Adverse Effects of Repeated Deep Drawdown and Re-impounding Cycles on the Clay Core of Earth Dams; a case study of the Karkheh Dam

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ABSTRACT

In this study a method is proposed for investigation the effects of reservoir water-level fluctuations which results in wetting and drying cycles (WDC) in parts of the dam body. The WDC adversely affect the mechanical behavior of material in those parts, especially in semi-arid climatic areas, such as Iran. The degradation pattern of tested specimens is used for updating the material behaviour in numerical simulations of the Karkheh earth dam, located south-west of Iran. First the results of unconfined compressive strength (UCS) tests were simulated for calibration of the degradation pattern. Next, a sensitivity analysis was performed on the parameters affecting the UCS, which showed that cohesion is more effective than elastic modulus or friction angle. The degradation rates at each cycle were applied to the properties of dam core materials according to the WDC. The calculated vertical and horizontal displacements of the dam were compared to the recorded data, based on the reservoir level, for the period of 17 years and in two cases of either including the material degradation or ignoring that. The results showed that considering the material degradation makes a difference in deformations growing up to about 10 %. Considering the magnitude and importance of deformations, this is a significant impact. Also, a series of simulations were conducted based on maximum and minimum permissible water level assumed for the next 7 years in both cases. The results showed that ignoring the degradation can result in up to 20% under estimating of the deformations. The results emphasize the necessity of further research on the subject.

KEYWORDS

Embankment dams, Deep Drawdown, Drying-Wetting Cycles, Compressive Strength, Permeability Increase.

1. Introduction

Extensive research has been conducted on the effects of saturation and drying on compacted clay soils. The outcomes of these studies cover a wide range of factors, including the influence of the number of WDC, the quality of the soil, and the initial moisture content. Moreover, several investigations have examined the variations in soil strength parameters caused by loading and unloading cycles that occur during rapid wetting and drainage processes. However, these studies have not addressed the problem in the context of an embankment dam and its clay core. The previous research has primarily focused on the behavior of compacted clay soils—such as changes in permeability, cracking, swelling, and strength reduction—considered individually and solely as a result of WDC.

In contrast, the present study aims to analyze and model the combined effects of WDC, loading–unloading processes, and the nonlinear behavior of compacted clay soils. Salehian-Dastjerdi and Hemmat [6] concluded that the application of successive WDC on a low-plasticity clay sample leads to a reduction in shear strength and an increase in the soil's internal friction angle. de Costa et al. [7] through studies conducted on agricultural soils in the state of Ceará, Brazil, found that repeated WDC due to irrigation reduces the soil's porosity. Rogers [8], as cited in Kholghifard et al. [9], demonstrated that repeated WDC on silt soil not only increase the swelling potential but also decrease the shear strength of the soil. Wang and Wei [10] concluded that the pore structure of soil changes under WDC. The variations in micropores were found to be reversible, whereas macropore changes were irreversible. Kampala et al. [11], by adding carbide to a silt soil sample and subjecting it to WDC, found that the soil's strength behavior improved under such cyclic conditions. Goh et al. [12], using a triaxial test on soil samples subjected to WDC, reported that the soil exhibited lower strength during the wetting phase compared to the drying phase. They also noted that the most significant changes in soil strength occurred during the first cycle. Shi et al. [13] investigated the effect of wetting duration in successive WDC on soil strength behavior. Their findings indicated that longer wetting periods led to a reduction in soil strength. Naramitkornburee et al. [14], through Unconfined Compressive Strength (UCS) tests on cement-stabilized soil samples exposed to successive WDC, concluded that such cycles reduce the compressive strength of the soil. Du et al. [15] examined the compressive strength of magnesium-stabilized soil samples under WDC and found that successive cycles lead to a decrease in compressive strength, with the reduction being directly proportional to the number of WDC.

Naini et al. [16] studied the bearing capacity and UCS of a low-plasticity clay subjected to repeated wetting and drying. Their results revealed that the cycles cause a decrease in both parameters, and that the bearing capacity and compressive strength are lower during the wetting phase than during drying. Wang and Hu [17] examined the effect of rapid WDC on soil aggregate stability. Based on their findings, rapid cycles reduced aggregate diameter and consequently decreased aggregate stability. Sayem et al. [18] investigated the strength behavior of soils subjected to successive WDC using consolidated drained (CD) triaxial tests. Their results showed that both cohesion and internal friction angle decreased with cycling, and that from the fourth cycle onward, the reduction in

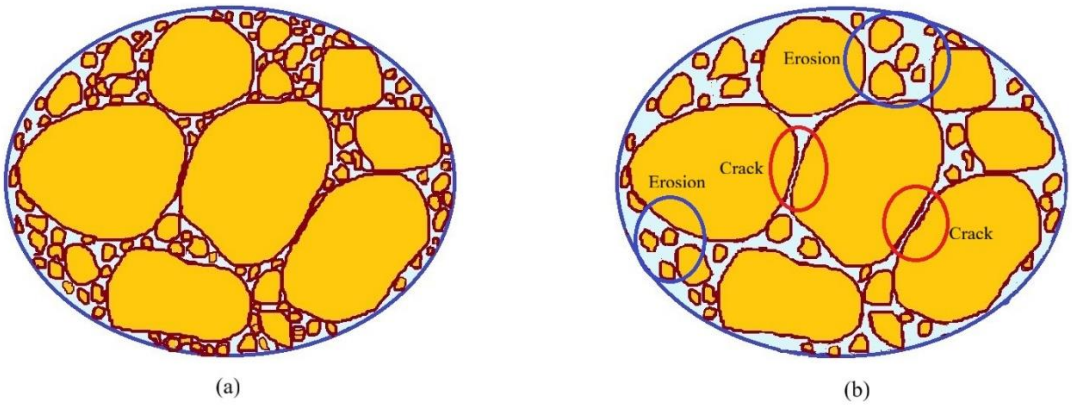


Figure. 1 Configuration of a compacted soil: (a) after compaction; (b) after WDC.

strength became nearly constant, indicating a stabilized behavior. Tang et al. [19] assessed soil strength under repeated wetting and drying using cone penetration tests and found that an increase in the number of cycles caused a reduction in soil strength, with the largest reduction occurring during the first cycle. Wang et al. [20] investigated a low-plasticity clay subjected to WDC and found that soil strength increased during drying, while the internal friction angle decreased. Akcanca and Aytekin [21] reported that lime addition to bentonite clay reduces its hydraulic conductivity. Gallage et al. [22] examined the influence of repeated wetting and drying on soil hydraulic conductivity and found that conductivity during drying was greater than during wetting. De Camillis et al. [23] also investigated the effect of repeated wetting and drying on soil hydraulic conductivity and found a significant increase in hydraulic conductivity with the number of cycles. Rosone et al. [24], based on lab tests on samples extracted from an in-situ embankment, found the mutual connection between hydraulic behavior (WDC and suction) and mechanical behavior such as strength, stiffness, and volumetric strains. Liu et al. [25], by applying WDC to a low-plasticity clay, concluded that successive cycles reduce shear strength while increasing the hydraulic conductivity of the clay. Luo et al. [26] indicated that with the increasing number of WDC, the relationships between shear stress and shear displacement have a tendency of transiting from strain-hardening to strain-softening type, and the greater number of WDC, the more significant signs of strain-softening. Also, that the shear strength parameters decreased first and then fluctuated slightly and irregularly near a certain value with the increase in the number of WDC. Ma et al. [27] investigated compacted low-plasticity clay subjected to controlled hydraulic WDC and observed that cyclic moisture fluctuations weakened water retention capacity, caused irreversible swelling–shrinkage deformation, and reduced the small-strain shear modulus by up to 35%. The soil progressively transitioned from a dense to a looser state, implying potential long-term instability of compacted embankments. Similarly, Cuisinier and Masrouri [28] examined lime- and cement-stabilized silty soils exposed to up to twelve WDC using both oven-drying and controlled-humidity protocols. Their results showed that repeated cycles caused marked reductions in UCS and increases in hydraulic conductivity, with degradation more severe under high-temperature drying due to leaching and microstructural damage. Cement treatment offered greater durability than lime, but both displayed substantial performance loss after several cycles. Complementarily, Sabatino et al. [29] reported that lightweight cemented soils also suffer stiffness and strength degradation after WDC, particularly under high relative humidity, as suction variations induce cement bond destruction. The amplitude of suction change and porosity level governed the extent of mechanical weakening. Collectively, these studies demonstrate that WDC trigger cumulative degradation of strength, stiffness, and hydraulic properties in compacted or cemented clayey soils, underscoring the necessity to incorporate environmental cyclic effects in the long-term design and durability assessment of geotechnical infrastructures. Estabragh et al. [30] studied swelling-shrinkage behavior of a compacted expansive soil (mixture of bentonite and kaolin) under WDC. It was concluded that the initial water content and compaction level significantly influence the volumetric behavior. Also, soils on the dry side of the optimum moisture content exhibit higher swelling potential. Cyclic wetting and drying significantly alter soil fabric through microstructural evolution, aggregate rearrangement, and pore network modification. Repeated shrink–swell processes induce crack formation, dissolution of interparticle bonds, and redistribution of fine particles, leading to changes in void ratio and pore size

distribution [31] [32] [33] [34]. Researchers have developed advanced constitutive models to better simulate the complex behavior of compacted clayey soils under cyclic wetting and drying [27, 35]. These models incorporate factors like suction (matric potential), void ratio, and stress history to predict the volume change and mechanical behavior of the soil. Periodic changes in the reservoir water level produce fluctuating hydraulic loadings on the soils imposes hydraulic loadings on slopes. In recent years, the effect of hydraulic fluctuation on suffusion has been emphasized. Prasomsri and Takahashi [36], Deng et al. [37], Wang et al. [38], Fu et al. [39] conducted different suffusion tests under various hydraulic fluctuations. The experimental results showed that hydraulic fluctuations could significantly promote the erosion process of internally unstable soil by increasing the fine particle eroded mass and hydraulic conductivity. Deng et al. [40] used finite element method and a suitable constitutive model, treated the unsaturated soil as a five-constituent mixture, by which both erosion and deposition could be captured by phase transition between deposition and fluidization of fines. The fines redistribution in the slope was modeled and the erosion was quantified based on the frequency of water level fluctuation. The numerical results indicated that a higher fluctuation frequency could promote fine particle loss in the zones near the slope surface, consequently inducing greater deterioration in the slope stability.

Liu et al. [41] studied the deformations of a dam body and analyzed how water levels fluctuations caused settlement deformation of the dam body. With the rise in the reservoir water level, the longitudinal cracks on the dam crest showed opening when the reservoir water level dropped. The fluctuation of the settlement deformation shows that the upstream side was larger than the downstream side, especially during the period of abrupt change in reservoir water level. Studies have also indicated that there is a progressive development to the plastic shear strain zone within the slope as the number of water level variation cycles is increased, and the change in the seepage field is closely related to the water level variations [42,43]. Chen et al. [44] investigated the effect of the shape of landslide slip surfaces and soil permeability on slope stability during reservoir fluctuating water level changes in the Three Gorges Reservoir area using numerical methods. It was indicated that line-shaped slopes with low permeability are most prone to instability, while chair-shaped slopes with high permeability are most stable. Also, as the water level drops, the slope's safety factor decreased initially and then increases.

Finite element analyses along with physical model experiments indicated that the safety factor, when the water level drops rapidly, is generally slightly lower than the safety factor when the upstream water level rises rapidly [45,46, 47].

A brief review of the previous studies clearly displays the need for assembling these studies in the context of structural analysis of the dam body, as these studies has only been performed on the specimens. The issues like the effect of size of the dam and its boundary conditions and the severity of the climate change, such as the duration of draught and rain intensity, need to be addressed, too [48, 49]. Also, the complex micromechanics of the soil under such hydromechanical loading path is too complex to be addressed here. Therefore, this study has been confined to a macro scale analysis of a dam based on micromechanics of the specimens.

Karkheh dam is a strategic infrastructure of southwest part of the country. Its huge dimensions make it a necessity to predict any possible problem in its performance. In this study, considering the latest waves of drought period, the long-term effects of the fluctuations of water level in the reservoir of Karkheh dam on the deformations of the impervious core is studied. The degradation of the compacted core due to WDC is included in this research.

2. Materials and methods

As this research is a numerical study on previously collected data, a brief discussion on numerical method and its details are presented here. Also, the data used in this research has been partly reported in earlier studies and partly has been obtained from the government agencies. The creative method of using the collected data, based on similarity of the effect of wetting and drying process on similar materials, has been discussed here.

2.1 Finite Element Method

The softwares developed based on finite element method, such as SIGMA/W, use a partial differential equation which depends on the type of problem under study. The coupled problems involving simultaneous solution of equilibrium and flow equations are formulated based on combination of linear momentum balance (eqn. 1) and fluid mass conservation (eqn. 2):

$$\nabla \cdot \sigma + \rho g = 0 \quad with\ \sigma = \sigma' - \alpha p I \qquad (1)$$

where σ is total stress, σ' is effective stress, p is pore pressure, α is Biot's coefficient (≈1 for most soils), ρ is density, and g is gravitational acceleration.

$$\frac{\partial}{\partial t}(\alpha \nabla \cdot \mathrm{u} + \mathrm{S} \cdot p) + \nabla \cdot q = Q \qquad (2)$$

where u is the displacement, S is the storage coefficient, q is Darcy flux, and Q is an external source/sink. The Darcy's law is defined as:

$$q = -k \cdot \nabla p \qquad (3)$$

where k is hydraulic conductivity. The effective stress-strain relationship for nonlinear materials is:

$$\Delta\sigma' = D_{tan}\,\Delta\varepsilon \qquad where\ \varepsilon = {}^{1}/_{2}(\nabla u + \nabla u^{T}) \qquad (4)$$

Here, D_{tan} is the calculated based on the constitutive equation of solid structure updated at each iteration. This constitutive equation can be any complex nonlinear elastoplastic model.

In general, the basic objective in a nonlinear analysis is to find the state of equilibrium of a body corresponding to the externally applied loads. In an incremental load formulation, these loads are a function of time, and at time t the nonlinear equilibrium problem can be formulated as a solution of the equation (5):

$$\{\psi^t\} = \{R(a)^t\} - \{\mathrm{F}^t\} = 0 \qquad (5)$$

where $\{\psi\}$ is the nodal unbalanced/residual forces, {F} is the externally applied nodal forces, {R} is nodal forces equivalent to element stresses, and, a is the nodal displacements. Due to equilibrium, at each stage i the eqn. (5) can be written as equation (6):

$$[K_i]\{\Delta u_i\} = \{\Delta F_i\} - \{F_{int,i-1}\} \qquad (6)$$

where: $[K_i]$ stands for stiffness matrix for the currently active elements, $\{\Delta u_i\}$ is incremental displacements, $\{\Delta F_i\}$ is applied load increment, $\{F_{int,i-1}\}$= internal forces from previous stage. In coupled systems the equilibrium at each step can be written as:

$$\begin{bmatrix} K_{uu} & K_{up} \\ K_{pu} & K_{pp} \end{bmatrix} \begin{bmatrix} \Delta \mathrm{u} \\ \Delta p \end{bmatrix} = \begin{bmatrix} R_u \\ R_p \end{bmatrix} \qquad (7)$$

where p is the vector of nodal pore pressure and u stands for the vector of the nodal displacements. K_{uu} represents the structural stiffness, *Kup* and *Kpu* represent coupling between pore pressure and deformation, and *Kpp* contains hydraulic conductivity and storage terms. Implementation of boundary conditions and their changes are conducted at the beginning each new stage.

2.2 Staged Construction simulation method

Staged construction analysis is a specialized simulation technique used to model how a structure or system is built up over time (in

"stages"), rather than assuming the entire structure exists and is loaded all at once. This is critical for geotechnical and civil engineering problems (e.g. embankments, tunnels, dams, or buildings) where stress history and construction sequence strongly influence behavior. The core concept in this analysis is simulating the actual sequence of material placement, excavation, or load application by using activating and deactivating elements, boundaries, or loads in a time-dependent or stepwise manner. At each construction stage new elements representing added material (like a new soil layer, concrete pour, or embankment lift) are activated and removed elements representing excavated material are deactivated. In order to deactivate an element two implementation methods are common. Either the element stiffness is removed from the global stiffness matrix, or the stiffness of the element is set to a very small value. Stress redistribution is computed after each stage via residual force method. Each analysis represents a step of construction, and these analyses are linked in a parent–child hierarchy. This means every child analysis inherits the stresses, pore pressures, and deformations calculated in its parent stage. Each new child analysis adds or removes material and automatically begins from the mechanical and hydraulic state of the previous one.

A typical staged construction workflow in GeoStudio begins with an initial analysis that establishes the in-situ conditions of the ground. This is often done with a steady-state SEEP/W run to compute pore pressures and a corresponding SIGMA/W gravity analysis to generate the initial stress field. Once the initial state is defined, the first construction stage is created as a child analysis of the initial one. In this new analysis, the first lift of fill material or the first excavation step is activated, and the software solves for the resulting changes in stress and deformation. If the construction process includes waiting periods—such as consolidation between embankment lifts-engineers can insert a transient coupled SIGMA/W–SEEP/W analysis to simulate the dissipation of pore pressures over time.

Managing complex construction sequences is conducted via a hierarchical approach. Each stage is visually represented as a node in the Analysis Tree, making it easy to trace the modeling history or adjust earlier steps. The coupling between SIGMA/W and SEEP/W allows both undrained and time-dependent (drained) responses to be captured accurately. Time control is highly flexible—the user can define the duration of each consolidation step or allow the solver to determine when steady-state conditions are reached. This design makes GeoStudio particularly well suited for embankment construction, soft soil consolidation, or staged excavations where both mechanical and hydraulic effects are significant.

2.3 Material properties of the validation stage

Results from previous tests, such as those by Panahi et al. [50], were used to evaluate the accuracy of the method used for determining the degree of material degradation in each wetting–drying cycle. The materials of tested specimens had been collected from the borrow area of the clay-core materials used in the Shahid Yaghoubi dam [50]. Shahid Yaghoubi dam, a rockfill dam with central clay core, is located 32 km from Torbat-e-Haydarieh city, in Kasalar watershed on the Kasalar river. The arid area and drought period has caused sever fluctuations in reservoir level. The properties of the materials used in the design of the Shahid Yaghoubi dam are presented in Table (1) [50]. Also, the variations after each cycle are presented in Table (2). Figure (2) presents the variations of UCS for different initial saturation ratio (ISR) and after each cycle of wetting and drying.

Table 1. Material properties of clayey compacted specimens of shahid Yghoubi dam [50].

Gs	L.L. (%)	P.I. (%)	w_{opt} (%)	$\gamma_{d,max}$ (kN/m^3)	C (kPa)	ϕ (°)	q $_{ucs}$, (kPa)	k (m/s)
2.69	45.5	22.5	17.3	17.70	100.24	29.96	551.39	10^{-9}

Table 2. UCS of compacted clay specimens at different ISR and after different WDC [50].

WDC \ Sr (%)	UCS (kPa)					
	Dry	20	40	60	80	Saturated
0	537.9	551.1	473.6	408.4	345.9	309.8
1	530.8	542.3	458.6	396.1	330.0	291.3
2	521.2	530.8	450.7	384.6	320.3	280.7
3	500.0	513.2	426.0	360.0	289.5	250.8
4	484.2	496.5	418.1	352.1	286.0	249.0
5	475.4	488.6	419.0	347.7	280.7	242.0
6	469.2	482.4	411.9	341.5	272.80	234.9
7	463.9	476.2	405.8	334.4	267.2	227.9

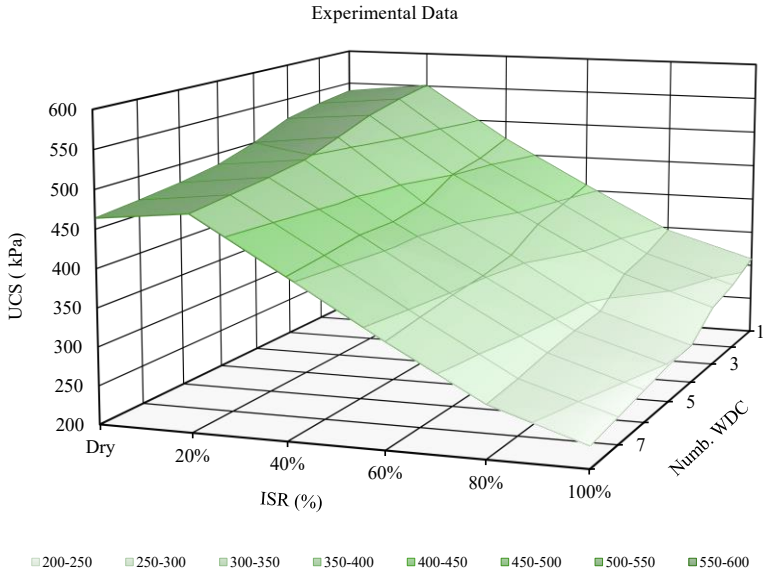


Figure 2. UCS of compacted clay specimens based on ISR and WDC.

2.4 Material properties and geometry of the Karkheh dam

The Karkheh Dam, an earth-fill embankment with a central clay core, is a major embankment dam located in Iran's Khuzestan province. This multi-purpose structure, is constructed using about 30 million cubic meters (Mm³) of different classes of soil and rock, and can store up to 7.8 billion cubic meters of water. The dam is 127 m in height, the crest width is 12 m and its length is about 3000m. The dam crest is situated at an elevation of +234.00 m above mean sea level (MSL), while the minimum foundation level is at +106.00 m MSL. The normal water level is maintained at +220.00 m MSL, and the reservoir has a total storage capacity of approximately 5,572 Mm³ at the maximum water level. The width at the base level is 1100 m. The upstream face has a slope of 1V:2.25H, while the downstream slope is 1V:2.50H. Figure (3) shows the cross section of the dam, its foundation and cut off wall. The dam's foundation is composed of

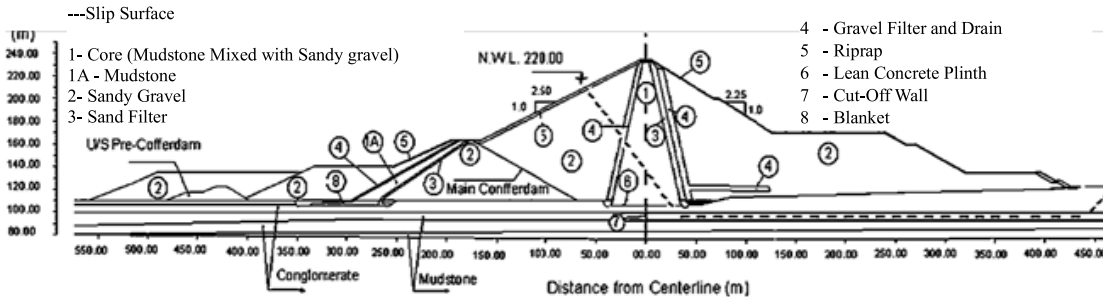


Figure 3. The configuration of the Karkheh dam

interbedded conglomerate and mudstone layers. Geotechnically, the dam site is within the highly active Zagros seismotectonic zone. The dam is underlain by thick alluvial deposits, consisted of gravel, sand and silt and sedimentary marl and limestone rock formations of the Zagros Fold Belt. The thickness of this alluvium varies between 30 to 70 meters. The water tightening measures consisted of a deep cutoff trench excavated beneath the clay core to key into the underlying impermeable marl, complemented by a triple-line grout curtain. This curtain was drilled to depths reaching 70 meters in certain sections. Sand and gravel filters, placed adjacent to the core, with a permeability of typically 10^{-4} to 10^{-5} m/s. The rockfill shells, which provide the embankment's structural stability, consist of quarried rock compacted in approximately 1-meter-thick layers. [51]

According to tectonic studies (MGCE, 1998), the nearest active feature is the Lahbary fault, located approximately 20 km from the dam and extending for 150 km. Also, the recorded available data on the water level of the Karkheh Dam, obtained from the Khuzestan Water and Power Organization, based on the water levels from 2002 to 2020 (1381–1399 in the Iranian calendar) the variations of 3-month average of water table level in the reservoir of the dam were calculated and plotted in Figure (4).

The seismological studies indicated that the peak ground horizontal accelerations of the dam site corresponding to Design Base Level (DBL) is 0.23 g, Maximum Design Earthquake (MDE) is 0.28 g, and the Maximum Credible Earthquake (MCE) is as high as 0.4 g at the top of bedrock**.** The design geotechnical properties of the materials are presented in Table (3). [51]

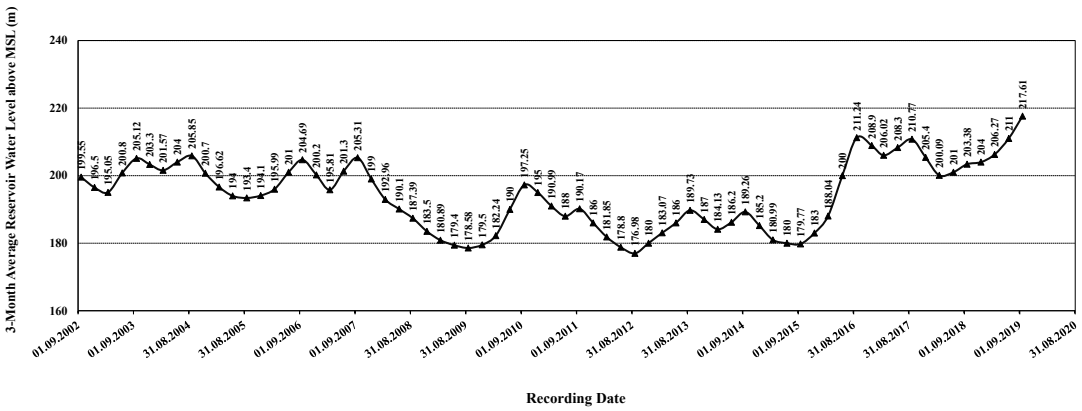


Figure 4. Variations of 3-month average of water table level in the reservoir of the dam

Table 3. Material properties and geometrical parameters used in simulations

Param.	Shell	Core	Filter	Cut off wall	Mudstone layers	Conglomerate layer (1)	Conglomerate layers (2) & (3)
γ_{dry} (kN/m^3)	20	17.4	19	21	19.5	21	21
$\gamma_{sat.}$ (kN/m^3)	22	20.2	20	22	21	23	23
Permeab. (cm/s)	10^{-4}	5×10^{-7}	10^{-3}	1×10^{-7}	5×10^{-8}	4.5×10^{-2}	1.1×10^{-3} (Cong. 2) 6.1×10^{-4}(Cong. 3)
E, (kPa)$\times10^4$	11	3.5	7	400	12	80	100
ν	0.25	0.35	0.27	0.25	0.3	0.25	0.25
C_{uu}, kPa	-	70	-	800	-	-	-
C', kPa	0	30	0	700	70	85	85
ϕ_{uu}, (°)	-	6	-	28	-	-	-
ϕ', (°)	39	20	35	33	22	39.4	39.4
ψ, (°)	10	2	8	10	5	10	10

The finite element discretization of the dam body was established through a systematic mesh convergence study. Multiple meshes with varying element densities were generated to assess their influence on the numerical accuracy and computational efficiency of the simulations. The optimal mesh was selected based on the criterion of achieving sufficient accuracy in the computed responses while minimizing the computational cost. The final discretization adopted for the analysis is presented in Figure (5).

2.4 Method of study

The objective of this study is to analyze the deformation and stability of an earth dam subjected to wetting and drying effects caused by fluctuations in the reservoir water level. The core of the dam, which is constructed from compacted clay soils, typically remains in an unsaturated condition. Therefore, understanding the behavior of these materials under environmental factors such as repeated wetting–drying cycles is essential.

In this study, first the degree of degradation of the compacted clay was determined as a function of the number of WDC based on findings from previous laboratory studies which quantified the changes in soil parameters after various WDC. These degrees of degradation were presented in the form of modification coefficients. In calibration stage the properties of tested specimens were modified by multiplying with modification coefficients and the resulted modified properties were used in numerical simulations. It worth mentioning that the micromechanics of the process is very complicated and includes some sensitive issues. However, this research is intended to check the feasibility of a linear approximation of degradation rate, via a comparison of numerical simulations with observation data. Next, the results of simulations were compared with those of experiments for validation. In sensitivity stage of simulations, the calculations are conducted using each of the main properties, while the other main properties

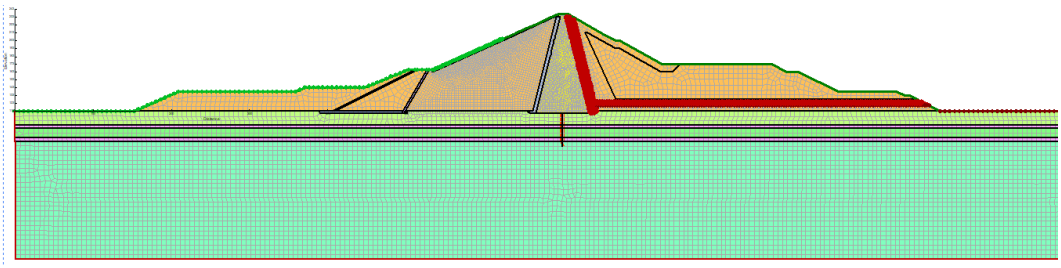


Figure 5. Discretization of the dam body employed in the finite element simulations

are constant. Also, in Karkheh dam simulations, the main design properties of the core of the Karkheh dam, were modified using the modification factors validated in calibration stage and according to the number of cycles each zone of the core experiences. The material properties in these zones were then manually updated in the Staged Construction mode of GeoStudio to reflect these effects accurately.

However, it is important to note that under laboratory conditions, the WDC are performed in a strictly controlled and systematic manner, whereas in large-scale structures such as earth dams, the field conditions are much more complex. In the problem in hand, the changes of water level in reservoir applies load variations, which results in stress changes and deformations. Also, the variations of material properties due to changes in saturation ratio or water content, contribute to changes of deformations, even under constant load. Therefore, at each water level, first the seepage analyses were carried out to identify the zones of the dam core which undergo wetting and subsequent drying due to water-level fluctuations.

3. Results and Discussions

This research is comprised of the following steps: a) numerical simulation of the results of laboratory tests on soil specimens: This step is aimed at calibration and validation of the assumed trend of degradation in material properties, b) sensitivity analyses to show which soil property is more effective, c) numerical analysis of the Karkheh dam: conducted based on the available data of reservoir water level and modified material properties in order to estimate the effect of WDC on the deformations of the dam.

3.1 Calibration simulations

The main objective of this stage of simulations is to validate the method of estimation of the degree of degradation of material properties of the core of a typical embankment dam after each cycle of wetting and drying. This is achieved based on the degree of agreement between experimental and simulation results of the UCS of tested specimens prepared with different ISR and after each cycle of wetting and drying.

Based on the Table (2), the percent of loss of UCS after each cycle of wetting and drying was calculated as presented in Table (4). This percentage was averaged over the specimens with different ISR, as presented in Table (4). Also, according to the tests results provided by Panahi et al. [48], after seven cycles, the cohesion and elastic modulus of specimens decrease by 80% and 11%, respectively. But, the internal friction angle and hydraulic conductivity of the specimens increase by 2.7% and 58%, correspondingly. Combining these figures with Table (4), a set of modification factors were calculated for these parameters, as presented in Table (5).

The simulation steps, including wetting, drying and loading steps, are displayed in Figure (6). Also, the loading step and outputs of computations are depicted in Figure (7).

Table 4. The percent of degradation of compacted clay specimens at different ISR and after different WDC.

	Loss of UCS after WDC, (%)						Average Loss after each WDC for all specimens, (%)
Sr (%) / WDC	Dry	20	40	60	80	Saturated	
0	0	0	0	0	0	0	0
1	9.52	11.76	22.08	16.67	20.22	22.58	17.14
2	13.10	15.29	11.69	15.48	12.36	12.90	13.47
3	28.57	23.53	36.36	33.33	39.33	36.56	32.95
4	21.43	22.35	11.69	10.71	4.49	2.15	12.14
5	11.90	10.59	-1.30	5.95	6.74	8.60	7.08
6	8.33	8.24	10.39	8.33	10.11	8.60	9.00
7	7.14	8.24	9.09	9.52	6.74	8.60	8.22

Table 5. The modified properties of compacted clay specimens used in numerical simulation of each W-D cycle.

WDC	Cohesion, (kPa)	Friction Angle, (^{0})	Permeability (m/s*10^{-7})	Modulus of Elasticity (MPa)
0	100.2	29.96	2.00	30000
1	86.5	30.1	2.20	29332
2	75.7	30.2	2.36	28806
3	49.3	30.5	2.74	27521
4	39.5	30.6	2.88	27048
5	33.9	30.7	2.96	26772
6	26.6	30.8	3.06	26421
7	20.1	30.9	3.16	26100

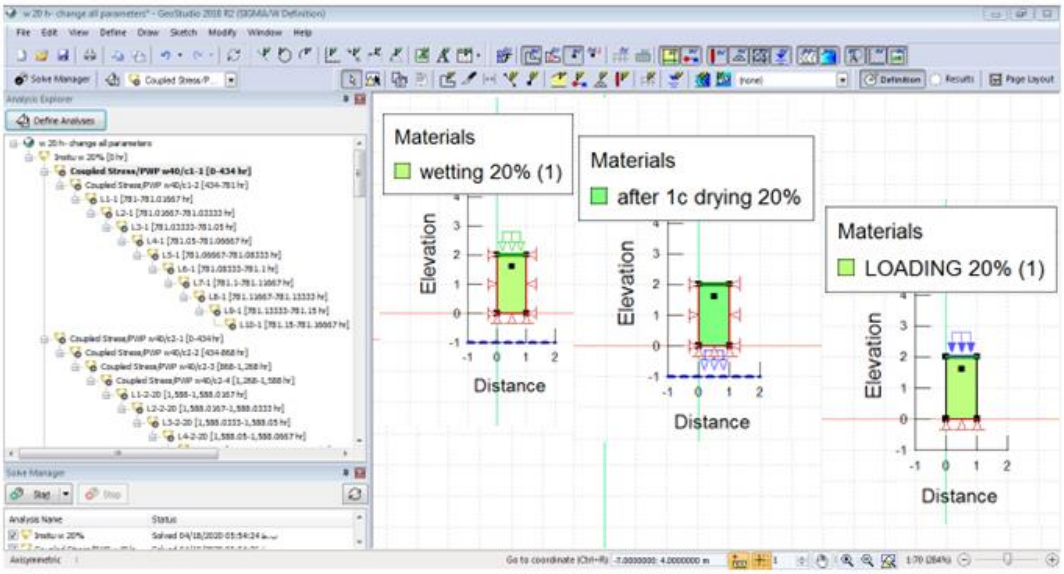


Figure 6. An artificial combined display of the steps of simulation of each test.

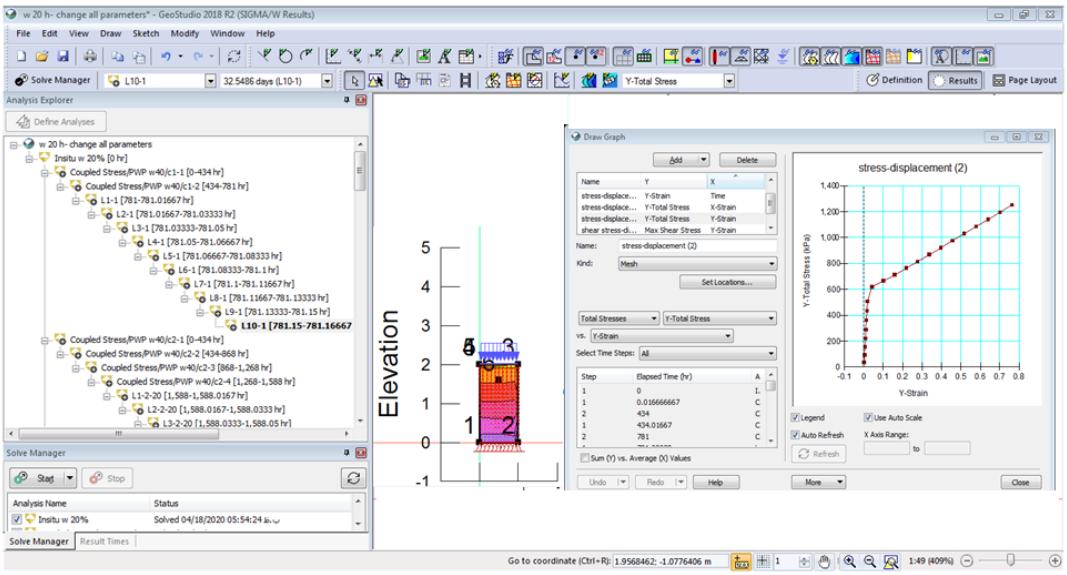


Figure 7. An artificial combined display of the output of software.

After determining the degree of changes of each material property following each number of WDC, numerical simulation of UCS tests was performed, and the method used to apply the effect of WDC was validated. In these simulations, the specimens were numerically subjected to designated WDC, and at the final drying stage, the moisture content was retained at the target level. Then the specimens were subjected to unconfined compression loading in ten steps taking a total of 10 minutes long. The results of simulated tests were compared with the physical test in Figure (8). The results show a maximum difference of about 17% and an average of 10%. The discrepancy between test results and simulation results can be attributed to two main points: a) the errors in selection of suitable values for parameters of main properties, such as friction angle and modulus of elasticity, b) the simulations are based on continuum mechanics, which assumes that the material is stable in high levels of strain such as 15%, which is used as the criterion of failure according to ASTM D2166. While during the experimental tests the specimens may fail physically and reach failure earlier and at lower strains such as 10%. As a result, the test would terminate sooner, and a lower compressive strength would be recorded for the samples compared to the software simulation.

3.2 Sensitivity Analysis

The purpose of this stage was to examine the sensitivity of the UCS of the specimens to the changes in each of the design parameters including cohesion, internal friction angle, hydraulic conductivity, and elastic modulus. Therefore, in this stage, each of the parameters were varied individually, while other parameters where kept constant at their initial value. The simulation process has followed the same procedure as in the validation analysis, and the soil initial parameters pertain to Shahid Yaghoubi dam. However, the degradation pattern for each property was assumed to be the same format as tested in validation stage. The results are presented in Figure (9).

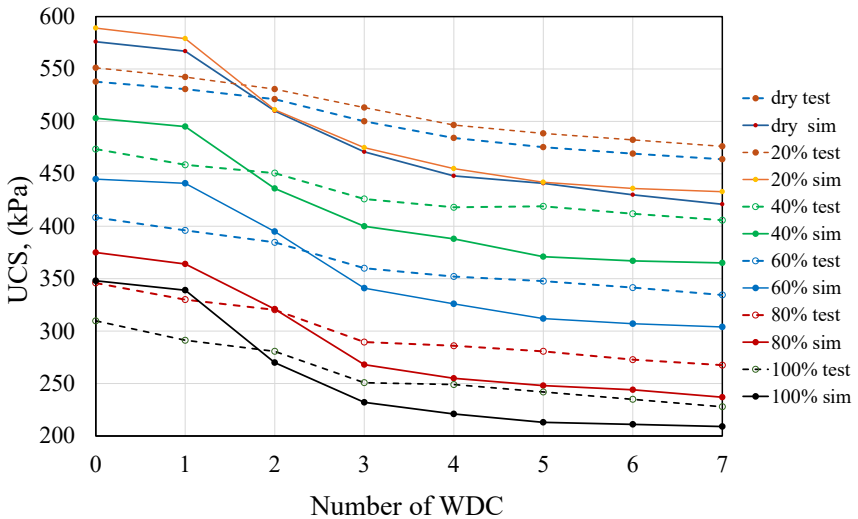


Figure 8. Comparison of the physical and simulated tests results.

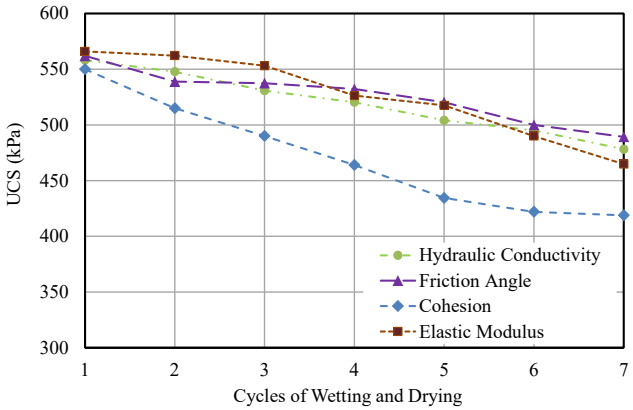


Figure 9. Effect of different material properties on UCS.

Figure (9) shows that during the first to third WDC, the reduction in the elastic modulus has the least effect on decreasing the strength of the samples. In the fourth to seventh cycles, the smallest reduction in strength corresponds to changes applied to the soil's internal friction angle. In general, it can be stated that applying changes to the parameters of elastic modulus, hydraulic conductivity, and internal friction angle results in UCS reductions of similar magnitude. However, changes in soil cohesion have a significantly greater negative effect on UCS, imposing a much larger reduction compared to the other parameters.

3.3 Karkhekh simulations

In order to show the effect of incorporating the degradations of material properties in numerical simulations, as compared to the design material properties, the numerical modeling was conducted in three stages. First, the Karkheh Dam was re-analyzed while incorporating the modifications factors calculated and validated earlier, to the properties of core of the dam in zones subjected to WDC. The objective was to estimate the resulting extra deformations, stress re-distributions. Next, the deformations of dam body during the next seven WDC, considering maximum and minimum permissible reservoir levels, 230.7 m and 178 m respectively, were predicted. In order to present the displacements values, five points along the central axis of the dam and at various elevations from the crest down to levels near the foundation were selected (Figure 10). The coordinates of the selected points are presented in Table (6). Finally, the stability of upstream slope was studied.

Table 6. Coordinates of the selected points

Point	1	2	3	4	6
X-coor.	700.7	700.2	700.7	701.2	702.4
Y-coor.	237	200	178.6	157.4	120

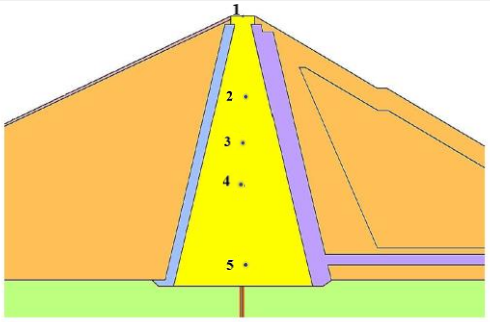


Figure 10. Location of selected points for graphs.

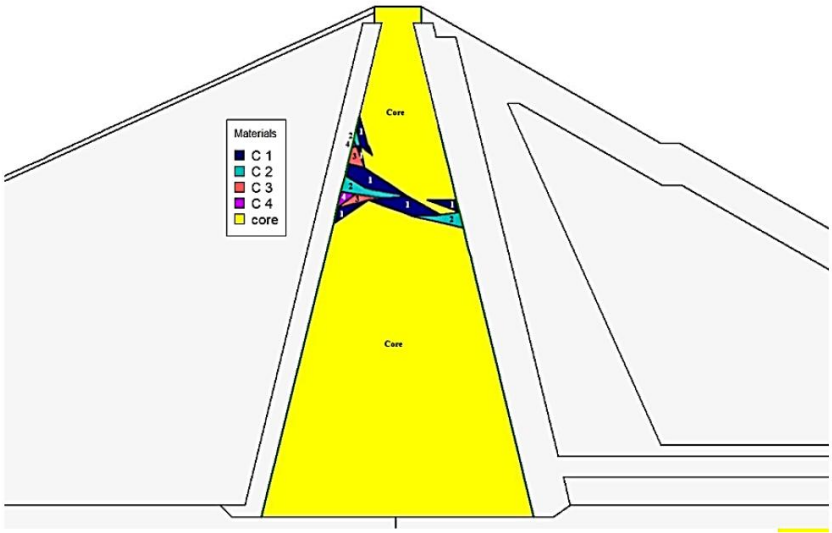


Figure 11. Location of areas which experienced repeated WDC and the number of cycles.

Based on the seepage analysis and considering the water table fluctuations during the period of study (2002 to 2020), some areas of the core of the dam have gone under the wetting-drying cycles. Figure (11) shows the number of WDC each part has undergone. The number is included in the legend of the area. The areas labeled as "core" include areas either stayed above the phreatic line or stayed saturated during the period of study. However, these after each cycle of wetting and drying the properties of the area has first been modified and then the changes were used in calculations of the next step.

3.3.1 Displacements in the period of 2002 to 2020

Vertical displacements

As one of the primary objectives of this research was to investigate the effect of WDC on the degradations in the soil properties of the affected zones and the resulting deformations induced within the dam body, the vertical displacement profiles are first presented. The results obtained from analyses for both cases of incorporating or ignoring the degradations in the core material properties following the WDC, are first presented in Figure (12) for a period of 18 years, from 2002 to 2020.

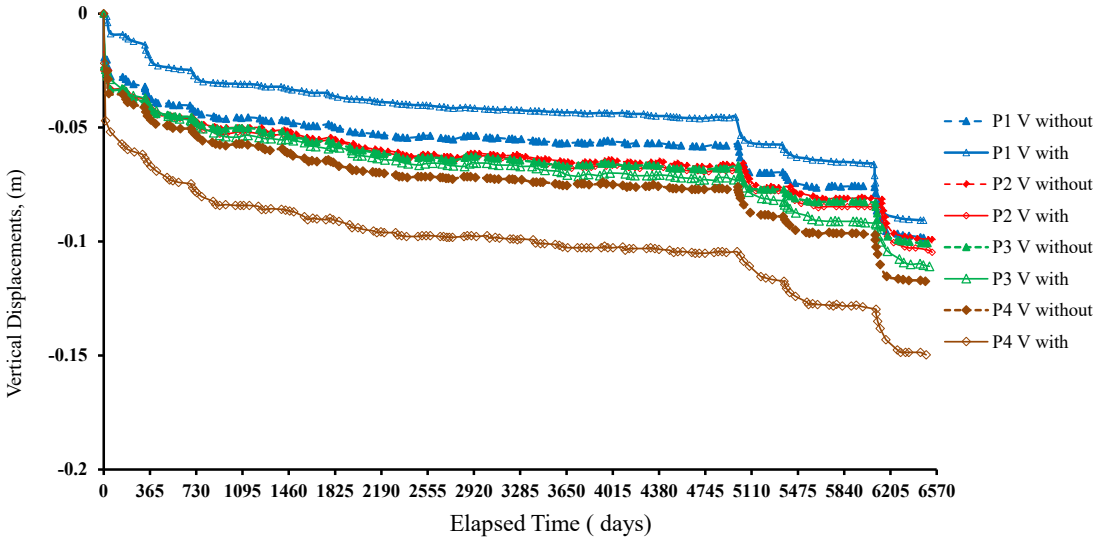


Figure 12. Vertical displacements of selected points under repeated WDC in a period of 18 years, from 2002 to 2020.

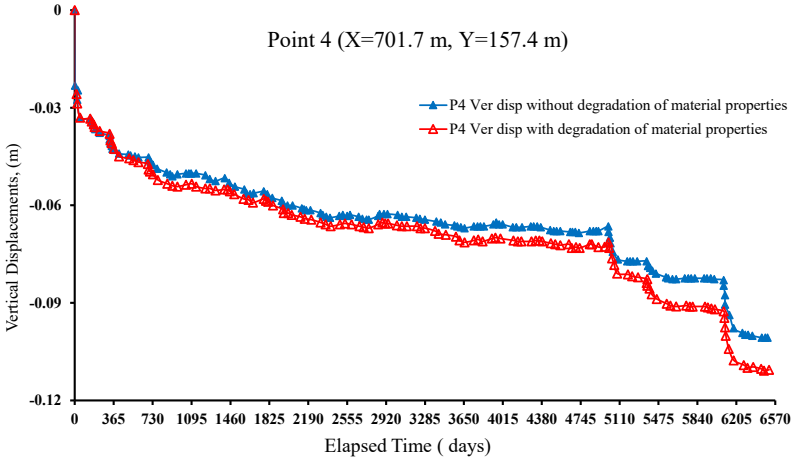


Figure 13. Comparison of calculated vertical displacements at point 4 with and without considering the core material degradation

Figure (12) shows that the horizontal displacements of all points in both conditions, with and without considering degradation of the properties of materials of the dam core after several WDC, have similar patterns and follow the same trend. As shown in Figure (12), the middle points have higher vertical displacements. Therefore, they experience the highest WDC effects. The average difference in vertical settlements between the two cases, including or ignoring the degradation of material properties, is as high as 10%. This shows the importance of the WDC process and its subsequent effects. For instance, the graphs presented in Figure (13) show this effect at the point 4 at the lower height of the dam. Comparing the graphs show a difference of 4 cm in 40 cm which is 10%.

Horizontal displacements

The horizontal deformations were also studied. Figure (14) shows the trend of variations of horizontal displacements along the vertical axis through the center of the dam for the period of 18 years, from 2002 to 2020. As expected, the upper part, including points 1 and 2, move towards upstream. While, lower part, including points 4 and 5 move towards downstream. This shows that at the lower parts the mechanical behaviour is dominant process, while in the upper parts this behaviour diminishes and the degradation effect is dominant. The middle part has the minimum absolute displacements, as it is located between the two parts which have opposite deformations.

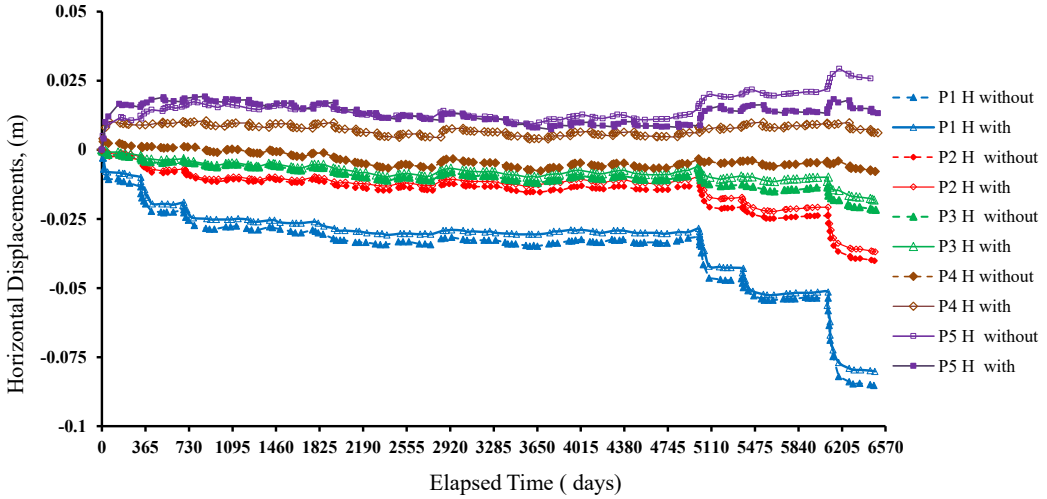


Figure 14. Horizontal displacements of selected points under repeated WDC for a period of 18 years, from 2002 to 2020.

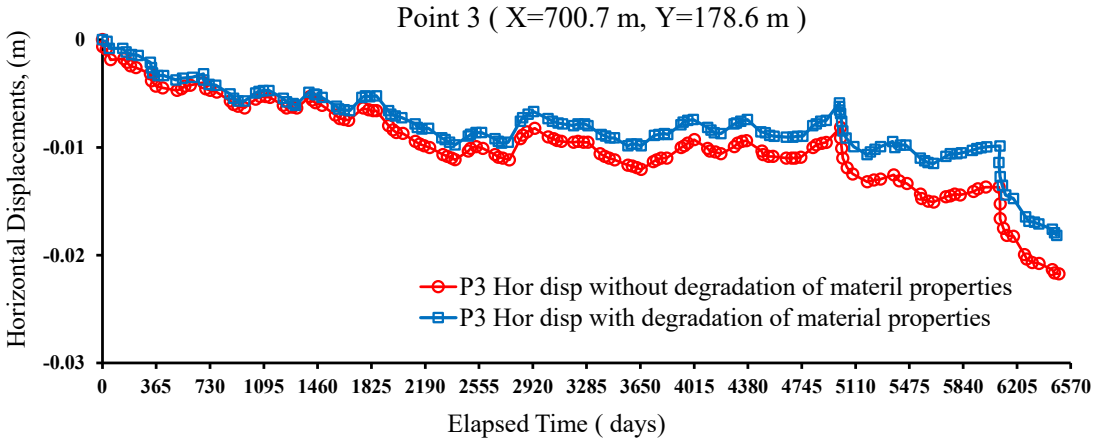


Figure (15). Comparison of calculated horizontal displacements at point 4 with and without considering the core material degradation for the period of 2002 to 2020.

This is due to the complex variations of effective stress, which governs the variations of deformations. The complexity arises from combined effects of variation of seepage pattern and variations of material properties.

The fluctuations in water level causes the small fluctuations in the displacements. This is due to changes in effective stresses due to changes of water level. For clarity, the horizontal displacements of point 3 are shown in Figure (15), seperately.

3.3.2 Prediction of vertical displacement for 2020 to 2027

A series of complementary calculations were conducted for predicting the dam behaviour in the next 7 years, considering the water level variations between the absolute minimum and maximum allowable water levels in the reservoir, 178 m and 230 m, correspondingly. The results are shown in Figure (16). These calculations, also, were conducted based on using either the original material properties or the degraded ones. In order to give a full understanding, the results are combined with the data of previous periods.

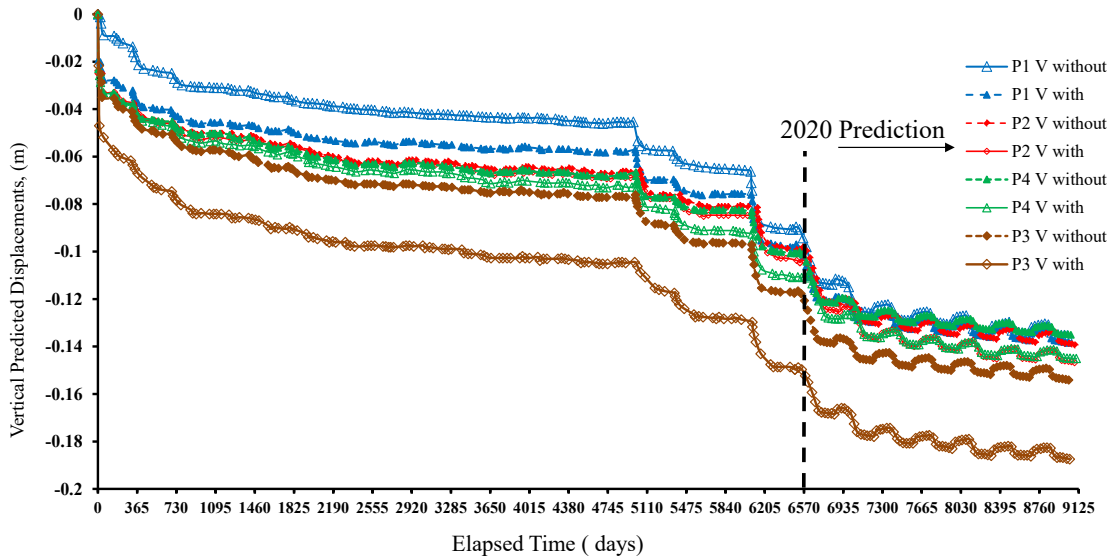


Figure 16. The predicted vertical displacements with and without considering the core material degradation for the period of 2002 to 2027.

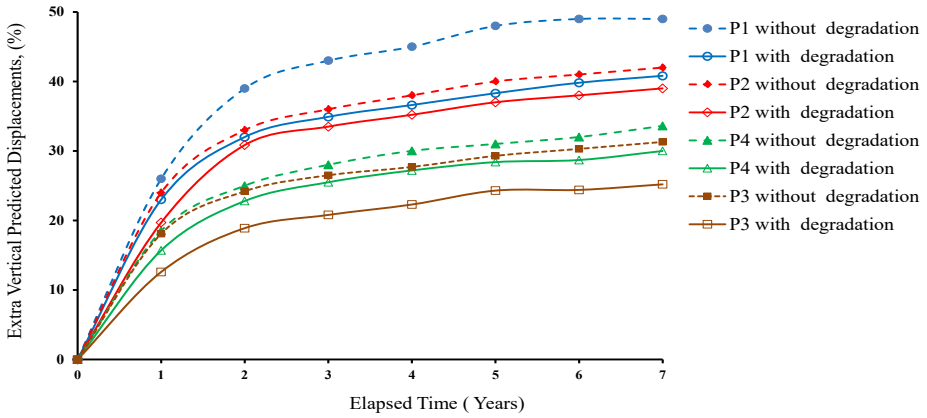


Figure 17. The percentage of increment of predicted vertical displacements with and without considering the core material degradation for the period of 2002 to 2027.

Figure (16) shows that, due to assumed sever changes in water level in the reservoir (62 m fluctuation) for the next 7 years, the vertical displacements at various points show a periodic pattern. Similar to what was described for vertical displacements, the largest displacements occurred during the time that water level was at its highest value since initial impoundment.

As stated earlier, the vertical displacements have increased at a decreasing rate. The percentage changes of the vertical displacements in each prediction step relative to the vertical displacements at the end of last step of simulation phase is presented in Figure (17) at each of the five points along the height of the dam.

4. Conclusions

This study investigated the effects of reservoir water-level fluctuations and associated WDC on the mechanical behavior, deformation patterns, and stability of the Karkheh earth dam, with particular emphasis on the long-term performance of the core material in a semi-arid climatic setting.

Coupled seepage and equilibrium time-dependent numerical analyses were conducted using GeoStudio software, and the material properties were updated manually according to the WDC each region of the dam core experiences.

By integrating laboratory testing with large-scale, and the research provided a comprehensive understanding of how cyclic environmental loading can progressively degrade key geotechnical properties of fine-grained soils within earth-dam structures.

Laboratory and numerical simulations consistently demonstrated that repeated wetting–drying cycles cause a measurable reduction in the compressive strength of the core soil. Although some discrepancies were observed between laboratory UCS values and software predictions, these differences were attributed to early failure of laboratory specimens, especially at high initial saturation ratios and at later WDC, rather than to numerical inaccuracy.

Numerical experiments further revealed that among the strength and hydraulic parameters considered, the loss of cohesion exerted the most significant adverse influence on soil strength, confirming the dominant role of bond degradation, suction reduction, and crack initiation during drying phases and crack expansion upon rewetting.

Analysis of 18 years of reservoir water-level data showed that sections of the mid-elevation core experienced between one and four wetting–drying events during dam operation.

Additional scenarios including water level in reservoir fluctuating between the maximum and minimum permissible levels for the next 7 years, indicated that large portions of the core would be subjected to WDC as a result of these fluctuations. These environmental loadings produced noticeable increases in vertical and horizontal displacements, with mid-

elevation zones exhibiting the greatest sensitivity.

Vertical settlements displayed a gradual, irreversible growth over time, approaching plastic behavior as the number of WDC increased.

Comparisons of scenarios, with and without modification of soil properties, confirmed that incorporating WDC-induced degradation leads to larger predicted deformations, demonstrating the structural implications of strength-parameter deterioration.

These findings highlight that climatic variability in semi-arid regions, through its significant influence on reservoir water levels, poses a significant long-term challenge to the integrity and stability of earth dams. Incorporating these effects into routine monitoring and design protocols is therefore essential for ensuring the sustainable and resilient performance of large earth-dam infrastructures.

However, it worths to remind that this study was performed based on assuming similarity of materials and their degradation rates of the two dams. Also, using the simplified linear model and assuming the worst-case scenario for prediction phase, were the limitations of this study. Resolving these limitations can enhance the conclusions in the next steps of this study.

Author Contributions

M O: Conceptualization, Methodology, Resources, Writing- original draft, Writing-review and editing, Visualization, Supervision, Project administration, Funding acquisition.

S J: Validation, Numerical analysis, Investigation, Resources, Data Curation.

A A: Writing-original draft, Writing-Review and editing, Visualization, Supervision, Funding acquisition.

Declaration of Interest Statement

No conflict of interest exits in the submission of this manuscript, and all of the authors are listed and have approved the enclosed manuscript for publication. On behalf of all authors, I would like to declare that the work described was original research that has neither been published previously, nor under consideration for publication elsewhere, in whole or in part.

Data Availability

The data presented in this study are available on request from the corresponding author.

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Conflict of Interest

The authors declare that they have no conflict of interest to declare.

Statements and Declarations

All of the authors would like to declare that the work described was original research that has neither been published previously, nor under consideration for publication elsewhere, in whole or in part.

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