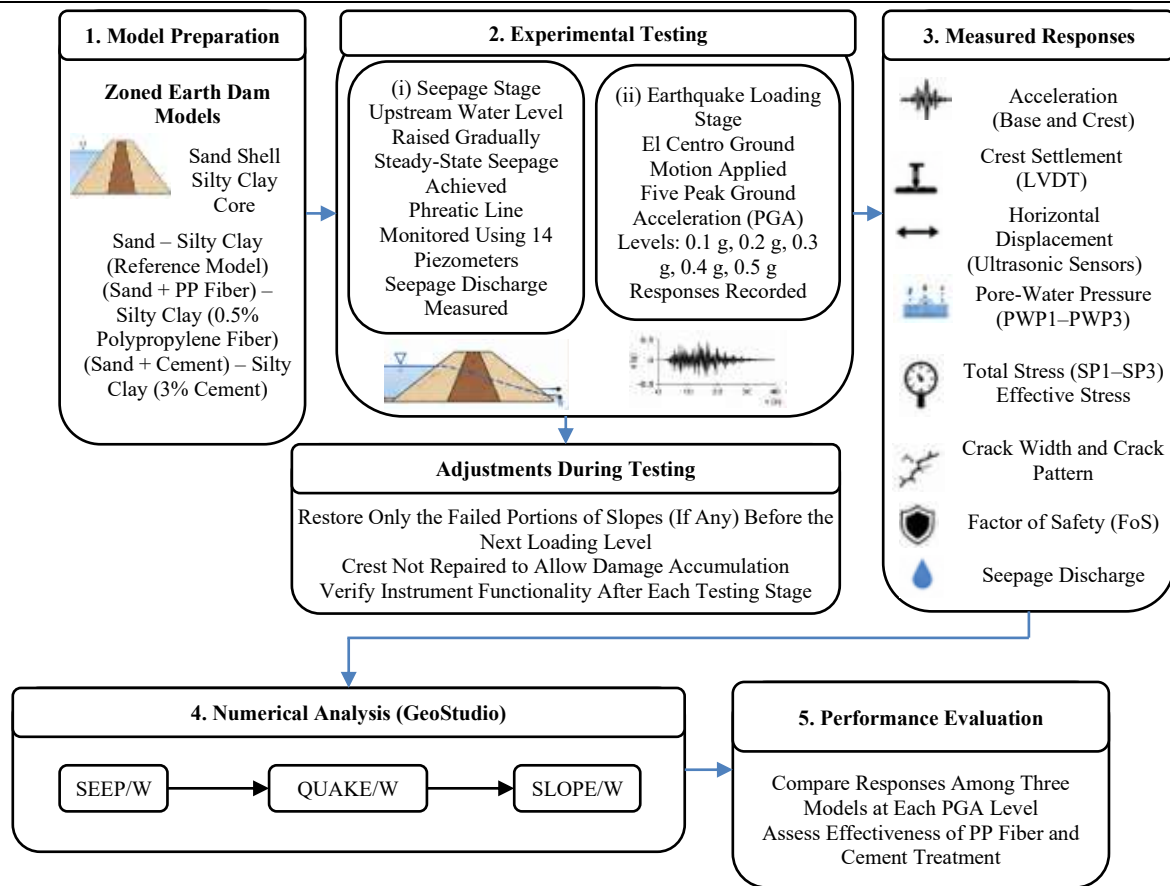


Figure 1. Conceptual framework of the experimental and numerical investigation of improved sand-silty clay zoned earth dams

Experimental Setup

Table 1. Shaking table specifications

Parameter	Value	Unit
Table type	Single-DOF horizontal shaking table	-
Maximum payload	1.0	ton
Main steel channel length	1.3	m
Number of main steel channels	2	-
Linear guide length	1.2	m
Number of sliders	4	-
Ball screw length	1.1	m
Ball screw diameter	50	mm
Steel plate dimensions	1.00 × 1.00	m
Servo motor model	ECMA-L111845RS	-
Rated output power	4.5	kW
Maximum torque	71.62	N·m
Maximum speed	3000	rpm

Tests were conducted in a glass-sided flume mounted on a laboratory shaking table. The shaking table was capable of generating horizontal motion in a single degree of freedom, which enabled the dam models to be subjected to controlled earthquake-type excitation after the seepage condition had been established. The transparent flume walls enabled monitoring of wetting changes, phreatic-line development, and slope condition during the hydraulic and dynamic testing stages. Table 1 summarizes the main specifications of the shaking-table system, including payload capacity, guide assembly, ball screw, steel platform dimensions, and servo-motor characteristics.

Physical Dam Models and Soil Materials

The experimental program was based on a zoned model composed of a sand shell and a silty clay core. The untreated Sand–Silty clay model was used as the reference case for evaluating the effect of shell improvement. Two additional models were then prepared by modifying only the sand shell. In the first improved model, polypropylene fibers with a length of 12 mm were mixed with the sand at 0.5% by dry weight. In the second improved model, the sand shell was treated with 3% cement. The silty clay core was kept unchanged in all three models to ensure that any observed difference in response could be attributed mainly to the shell treatment and not to variations in core material or model geometry.

Table 2 presents the engineering properties of the silty clay core, untreated sand, fiber-reinforced sand, and cement-treated sand. The addition of polypropylene fibers caused a minor change in unit weight and increased the apparent cohesion and friction angle of the sand. Cement treatment produced a greater increase in the strength parameters and a marked reduction in the hydraulic conductivity of the shell material. To provide a common basis for comparison, the same overall dam geometry and core dimensions were used for the three models, as shown in table 3. All tests were performed with the same geometry to ensure that the comparison reflected the effect of shell modification and not differences in embankment shape or core arrangement. Figure 2 (A,B,C) shows photographs of the three prepared models.

Table 2. Engineering properties of the soils used in the physical dam models

Soil Material	USCS	Unit Weight γ (kN/m ³)	Cohesion c (kPa)	Friction Angle ϕ (°)	Hydraulic Conductivity k (m/s)
Silty clay	CL-ML	18.10	10	26	8.3×10^{-7}
Sand	SP	16.30	0	33	1.0×10^{-4}
Sand + polypropylene fiber (Sand+PP)	SP	16.31	5	35	1.2×10^{-4}
Sand + cement (Sand+Cem)	SP	16.78	24	36	5.1×10^{-5}

Table 3. Dimensions of the physical dam model

Parameter	Value	Unit
Height	0.50	m
Crest width	0.25	m
Base length	2.50	m
Model width (thickness)	0.50	m
Upstream slope	1V:2.5H	-
Downstream slope	1V:2H	-
Core height	0.4	m
Core crest width	0.15	m
Core base width	0.95	m
Core slope	1V:1H	-



(A)



(B)



(C)

Figure 2. Zoned earth dam models: (A) Sand-silty clay, (B) (Sand+PP)-Silty clay, and (C) (Sand+cem)-Silty clay

Model Designation

The model notation is consistent with the use of shell-core material combination. Sand-Silty clay represents the baseline model with a shell made of raw sand, while Silty clay indicates the core material of the test specimen. On the other hand, (Sand + PP) – Silty clay stands for the model wherein the sand shell was reinforced with polypropylene, while (Sand + Cem) – Silty clay represents the model where the sand shell is coated with cement.

Instrumentation

The instrumentation was configured for monitoring the key hydraulic and dynamic behavior aspects of the model. There were two accelerometers used, one located on the base of the shake table for measuring the input acceleration and the other on the dam crest for measuring the output acceleration.

Table 4. Instrumentation used in the experiments

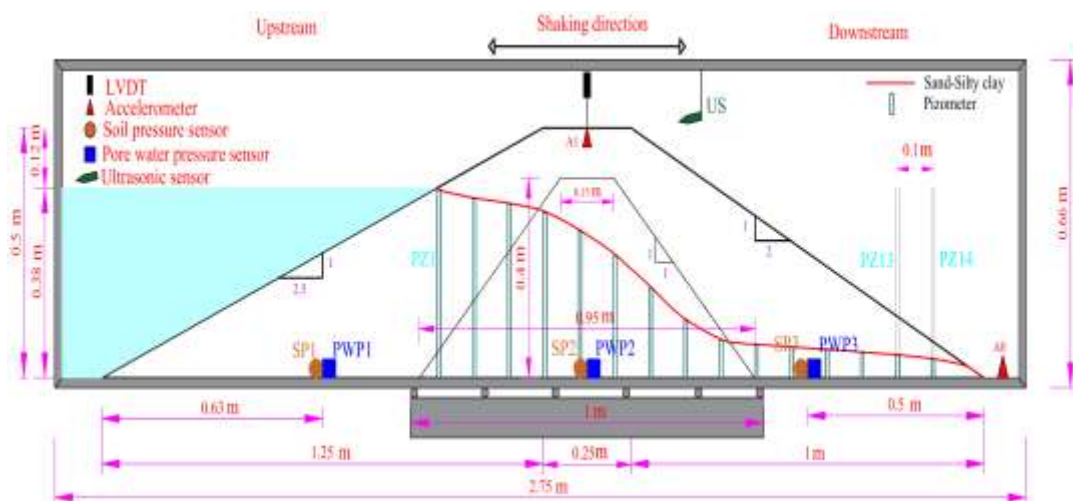
Instrument	Symbol	Measured Parameter	Location
Accelerometer	A0, A1	Acceleration	A0: at shaking table base, A1: at dam crest
Linear Variable Differential Transformer	LVDT	Settlement	crest centerline
Ultrasonic sensor	US	Relative horizontal displacement	Near downstream crest, fixed to the flume
Pore water pressure sensor	PWP1-PWP3	Pore water pressure	(All sensors located at the baseline) PWP1 & SP1: at 0.625 m from upstream heel, PWP2 & SP2: 1.375 m from upstream heel, and PWP3 & SP3: 0.50 m from downstream toe
Soil pressure sensor	SP1-SP3	Total stress	

The vertical crest settlement at the centerline was monitored through LVDT measurements. The relative

horizontal displacement close to the downstream crest was monitored using an ultrasonic gauge. Three pore-water pressure sensors and three total-stress sensors were installed along the model base at upstream, central, and downstream positions. Fourteen piezometers were also installed to delineate the steady-state phreatic line before dynamic loading. The locations of the instruments and measured quantities are given in table 4 and shown in figure 3 (A,B).



(A)



(B)

Figure 3. Shaking table apparatus and instrumentation: (A) photograph, (B) schematic diagram

The seismic and hydraulic performance of the tested dam models was evaluated using several response parameters obtained from the instrumentation system. The corresponding calculation procedures are summarized below.

Calculation Metrics

Crest Acceleration

The crest acceleration was measured directly by the accelerometer installed at the dam crest (A1). The peak crest acceleration was determined as equation 1

$$PCA = \max(|a_c(t)|) \quad (1)$$

Where, PCA = peak crest acceleration (g), $a_c(t)$ = time-history acceleration recorded at the crest.

Peak Relative Acceleration

The relative acceleration amplification between the crest and shaking-table base was calculated as equation 2.

$$PRA = PCA - PBA \quad (2)$$

Where, PRA = peak relative acceleration (g), PCA = peak crest acceleration (g), PBA = peak base acceleration (g).

Crest Settlement

Permanent crest settlement was obtained from the LVDT measurements as equation 3.

$$S = H_0 - H_f \quad (3)$$

Where, S = permanent settlement (mm), H_0 = initial crest elevation, H_f = crest elevation after shaking.

Relative Horizontal Crest Displacement

The relative crest displacement was measured using the ultrasonic sensor and expressed as equation 4.

$$D = |x_f - x_0| \quad (4)$$

Where, D = horizontal displacement (mm), x_0 = initial crest position, x_f = crest position after shaking.

Pore-Water Pressure

Peak pore-water pressure at each sensor location was determined from equation 5.

$$u_{max} = \max(u(t)) \quad (5)$$

Where, u_{max} = maximum pore-water pressure (kPa), $u(t)$ = recorded pore-water pressure time history.

Testing Procedure

Prior to testing, each model of dam was built within the flume, based on the size specifications provided in table 3. The materials for the shell and the core were placed in layers, compacted to meet the engineering parameters specified in table 2. Following model fabrication, all equipment used during the test (the accelerometers, piezometers, soil-pressure transducers, LVDT, and ultrasonic displacement sensor) was tested for reliable operation.

Hydraulic testing came first. Water was added slowly from the upstream side until steady seepage was achieved. Steady seepage was deemed to have been reached when two successive measurements with the piezometers and seepage flow rates did not differ. Based on this measurement, the phreatic line was plotted through the readings taken from the fourteen piezometers installed, while noting the seepage flow rate.

After the hydraulic stability was achieved, the scaled El Centro earthquake ground motion was introduced with increasing PGA values of 0.1, 0.2, 0.3, 0.4, and 0.5 g, illustrated in figure 4. The earthquake action was introduced at progressively increasing PGA values, so that cumulative effects on damage could be assessed. Post-shaking analysis included measurements for crest acceleration, displacement, settlement, pore water pressure, and surface damages before introducing another loading level.

After each load cycle, visual inspection of the physical model was conducted. If there is local landslide and surface sloughing in the slopes, only those damaged areas will be restored to preserve the geometry of the entire model for further loading stages. However, any other damages, including crest settlement and cracking, were deliberately left unmodified to enable cumulative damage to develop. In addition, connection and function of all sensors were rechecked before each new test stage. Throughout the entire experiment, no changes were made in the core material, the shell of the model, and instruments installed in the model.

Figure 4 shows the acceleration record of the El Centro earthquake considered as the seismic loading input for the shake table testing. The x-axis denotes the time taken in seconds (s), whereas the y-axis gives the value of ground acceleration in terms of g. The ground acceleration time history record was scaled at PGA levels of 0.1 g, 0.2 g, 0.3 g, 0.4 g, and 0.5 g and loaded consecutively to the models of each dam.

As can be seen from the acceleration record, the pattern is extremely irregular and composed of alternating positive and negative acceleration pulses. These features are typical of the actual ground shaking experienced during an earthquake. There is high intensity of shaking at the start 10 seconds of the record after which the acceleration slowly fades out, but there are still some significant acceleration peaks up to around 30 seconds into the test. The incorporation of the El Centro ground motion record enables the dam model to undergo cyclic loading similar to those induced by earthquake inertial forces. The magnitude of shaking increases linearly as the PGA values rise from 0.1 g to 0.5 g, resulting in higher amplification, settlement, displacement, pore water pressure formation, and cracking within the dam. The use of identical ground motion records at varying PGA values makes it possible to assess the seismic response of the bare, fiber-reinforced, and concrete-stabilized dam models using identical loading conditions. In this way, the difference in the response recorded is mainly due to the variation in shell material characteristics.

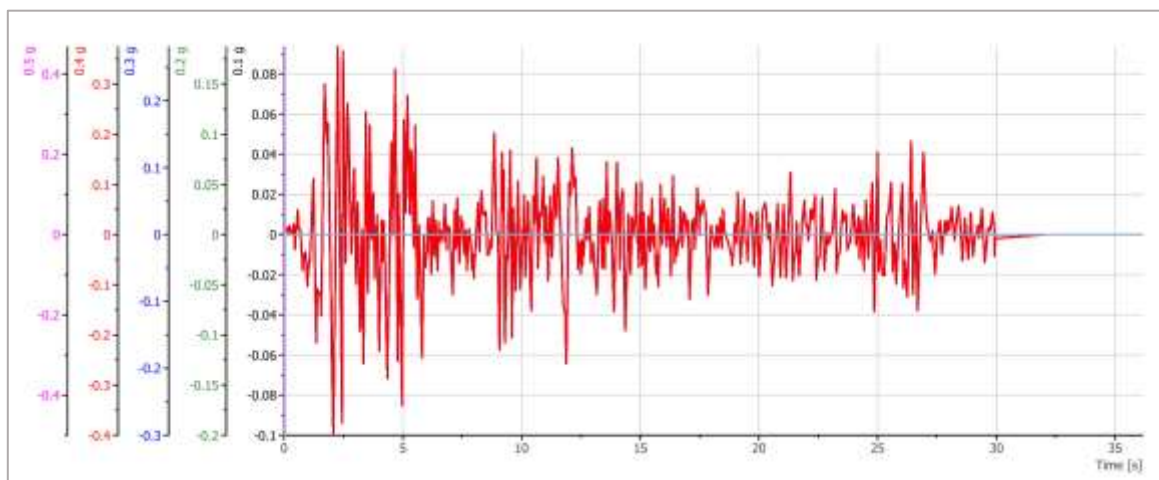


Figure 4. El Centro input motion

Numerical Calibration and Stability Assessment

To complement the observations made in the laboratory, numerical analyses were conducted using GeoStudio. SEEP/W was first used for steady-state seepage analysis and comparison of the computed phreatic line with the piezometer readings. The resulting hydraulic condition was then transferred to QUAKE/W to evaluate the dynamic response of the tested models under the applied El Centro motions. Subsequently, the stability of the upstream and downstream slopes was analyzed under the corresponding seepage and seismic conditions using SLOPE/W. As the factor of safety is not a directly measurable laboratory output, the calculated stability results were interpreted together with the physical evidence obtained from the tests, such as settlement, crack development, and the observed condition of the upstream and downstream slopes. A factor of safety of 1.5 was used only as a reference criterion to discuss slope performance, but not as a measured experimental value.

RESULTS AND DISCUSSION

Steady-State Seepage Behavior

As indicated in figure 5, the values of seepage for the three investigated models were very close to each other. The value of seepage for the untreated Sand–Silty clay model was $2.69 \times 10^{-7} \text{ m}^3/\text{s}/\text{m}$, while for (Sand+PP)–Silty clay and (Sand+Cem)–Silty clay models, it amounted to 2.75×10^{-7} and $2.41 \times 10^{-7} \text{ m}^3/\text{s}/\text{m}$, respectively. The closeness of seepage values suggests that silty clay core continued being the seepage controlling layer in all three models. Thus, the alteration of sand shell had no significant effect on the hydraulic behavior expressed by the amount of total discharge. The somewhat increased values of discharge in the case of fiber-reinforcement may be attributed to high permeability of fiber-filled sand, while low discharge values observed for cementation treatment should be ascribed to the reduction in permeability due to cementation of the sand [3][6].

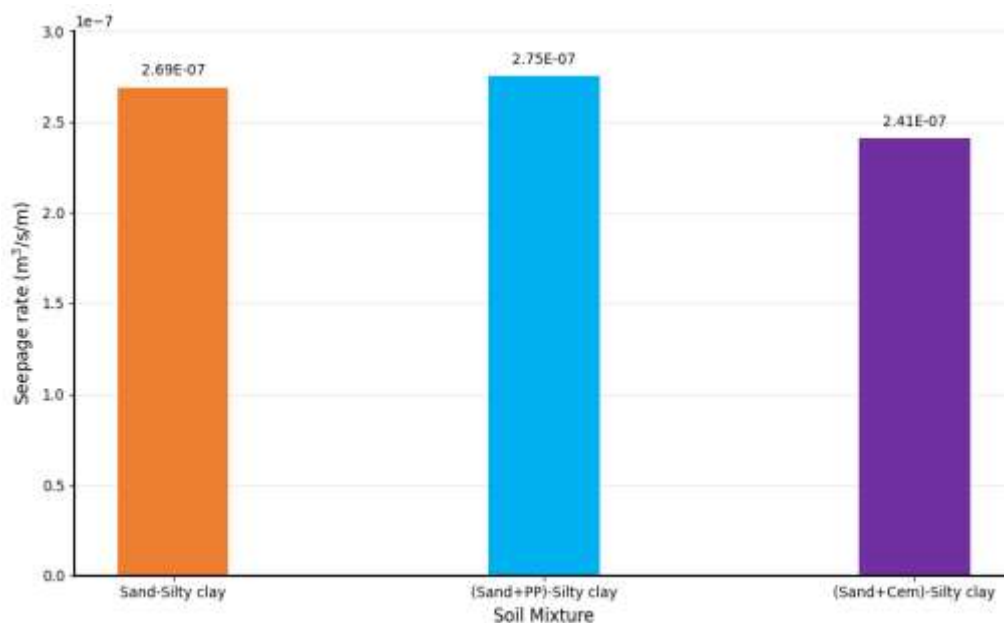


Figure 5. Seepage rate of the tested models

The phreatic-line response in figure 6 is more useful for explaining the downstream hydraulic condition than the discharge value alone. While the (Sand+PP)–Silty clay model produced the highest discharge, the seepage line near the downstream side was lower, indicating that the shell still served as an effective drainage zone. In contrast, the downstream seepage line for the (Sand+Cem)–Silty clay model was higher despite its lower total discharge.

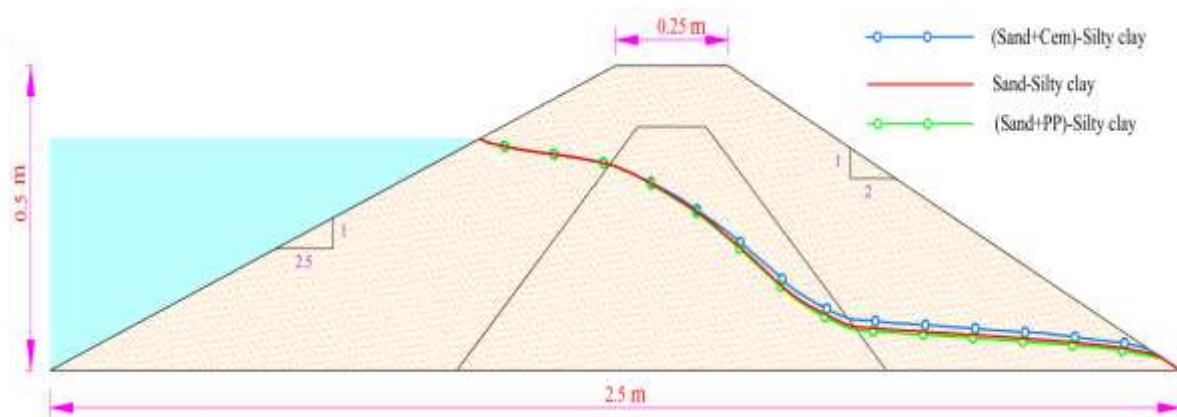


Figure 6. Schematic representation of the measured seepage lines

This behavior was due to the reduction in shell permeability after cement treatment, which limited drainage through the downstream shell and allowed a greater degree of wetting to develop in that zone. Therefore, the findings indicate that a lower seepage rate does not necessarily mean a lower phreatic surface. In the current models, the quantity of seepage was controlled by the core, while the downstream drainage pattern and position of the seepage line were controlled by shell permeability [6][12].

Dynamic Response

The dynamic measurements in figures. 7, 8, and 9 show that increasing the input PGA produced a gradual increase in crest acceleration, peak relative acceleration, and relative crest displacement across the three models. The untreated Sand–Silty clay model remained the most responsive case throughout the loading sequence, which reflects the limited capacity of the untreated sand shell to restrain motion when combined with a low-permeability silty clay core. By contrast, both shell-improvement methods reduced the transmitted response at the crest. The reduction was more consistent in the (Sand+Cem)–Silty clay model, while the (Sand+PP)–Silty clay model showed an intermediate behavior between the untreated and cement-treated cases.

The acceleration results should be interpreted together with the deformation and pore-pressure responses rather than from peak values alone. In figure 7, The untreated Sand–Silty clay model exhibited the highest upstream pore-water pressures and a lower rate of increase at the higher PGA levels. This would imply that the upstream shell had attained a critical cyclic state such that any additional shaking would not result in considerable increases in the pore-water pressure since there had been a substantial loss of effective stresses. The (Sand + PP) - Silty clay specimen resulted in reduced pore pressures at low levels of shaking, but the increase became larger at 0.4 g and 0.5 g. This implies that the polypropylene fibers were effective in delaying degradation of the shell, but could not prevent it under stronger shaking loads [8].

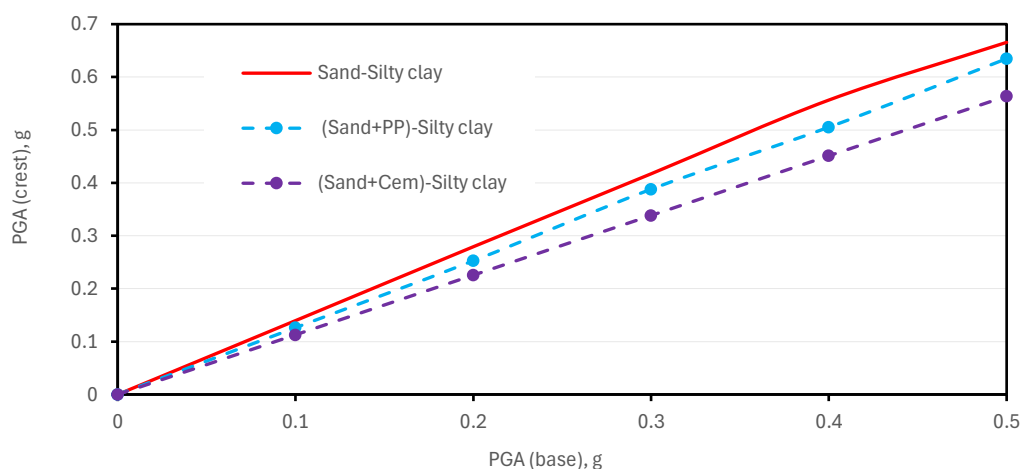


Figure 7. Crest acceleration

The results obtained for displacements followed a similar trend to those for accelerations. From figure 8 below, it is clear that the unmodified Sand – Silty clay specimen experienced relatively large displacements compared to those for the cement modified specimen whose displacements were the least along the whole loading cycle. Therefore, it can be concluded that improvement of the shell not only reduced the motion transmission through the crest, but also reduced the displacements of the embankment.

Permanent settlement in figure 8 gives a clearer indication of the accumulated damage during the loading sequence. Settlement increased with each PGA level in all models, but the untreated model accumulated the largest vertical deformation. At 0.5 g, the crest settlement was about 26 mm in the untreated Sand–Silty clay model, compared with about 18 mm in the (Sand+PP)–Silty clay model and about 5 mm in the (Sand+Cem)–Silty clay model.

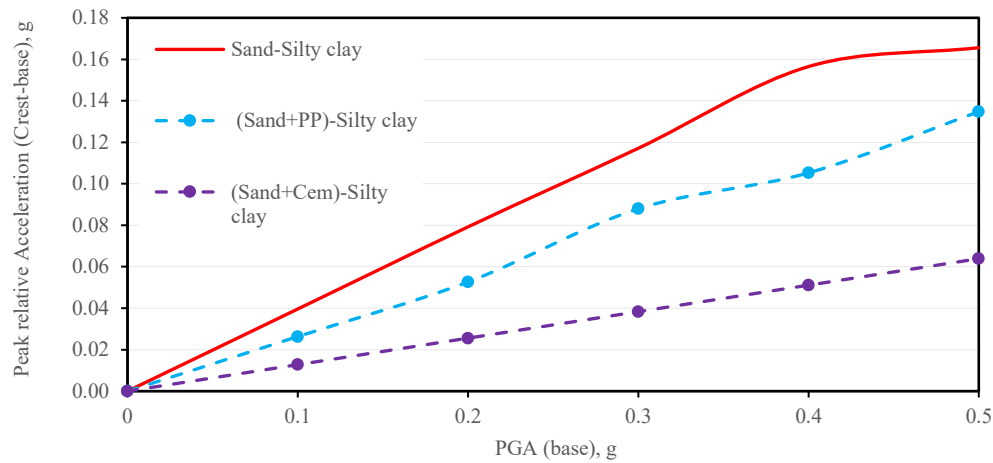


Figure 8. Peak relative acceleration

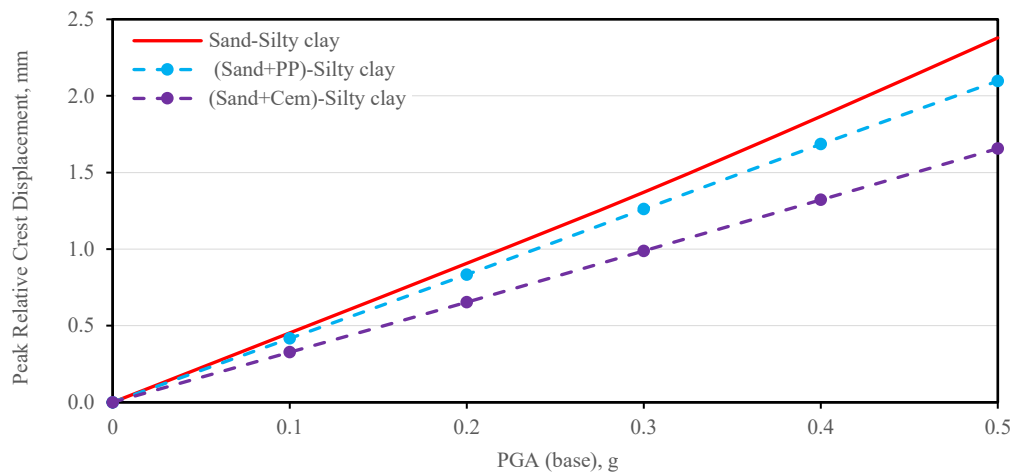
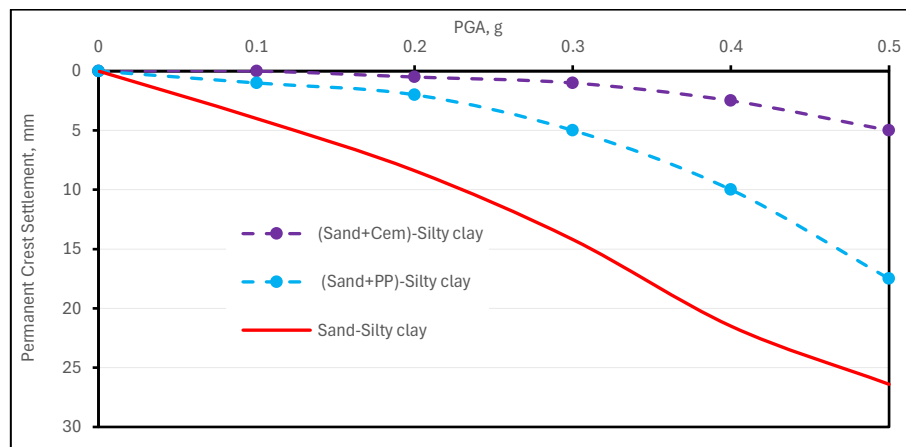


Figure 9. Peak relative crest displacement

The post-test photographs in figure 10 (A), 10(B) and figure 10(C) support this interpretation, as the cement-treated model retained a more stable crest profile after the final shaking stage. These results indicate that cement treatment provided the strongest control of cumulative deformation, while polypropylene fibers gave a partial but still measurable improvement over the untreated shell.



(A)



(B)



(C)

Figure 10. Permanent crest settlement: (A) Measured settlement of the tested models under different PGA levels, (B) (Sand+PP)-Silty clay after 0.5 g, and (C) (Sand+Cem)-Silty clay after 0.5 g

Pore-Water Pressure and Effective Stress at the Upstream Location

Figure 10 shows that an increase in the upstream pore water pressure occurred in all three models as the PGA was raised; however, the rate of increase was not the same for all of them. In the case of the untreated Sand-Silty clay model, it was found to have the highest value of upstream pore water pressures. Its rate of increase decreased when PGA increased. This indicates that its upstream part approached critical cyclic state, where any subsequent shaking could result in insignificant pore pressure build-up, since most of its effective stress had been lost. The (Sand+PP)-Silty clay model decreased its pore-pressure build-up at early stage of loading, but there was an increase in pore pressure at 0.4 g and 0.5 g. It means that polypropylene fibers postponed the failure of sand shell to some extent. The (Sand+Cem)-Silty clay model indicated the least increase, which could be associated with its high stiffness due to cement treatment [8].

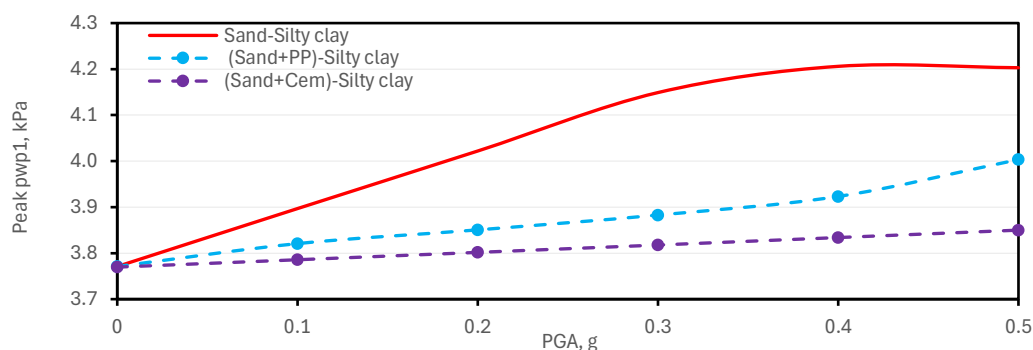


Figure 11. Peak pore-water pressure at upstream

Figure 11 illustrates the peak pore-water pressure at upstream. These results, which can be seen from figure 12, prove the above interpretation. The untreated sample demonstrated the most significant drop in effective stress, as it went down to zero effective stress at 0.5 g, showing an extremely unstable state of the upstream side. Although the fiber-reinforced sample was capable of maintaining relatively higher values of effective stress compared to the untreated sample, it had less stability at the last stage of testing. The cement-treated sample exhibited the highest effective stress values during loading. It is clear that the cementing material was more efficient in keeping stress in the soil skeleton.

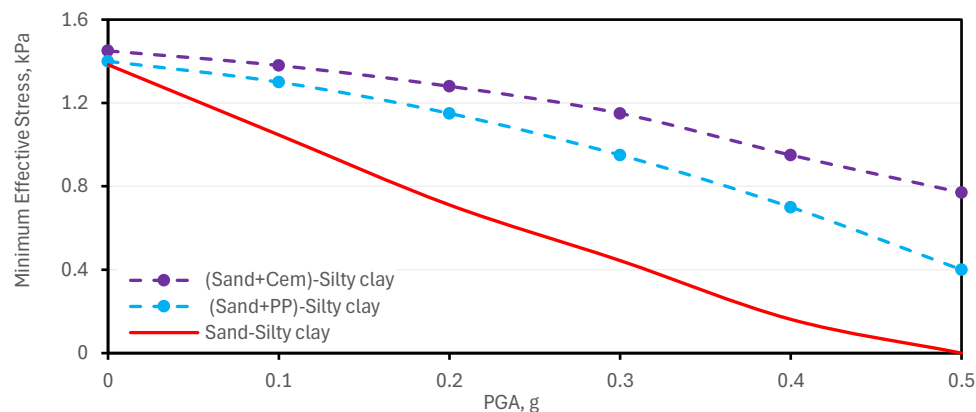


Figure 12. Minimum effective stress at upstream

Pore-Water Pressure and Effective Stress at the Central Location

For the central sensor, the recorded pore pressures were greater compared to those measured at the upstream face, as shown in figure 13. At this position, the embankment geometry is tighter, resulting in high pore water pressure due to the effect of saturation and overburden. Although this trend is observed for all cases, it should be noted that there were differences in the way the three models behaved. Specifically, the unprocessed Sand-Silty clay model had the highest pore pressures while both treated shell models produced lower pore pressures within the embankment. It can be seen that the (Sand+Cem)-Silty clay model resulted in lower pore pressures than the (Sand+PP)-Silty clay model [4][9].

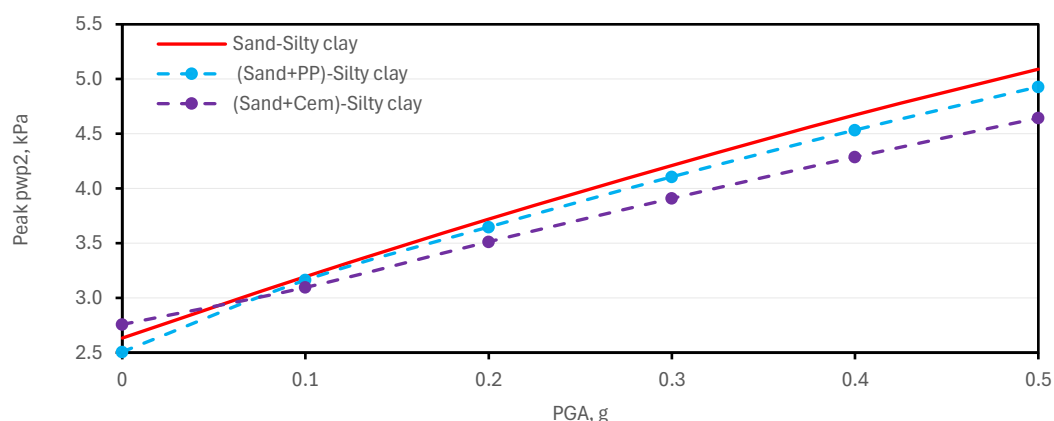


Figure 13. Peak pore-water pressure at central

In all cases, the effective minimum principal stress was always above zero for the entire period of vibration, as indicated in figure 14. As such, even though there was a relatively higher pore-water pressure in the central region compared to others, it still did not experience the same critical pore-pressure level as in the upstream portion. From this observation, it can be stated that in assessing the instability of the structure, not only pore-water pressure but the local total stress and the location of the sensor inside the dam must also be taken into account. The highest level of effective stress was

recorded for the cemented shell while the lowest was for the untreated one.

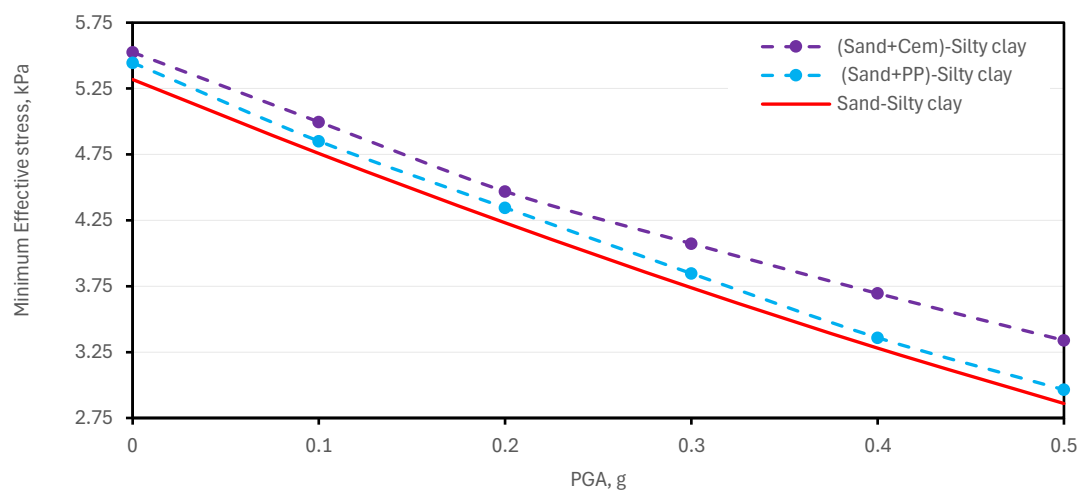


Figure 14. Minimum effective stress at central

Pore-Water Pressure and Effective Stress at the Downstream Location

While examining figure 15, one can find the biggest disparity between the untreated and treated shells in the downstream position. In the Sand–Silty clay untreated shell, the pore water pressure kept growing along with PGA, suggesting that the downstream shell had not managed to regulate the combined effect of both seepage and cyclic deformations. Even though the (Sand+PP)–Silty clay shell managed to minimize the phenomenon in question, pore pressure still grew in case of larger shake amplitudes. The (Sand+Cem)–Silty clay shell showed the smallest downstream pore water pressure among all three models studied. Even though cementation resulted in bigger downstream seepage lines for the constant state, the higher bonding ability of such material minimized pore pressure formation in shaking [5][10].

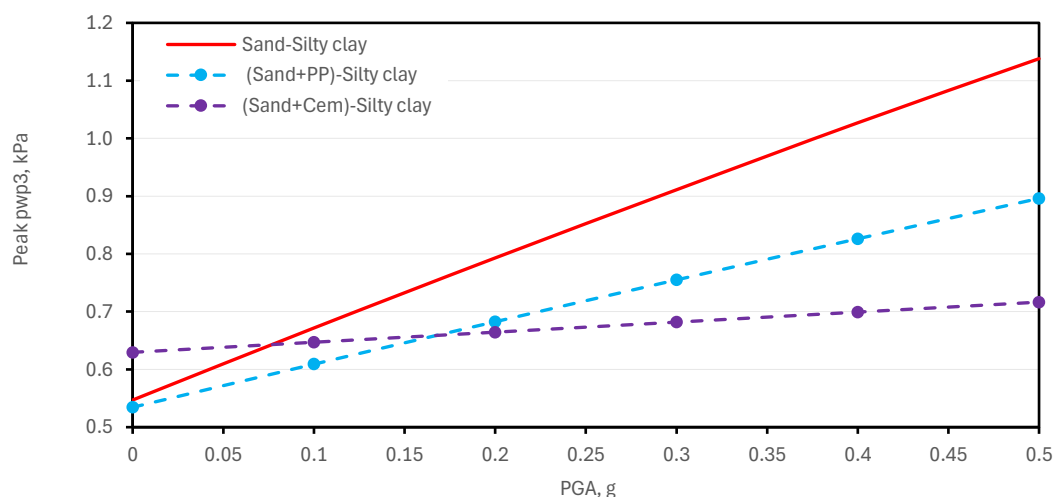


Figure 15. Peak pore-water pressure at downstream

Similarly, the effective-stress plot in figure 15 has been interpreted in the same way. In comparison with other shells, the untreated sample has the minimum value of effective stress, implying a relatively weak downstream performance. The presence of fiber reinforcement enabled the model to have higher effective stress compared with the untreated case; however, the result is still mediocre. The cement shell has been able to retain the highest value of effective stress, which confirms that there is reduced pore pressure formation in the soil structure. The finding shows that besides the seepage line, there was another factor that influenced the stability of the shell downstream [5][11].

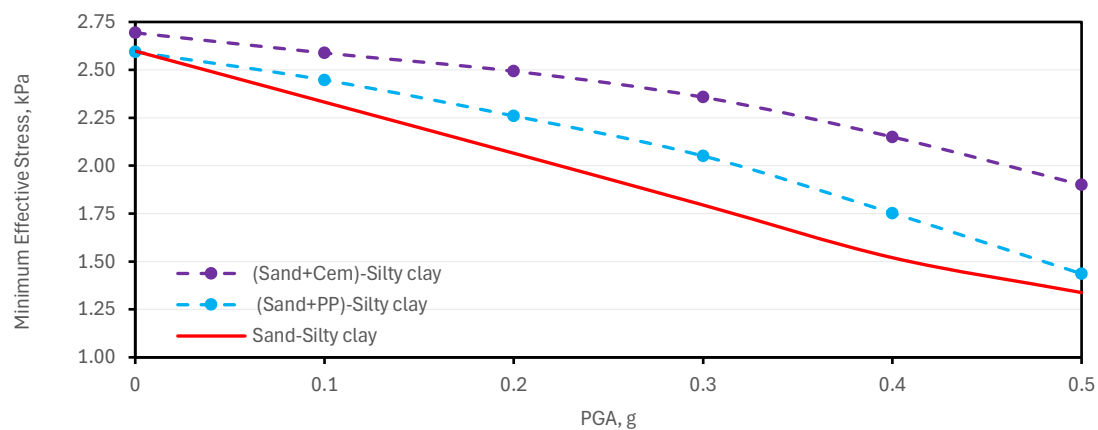


Figure 16. Minimum effective stress at downstream

Slope Stability and Crack Development

The stability results provided in figures. 16 and 17 show that the factor of safety gradually decreased with increasing input PGA. This trend was observed for both slopes, but it appeared earlier for the downstream slope. Further, the earlier decrease on the downstream side is consistent with the combined effects of seepage, cyclic loading, and pore-pressure generation in that region. The factor of safety, since it was calculated in a calibrated numerical analysis, should be interpreted in conjunction with the laboratory observations rather than as an actual measured value. The untreated Sand–Silty clay model exhibited the lowest stability values during shaking. The untreated and (Sand+PP)–Silty clay models were below the adopted reference level of 1.5 at the end of loading, which suggested that an unfavorable stability condition was reached. By contrast, the (Sand+Cem)–Silty clay model showed the highest calculated stability and had less visible slope deterioration compared with the other two models [13][15][17].

The crack measurements in figure 18 and the post-test photographs in figure 19 support the stability interpretation by showing the accumulated surface damage after shaking. The untreated Sand–Silty clay model experienced the most severe crest deterioration, including crack widening and localized crest failure at the higher PGA levels. The fiber-reinforced model demonstrated significant decrease in damage with the maximum crack width limited to only 15 mm at 0.5 g. However, cracks were still observed which means that even if fibers were successful in minimizing deformation, it could not completely prevent the appearance of cracks. For its part, the cemented model registered the minimum crack width not exceeding 5 mm at the last stage of the experiment and had only some signs of cracking at the crest and the top upstream area. This suggests that the application of cement was more successful than the application of polypropylene fibers [11][16]. Figure 20 (A), (B), and (C) shows the visual cracking and upstream slope response after 0.5 g: (Sand-Silty clay), (Sand+PP)-Silty clay, and (Sand+Cem)-Silty clay

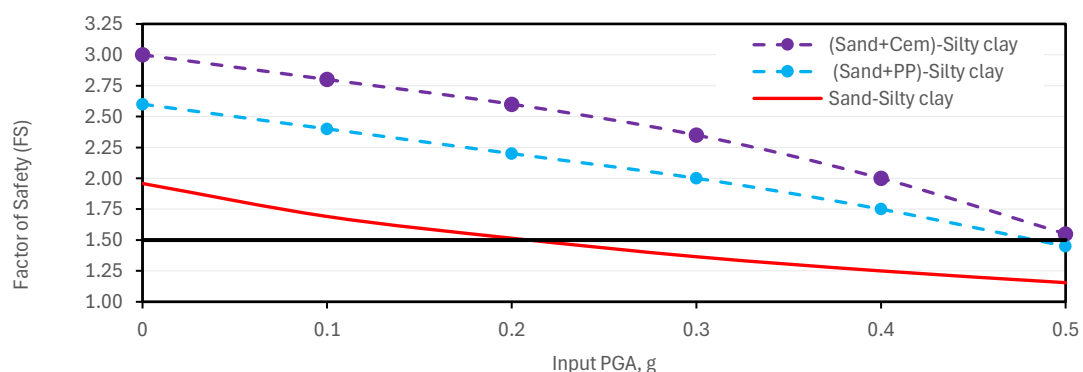


Figure 17. Upstream slope factor of safety

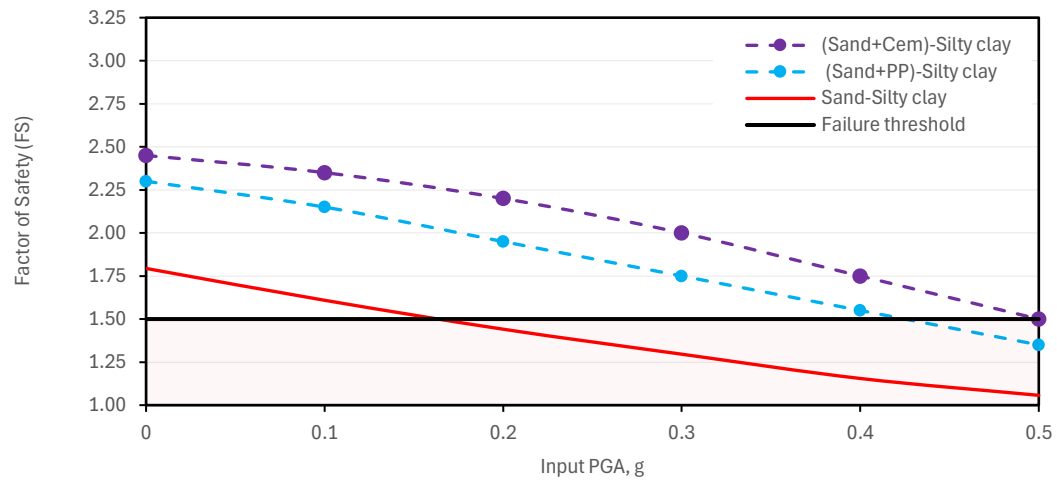


Figure 18. Downstream slope factor of safety

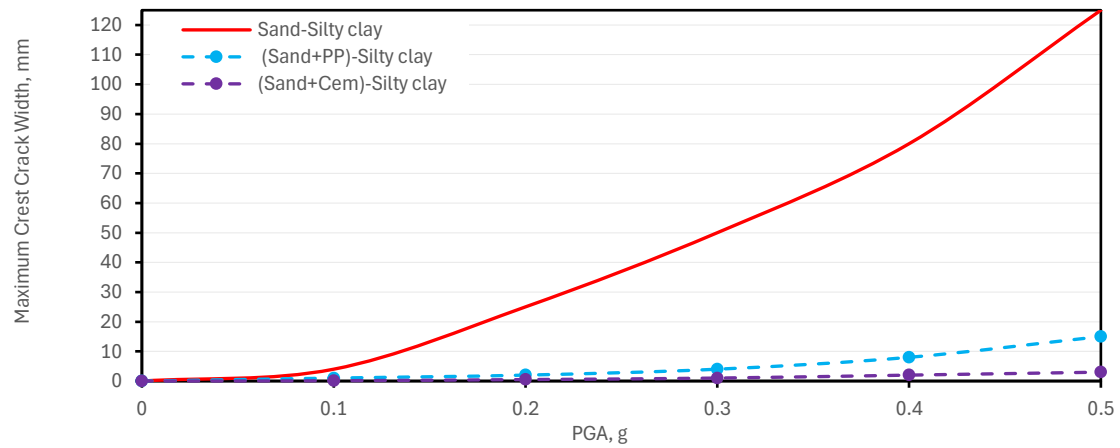


Figure 19. Maximum crest crack width



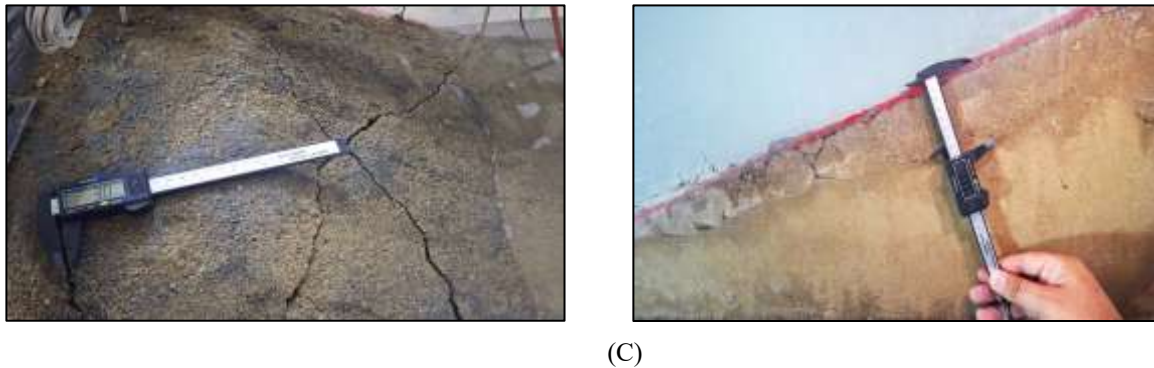


Figure 20. Visual cracking and upstream slope response after 0.5 g: (A) Sand-silty clay, (B) (Sand+PP)-Silty clay, and (C) (Sand+Cem)-Silty clay

Table 5 demonstrates the comparison with existing studies in experimental investigation on seismic performance improvement of earth dams.

Table 5. Comparison with previous experimental investigations on seismic performance improvement of earth dams

Study	Improvement Method	Test Type	Key Performance Indicators	Main Findings
[3]	Geosynthetic clay liner and sloping core configuration	Full-scale shaking table test	Crest deformation, seismic stability	Improved zoning reduced seismic deformation and enhanced dam stability under earthquake loading.
[5]	Evaluation of excess pore-water pressure effects in zoned dams	Numerical and dynamic analysis	Pore-water pressure, effective stress, seismic response	Excess pore-water pressure significantly influenced seismic performance and slope stability.
[8]	Fiber-reinforced sand under cyclic loading	Cyclic triaxial testing	Pore-water pressure generation, cyclic resistance	Polypropylene fibers delayed pore-pressure buildup and improved cyclic resistance.
[9]	Fiber-reinforced dense sand	Cyclic laboratory testing	Deformation resistance, cyclic behavior	Fiber inclusion reduced particle rearrangement and cyclic deformation.
[10]	Cement-treated sand	Laboratory mechanical testing	Strength and stiffness characteristics	Cement treatment significantly increased sand stiffness and resistance to deformation.
[11]	Crest improvement of small earth dams	Shaking table test	Crest settlement, crack development	Improved crest zones enhanced seismic stability and reduced cracking.
Present Study	Polypropylene-fiber and cement-treated sand shells	Seepage–earthquake coupled shaking table test	Seepage discharge, phreatic line, acceleration, displacement, pore pressure, effective stress, settlement, factor of safety, crack width	Cement treatment provided the best overall seismic performance, while fiber reinforcement provided moderate improvement. The coupled hydraulic–seismic response of zoned earth dams was comprehensively evaluated.

CONCLUSIONS

In this research, an attempt was made to evaluate the effects of sand-shell improvement by adding polypropylene fiber reinforcement and cement modification on the hydraulic and seismic behavior of miniature Scale Sand-Silty Clay zoned earthen dams. Three dams were considered with similar seepage condition and excited with El Centro earthquake motion having PGA of 0.1g to 0.5g. It was observed that improvement in shell has great impact on the dynamic behavior and stability of such dams. Based on the results of seepage analysis, there was little variation in discharge among the three tested models, recording values of around 2.69×10^{-7} , 2.75×10^{-7} , and 2.41×10^{-7} m³/s/m for the untreated, fiber-reinforced, and cement-treated model, respectively. The above results clearly prove that the silty clay core is the dominant seepage control component of the levee. The effects of seismic loads produced

more variation; hence, the untreated Sand-Silty Clay model recorded the largest value of crest acceleration, relative displacement, pore water pressure build up, settlement, and crack formation. At 0.5g, the settlement of the crest for the untreated model was about 26mm, compared to only 18mm and 5mm in the fiber-reinforced and cement-treated model, which resulted in a decrease of around 31% and 81%, respectively. In the same vein, the crack width reduced from around 125mm in the untreated model to 15mm and 5mm in the fiber-reinforced and cement-treated model, respectively. On the whole, polypropylene fibers offered an average improvement effect due to postponement of deformation and pore pressure generation; however, the cement-based treatment proved to be the most successful technique in terms of enhancing the seismic behavior of the shell structure. Further studies might focus on examining the issue of long-term durability of the shell structures following treatment, as well as on analyzing the influence of different concentrations of reinforcing fibers and cement, varying number of earthquakes, and fluctuating water level in the reservoir.

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