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Experimental Assessment of Soil Consolidation properties Representing Geotechnical Irregularities in Earth-fill Dam for Static and Seismic Non-linear Analysis

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The static and seismic stability of earth-fill dam embankments is significantly affected by geotechnical anomalies, including heterogeneous soil properties. This paper provides an experimental assessment of soil consolidation and geotechnical variability in earth-fill dams. Laboratory tests were conducted on samples taken from Al-Moshanaf dam that had slope stability failure on its upstream face and located in southern Syria an area well known for widespread of expansive clay soils. In addition to old boreholes, field and laboratory tests performed in 2018 that confirms anomalies due to clay procurement from different quarries, new specimens confirm irregularities in Dam that was designed and executed as a homogenous earth-fill dam. Lithological section confirms existing different geotechnical properties in dam body. Experimental study aims to obtain moisture content, unit weight, grain size distribution, Atterberg limits, specific gravity and consolidation parameters, to analyze those results then to investigate their relationship with slope stability failure of the dam.

Comparison of old and new tests indicate variability in geotechnical properties inside the dam body, unit weight of old and new specimens reveals an average increase of 6%, also a progressive material degradation due to seepage-induced clay migration at upstream face, resulting in different soil settlement behavior. Consolidation tests, following ASTM D2435 and ASTM D4546, reveal high differential swelling percentages between adjacent zones that reaches 90%, and compression index variations, including seepage-exposed zones, that may lead to potential stress concentrations and instability at critical zones interfaces. The comparative analysis of consolidation methods highlights nonlinear responses of embankment soils to cyclic wetting, laboratory tests show that the maximum swelling-to-compression differential ratio of adjacent zones is 10% for first cycle of loading, whereas it rises to 67% in the second loading cycle the reason that cracks may develop, emphasizing the need for refined predictive stability models in dam rehabilitation.

By quantifying consolidation trends and geotechnical irregularities, this paper seeks to bridge gaps in geotechnical assessment methodologies. The findings provide foundational data to support future non-linear numerical modeling efforts, helping refine static and seismic design strategies for earth-fill dam rehabilitation and stability evaluation.

Keywords: Earth-fill dam, Geotechnical anomalies, Soil consolidation, Consolidation tests, Comparative analysis, Cyclic wetting, Numerical analysis.

دراسة تجريبية لتقدير خصائص انضغاطية عينات تربة تمثل مناطق عدم الانتظام الجيوتكنيكي في السدود الترابية لأغراض التحليل اللاخطي الستاتيكي والزلزالي

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الملخص:

يتأثر استقرار ردميات السدود الترابية بشكل كبير بعدم الانتظام الجيوتكنيكي، بما في ذلك تباين خصائص التربة. يقدم هذ البحث دراسة تجريبية لانضغاط التربة والتباين الجيوتكنيكي في السدود الترابية. تم إجراء اختبارات مخبرية على عينات مأخوذة من سد المشنف الشمالي بمحافظة السويداء، الذي تعرض لانهيار وظهور سطح انزلاق على وجهه الامامي، حيث يقع السد في المنطقة الجنوبية في سوريا، وهي منطقة معروفة بانتشار واسع للترب الغضارية الانتفاخية. بالإضافة إلى السبور والاختبارات الحقلية والمخبرية القديمة المنفذة عام 2018 والتي أكدت وجود مناطق شاذة في جسم السد بسبب استخدام غضار من مقالع مختلفة، أكدت العينات الجديدة التي تم أخذها في هذا البحث وجود مناطق شاذة في جسم السد المصمم أساسا كسد ترابي متجانس. وهو ما أكدته أيضا أكدت المقاطع الليثولوجية في جسم السد. تهدف الدراسة التجريبية إلى تحديد محتوى الرطوبة، والكثافة، والتدرج الحبي، وحدود أتربرغ والوزن النوعي، ومعاملات الانضغاطية، وذلك لتحليل تلك النتائج ثم التحقق من علاقتها بانهيار الوجه الأمامي للسد. بينت مقارنة نتائج الاختبارات القديمة والجديدة إلى وجود تباين في الخواص الجيوتكنيكية داخل جسم السد وتدهور تدريجي للمواد بسبب هجرة ذرات الغضار الناجمة عن الرشوحات من الوجه الأمامي، مما أدى إلى سلوك مختلف للتربة من ناحية الهبوطات. كما كشفت اختبارات الانضغاطية، وفقاً للمواصفتين القياسيتين ASTM D2435 وASTM D4546، عن نسب انتفاخية عالية بين المناطق المتجاورة تصل الى 90% وتباينات في قرينة الانضغاطية، بما في ذلك المناطق المعرضة للرشوحات، مما قد يتسبب في تركيز الإجهادات وعدم استقرار عند السطوح البينية للمناطق المختلفة الخصائص الجيوتكنيكية. تسلط الدراسة المقارنة لنتائج تجارب الانضغاطية، الضوء على السلوك اللاخطي للتربة نتيجة تعرضها للترطيب والتجفيف الدوري، بينت النتائج المخبرية أنه بالنسبة لدورة التحميل الأولى تكون نسبة الفروقات الأعظمية بين سلوك الانتفاخ والانضغاط للمناطق المتجاورة تصل الى 10% بينما تزيد في دورة التحميل الثانية لتبلغ 67% مما يزيد إمكانية تطور الشقوق بين هذه المناطق وهذا يؤكد الحاجة لنماذج رقمية تحليلية مطورة لدراسة الاستقرار عند إعادة تأهيل السدود. من خلال وضع سلوك الانضغاطية والشذوذ الجيوتكنيكي في إطار كمي، تسعى هذه الورقة إلى سد الفجوات في منهجيات التقييم الجيوتكنيكي اللاخطي. وتوفر النتائج بيانات أساسية ضرورية للنمذجة الرقمية، مما يساعد في تحسين استراتيجيات التصميم الستاتيكي والزلزالي وإعادة تأهيل السدود الترابية وتقييم استقرارها.

الكلمات المفتاحية: السدود الترابية، عدم الانتظام الجيوتكنيكي، انضغاطية التربة، تجارب الانضغاطية، دراسة مقارنة، تأثير الترطيب الدوري للتربة، النمذجة الرقمية.

Introduction:

Earth-fill dams are critical infrastructure for water storage, flood control, and irrigation. However, their long-term stability is increasingly affected by geotechnical irregularities, pose significant risks to dam integrity, often creating conditions where conventional design assumptions —based on uniform soil behavior — fail to capture the complexity of real-world dam responses. Mosadegh et al [2].

In southern Syria, multiple earth-fill dams, including Al-Moshanaf, have exhibited severe geotechnical anomalies, due to seepage losses, consolidation variations, and aging materials. Investigations into these dams reveal localized zones of differential settlement, emphasizing the need for advanced geotechnical assessments rather than relying solely on conventional engineering approaches. Chakraborty et al [1]. Similar challenges have been documented in embankment dams across the United States, Spain, and Iran. Aminfar et al [3]. emphasizing the global relevance of this issue and the effects of irregularity of dam materials on developing cracks resulting from differential settlements and swelling during wetting cycles.

Given the complexity of geotechnical variability, the stability of earth-fill dams is largely dictated by the geotechnical characteristics. Adapa et al [9]. and consolidation behavior of embankment materials. Understanding the hydro-mechanical response of embankment soils is critical for effective assessments. This study presents an experimental assessment of soil consolidation and geotechnical irregularities within dam embankments, focusing on the behavior of different zones of the dam.

1. Methodology:

Conventional geotechnical assessments often fail to capture the nonlinear responses of embankment dams. This research adopts an experimental approach to assess soil consolidation and geotechnical irregularities affecting earth-fill dam embankments and aims to quantify settlement behavior across embankment zones. A comprehensive series of laboratory tests was conducted on soil samples extracted from multiple sections of dam embankments in southern Syria, focusing on moisture content, density variations, grain size distribution, Atterberg limits, and compressibility characteristics. Consolidation tests, following ASTM D2435 and ASTM D4546 standards, were performed to evaluate compression indices, swelling behavior.

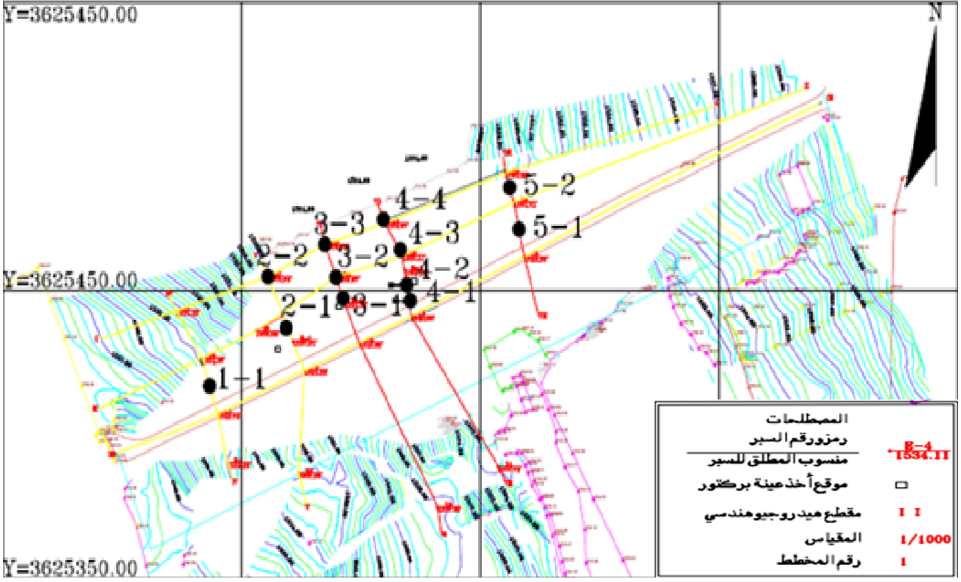


Fig (1) plan new extracted samples and dam section.

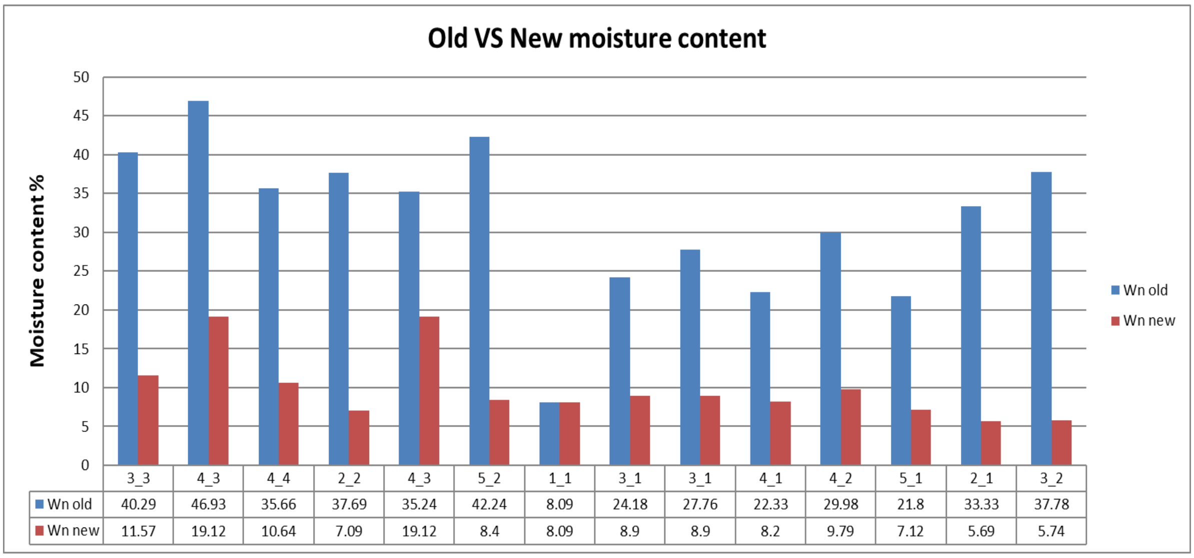
Table (1) new extracted samples

Old sample	Borehole	Level (m)	Dam section	New sample
180	C4	1537	VII-VII	4-1
181	C4	1534	VII-VII	4-2
160	B4	1531	VII-VII	4-3
157	A4	1523	VII-VII	4-4
237	C5	1538	VIII-VIII	5-1
162	B5	1532	VIII-VIII	5-2
175	C3	1533	VI-VI	3-1
245	E3	1531	VI-VI	3-2
155	A3	1529	VI-VI	3-3
244	E2	1535	V-V	2-1
172	A2-B2	1529	V-V	2-2
236	C1	1537	IV-IV	1-1

To ensure comparative analysis, newly extracted samples were systematically compared to historical records of dam material properties, Table.1, highlighting variability in soil composition due to environmental exposure and hydraulic influences. The findings from these laboratory investigations serve as a foundation for understanding material compatibility in dam evaluation and rehabilitation efforts, Fig.1.

2. Experimental Assessment:

A comparison of the moisture content of old and new samples revealed a significant reduction in the moisture of recently collected samples due to the dam drawdown between 2018 (immediately after the slip occurred on the front face), and 2024 (when the new samples were taken). Additionally, the upstream face was exposed to weathering and evaporation during this period, as the clay was exposed across the relatively wide slip zone. Notably, the moisture content of both old and new samples taken from the upper sections of the dam—considering that the reservoir storage rarely reached its maximum capacity throughout the dam’s operational history—applies to samples (1-1, 3-1, 4-1, 5-1). It is worth emphasizing that sample (1-1) exhibited its minimum moisture content inherently, as it is located on the left abutment of the dam where the storage level never reached the sample’s elevation, Fig.2.



	3_3	4_3	4_4	2_2	4_3	5_2	1_1	3_1	3_1	4_1	4_2	5_1	2_1	3_2
■ Wn old	40.29	46.93	35.66	37.69	35.24	42.24	8.09	24.18	27.76	22.33	29.98	21.8	33.33	37.78
■ Wn new	11.57	19.12	10.64	7.09	19.12	8.4	8.09	8.9	8.9	8.2	9.79	7.12	5.69	5.74

Fig (2) comparison of the moisture content of old and new samples

A comparison of the bulk natural unit weight of new and old samples reveals an increase in the bulk unit weight of the new samples, with average variations not exceeding 6%, Fig.3.

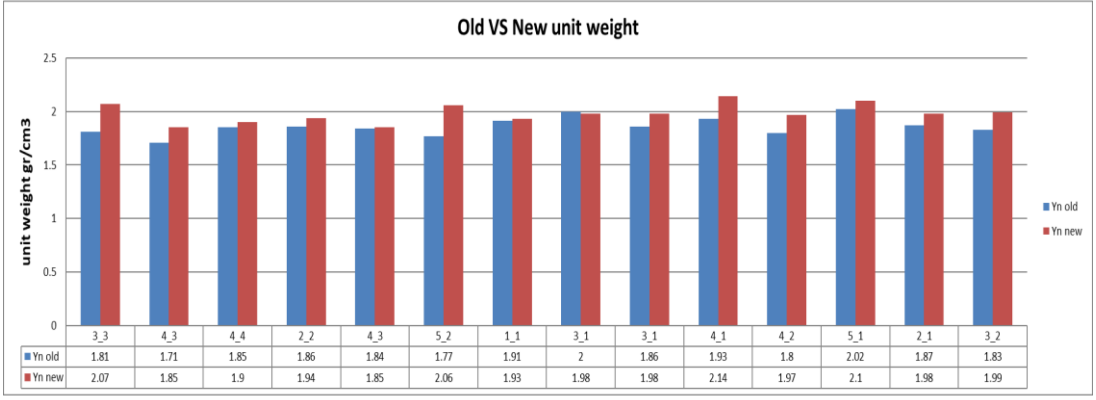
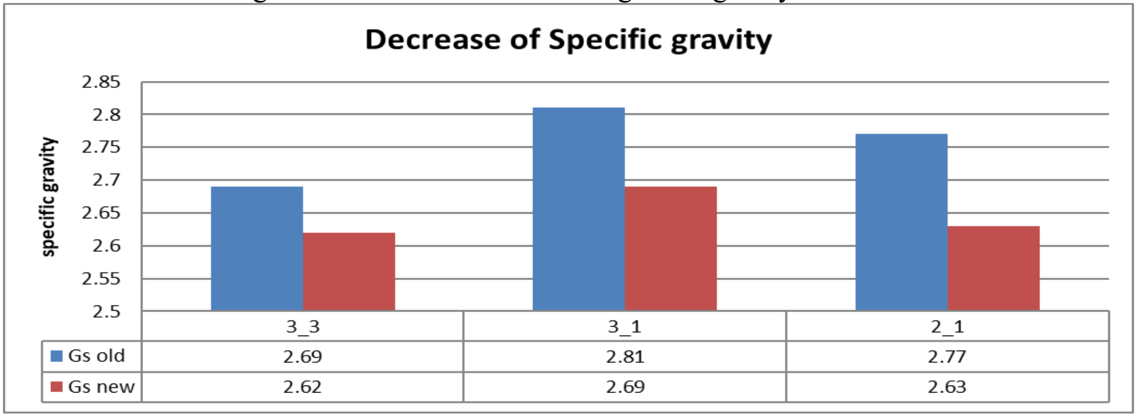


Fig (3) comparison of the bulk natural unit weight of new and old samples

The notably higher natural unit weight of the new samples compared to the natural unit weight of the old samples is striking. However, correlating the results of the unit weight tests with those of the specific gravity tests Fig.6, and void ratio tests reveals that the decrease in the specific gravity of the new samples, Fig.4 was accompanied by a more significant reduction in the void ratio, Fig.5, resulting from the prolonged drawdown of the dam reservoir. By considering the relationship between unit weight, specific gravity, and void ratio, it becomes evident that the slight increase in natural unit weight is logically consistent.



Fig(4) decrease in the specific gravity of the new samples.

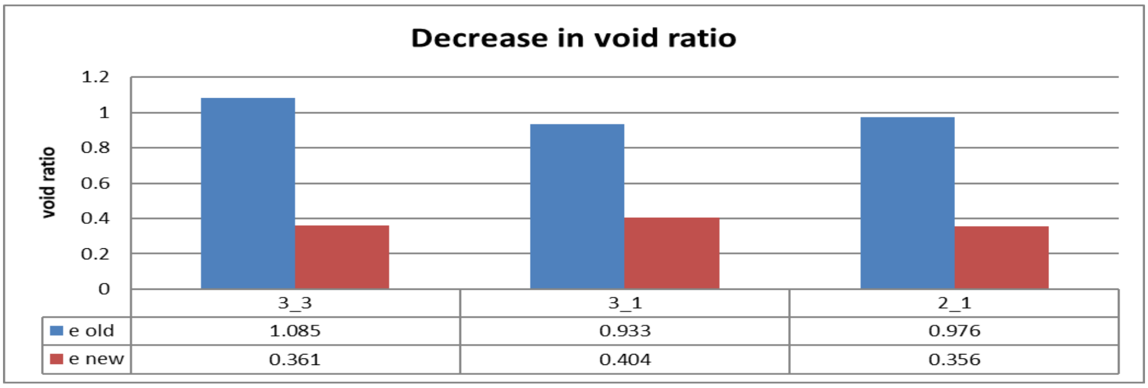


Fig (5) decrease in the void ratio of the new samples

The specific gravity (Gs) of soil samples provides insight into mineral composition, density characteristics, and material changes due to long-term environmental exposure. Laboratory tests revealed notable variations in specific gravity values across different embankment zones, correlating with changes in moisture content, seepage history, and loss of fine particles. Adapa et al [9]. A comparison of the specific gravity of new and old samples, Fig.6, indicates a reduction in the specific gravity of the new samples compared to the old ones, with the largest decrease (0.23) observed in sample 2-2 located at the upstream toe of the dam. (Sample, 2-2), where fine clay particles were washed out due to persistent seepage effects, weakens soil density and permeability characteristics. Adapa et al [9]. In general, newly extracted soil samples exhibited lower specific gravity values compared to historical records, indicating material degradation and particle loss, particularly within zones exposed to seepage. Sánchez-Martín [5]. Majeed [4].

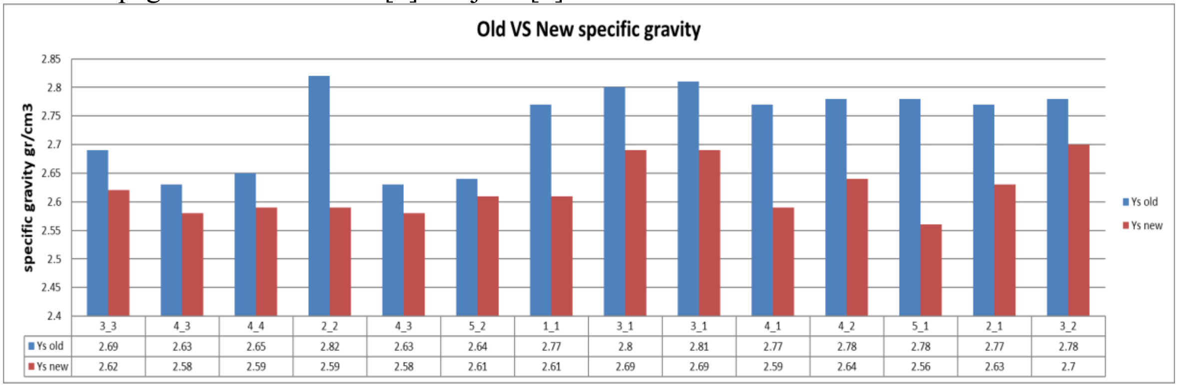


Fig (6) comparison of specific gravity of new and old samples

Analysis of grain size distribution confirms a shift in material composition, with reduced clay fractions and increased silt content across exposed embankment zones. This transformation is linked to seepage-driven particle migration, where clay constituents were progressively removed from dam interfaces, Fig.7, Fig.8. The general decline in specific gravity across the samples coincides with a reduction in clay content and an increase in silt content.

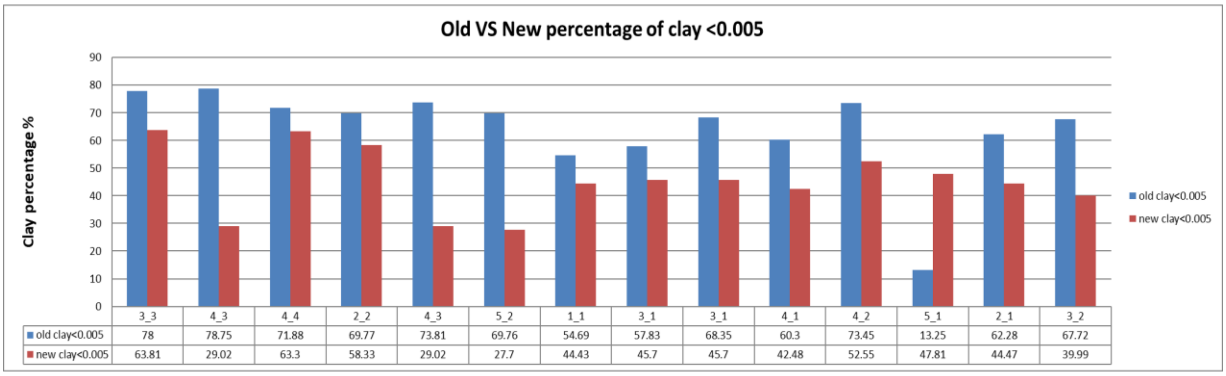
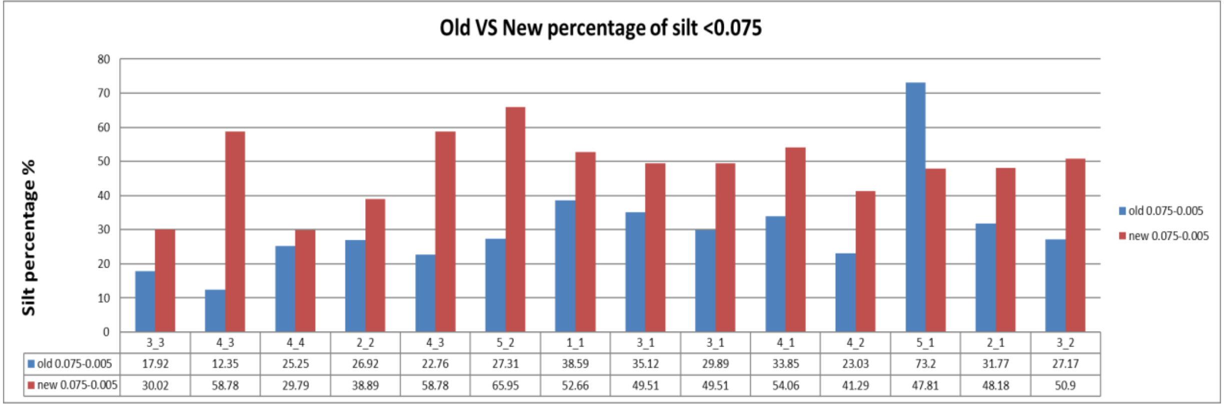


Fig (7) comparison of clay percentage of new and old samples



	3_3	4_3	4_4	2_2	4_3	5_2	1_1	3_1	3_1	4_1	4_2	5_1	2_1	3_2
🟦 old 0.075-0.005	17.92	12.35	25.25	26.92	22.76	27.31	38.59	35.12	29.89	33.85	23.03	73.2	31.77	27.17
🟥 new 0.075-0.005	30.02	58.78	29.79	38.89	58.78	65.95	52.66	49.51	49.51	54.06	41.29	47.81	48.18	50.9

Fig (8) comparison of silt percentage of new and old samples

The sample 5-1 is anomalous when comparing to other specimen the reason is that it should relate to the corresponded sample 162-located in the zone directly beneath it, taking into consideration similar location and situation at upstream face under the effect of suffusion while specimen 237 located inside the dam body unaffected by this phenomenon. Considering that all new samples are situated on the front face of the dam, which was repeatedly subjected to reservoir water level fluctuations during the dam's operational history, the loss of fine clay particles due to suffusion. Horikoshi et al [14] is evident. This phenomenon likely resulted from seepage through the dam body during each drawdown operation, explaining the lower specific gravity of the new upstream-face samples compared to their counterparts from within the dam's core, Fig.9.

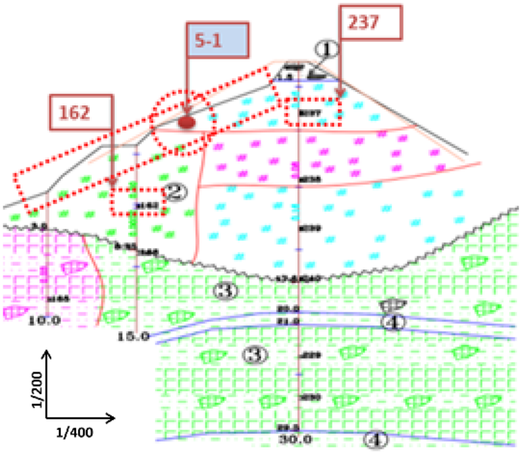
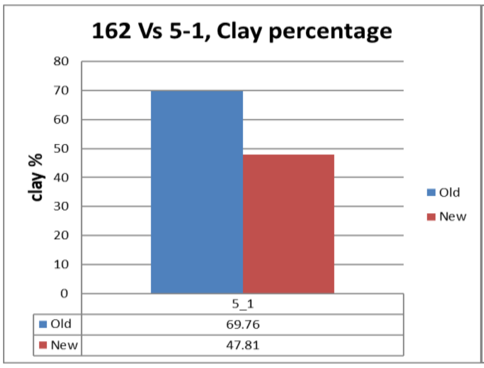
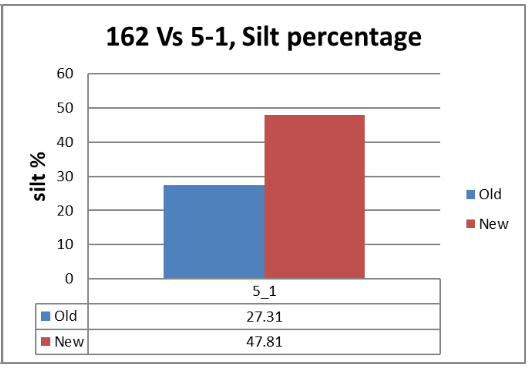


Fig (9) location of sample 5-1 sample



	5_1
🟦 Old	69.76
🟥 New	47.81

Fig (10) 5-1 VS 162 clay percentage.



	5_1
🟦 Old	27.31
🟥 New	47.81

Fig (11). 5-1 VS 162 silt percentage.

A comparison of the anomalous sample 5-1 with sample 162 -located in the zone directly beneath it, that is the corresponded specimen taking into consideration similar location and situation at upstream face under the effect of suffusion while specimen 237 located inside - reveals an increase in silt content, Fig. 10, and a decrease in clay content, Fig.11, suggesting changes in grain redistribution, hence it is critical to account for the presence of an additional zone on the upstream face of the dam caused by suffusion, and the associated changes in soil gradation (particle size distribution) within this region. Consolidation tests conducted on embankment soil samples provided critical insights into settlement trends, compressibility behavior, and structural stability of earth-fill dams. Using ASTM D2435 (standard one-dimensional consolidation test) and ASTM D4546 (evaluation of wetting-induced volume change), the study quantified swelling tendencies, compression indices, and differential expansion effects across embankment zones.

ASTM D4546-14 is particularly relevant for evaluating the behavior of earth-fill dams under wetting-induced deformation. In this test, specimens are examined in their natural moisture state and subjected to gradual loading equivalent to the overburden pressure of the soil column above them. Following this, they are inundated, simulating the first filling of a dam reservoir.

The loading-unloading cycle during the initial phase replicates the response of the soil structure to first reservoir filling, while the subsequent cycle mimics second reservoir filling, ensuring the test conditions closely resemble real-world site behavior. This precise imitation of field conditions makes ASTM D4546-14 more suitable than ASTM D2435 for assessing the long-term stability and settlement characteristics of earth-fill dams, particularly in response to saturation and cyclic reservoir operatio

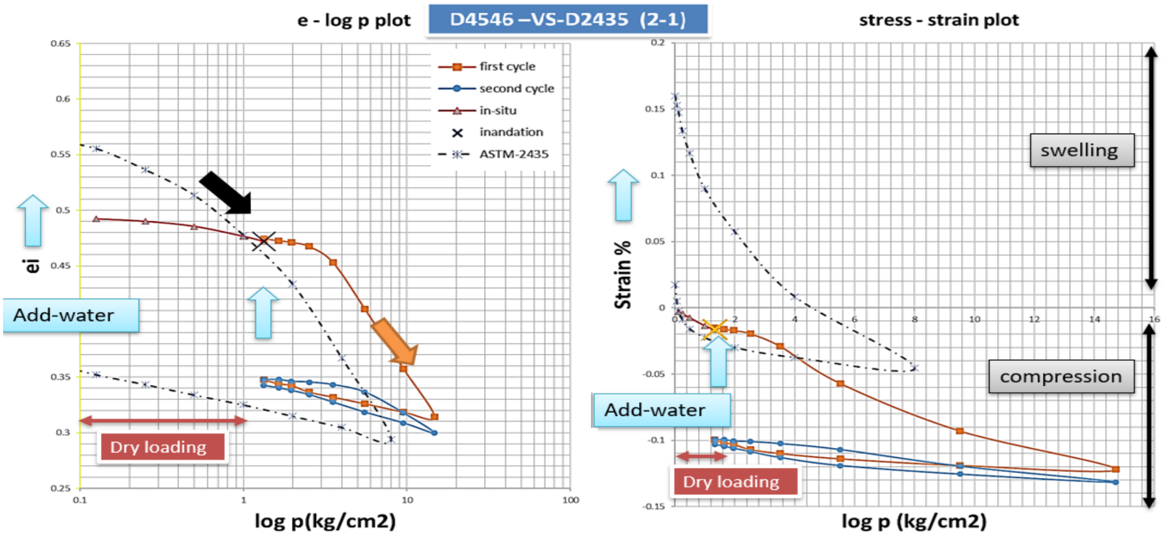


Fig (12) consolidation test of sample (2-1), D-4546 VS D-2435.

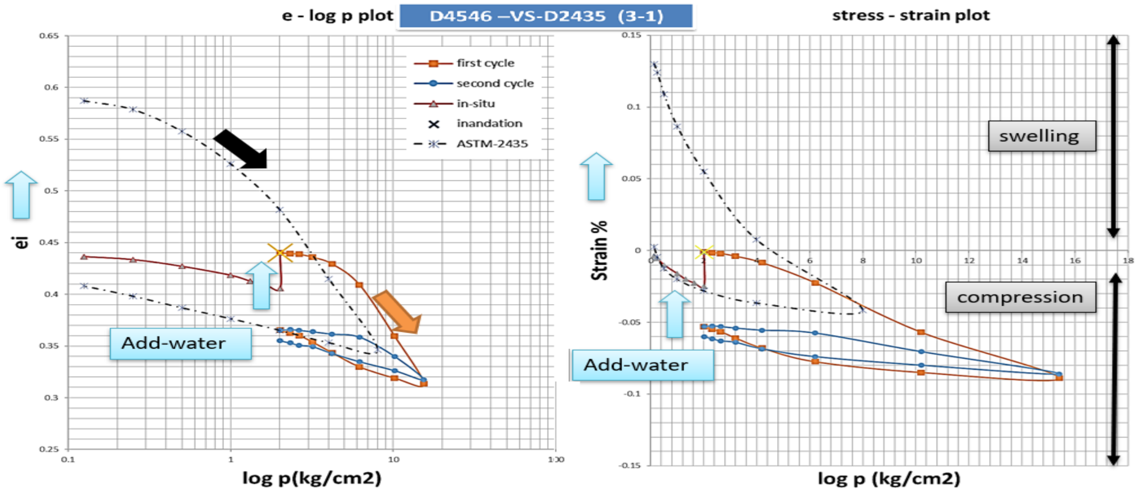
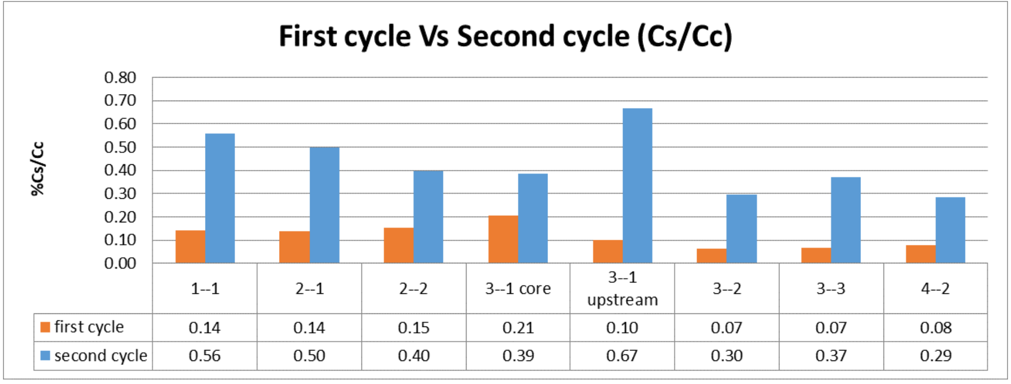


Fig (13) consolidation test of sample (3-1), D-4546 VS D-2435.

The diagram above, Fig.12, Fig.13, illustrates the distinct behavior of the specimen under loading and wetting conditions that closely replicate field conditions, as per ASTM D4546-14. In this test, the specimen is subjected to the in-situ overburden pressure corresponding to its position within the dam body, ensuring that it remains within the compression domain during testing. When tested using ASTM D2435, the specimen exhibits significant compressibility due to its high swelling potential, causing it to prematurely enter the compression phase within a short segment of the loading-unloading cycle. Guo et al [13]. This early-stage expansion alters deformation predictions and keeps the sample in a fully saturated state, neglecting drying-induced volume changes observed in dam reservoirs conditions that do not fully reflect real-world dam behavior. Conversely, ASTM D4546 provides a more accurate representation of cyclic saturation effects by maintaining samples within effective overburden stress, preserving realistic embankment conditions. Duttine et al [10]. It also simulates first and second filling cycles through the application of in-situ overburden pressure followed by inundation, closely mirroring field conditions. Consequently, all subsequent consolidation tests are conducted in accordance with ASTM D4546-14. The greater compression, occurs during the first loading cycle corresponding to the initial filling and drawdown phase of the dam (i.e., the highest compression and thus the largest settlement would occur during the first filling), a comparison of the swelling-compression ratio (Cs/Cc) between the first and second loading cycles (corresponding to the second phase of filling and drawdown) , Fig.14, indicates that repeating the second cycle of filling and drawdown would induce greater relative compression and swelling.

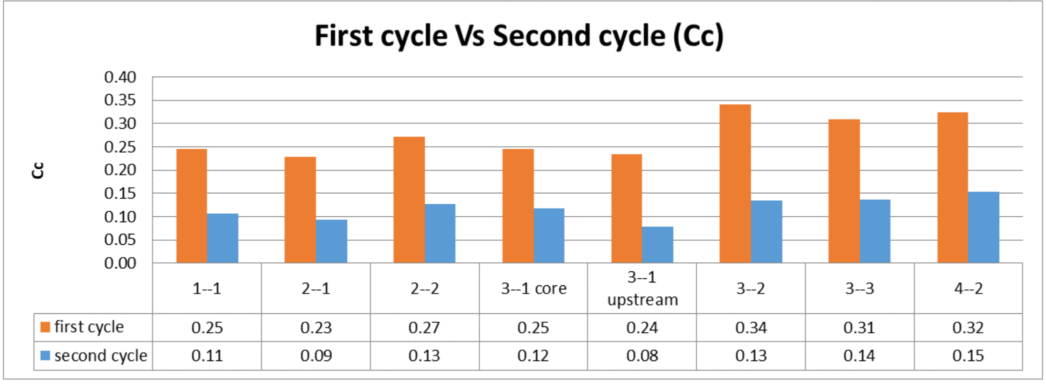
This would likely result in an increased probability of crack initiation and propagation over time. Talukdar et al [12]. Secchi et al [11].



	1--1	2--1	2--2	3--1 core	3--1 upstream	3--2	3--3	4--2
🟧 first cycle	0.14	0.14	0.15	0.21	0.10	0.07	0.07	0.08
🟦 second cycle	0.56	0.50	0.40	0.39	0.67	0.30	0.37	0.29

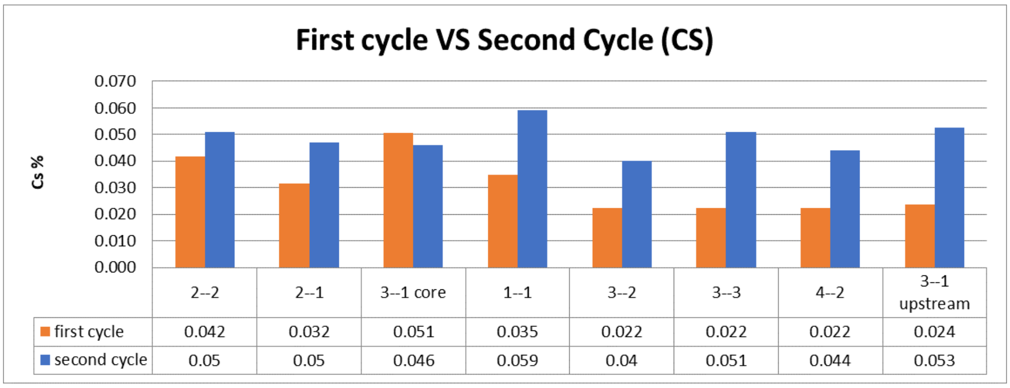
Fig (14) comparison of the swelling-compression ratio (Cs/Cc) between the first and second loading cycles

The most significant variation is observed in samples (1-1) and (3-1 upstream): for sample (1-1) during the first loading cycle, the swelling-to-compression ratio is 14%, whereas it rises to 56% in the second loading cycle. for sample (3-1 upstream) during the first loading cycle, the swelling-to-compression ratio is 10%, whereas it rises to 67% in the second loading cycle, Fig.14. comparison of the compression and swelling indexes (Cc, Cs) between the first and second loading cycles are demonstrated in Fig.15 and Fig.16.



	1--1	2--1	2--2	3--1 core	3--1 upstream	3--2	3--3	4--2
🟧 first cycle	0.25	0.23	0.27	0.25	0.24	0.34	0.31	0.32
🟦 second cycle	0.11	0.09	0.13	0.12	0.08	0.13	0.14	0.15

Fig (15) comparison of the compression index (Cc) between the first and second loading cycles.



	2--2	2--1	3--1 core	1--1	3--2	3--3	4--2	3--1 upstream
🟧 first cycle	0.042	0.032	0.051	0.035	0.022	0.022	0.022	0.024
🟦 second cycle	0.05	0.05	0.046	0.059	0.04	0.051	0.044	0.053

Fig (16) comparison of the swelling index (Cs) between the first and second loading cycles.

To achieve a clearer understanding of the relationship between the compressibility characteristics of representative samples from different zones within the dam body and how these characteristics influence their mutual behavior, the locations of these samples in the dam body were correlated with their compressibility properties and the crack previously observed on the upstream face of the dam. A comparison of the results from the first set of oedometer tests reveals a correlation between samples (2-1) and (2-2), Fig.17, Fig.18. located on the same cross-sectional plane at the initiation of the slip surface, Fig.19.

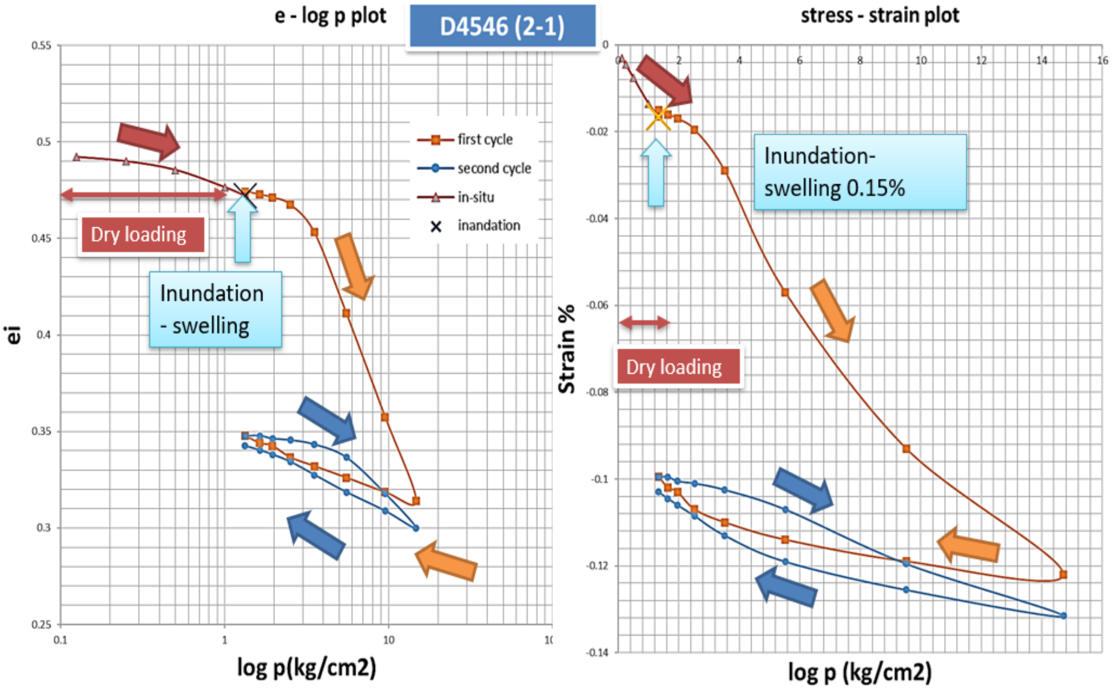


Fig (17) consolidation test of sample (2-1).

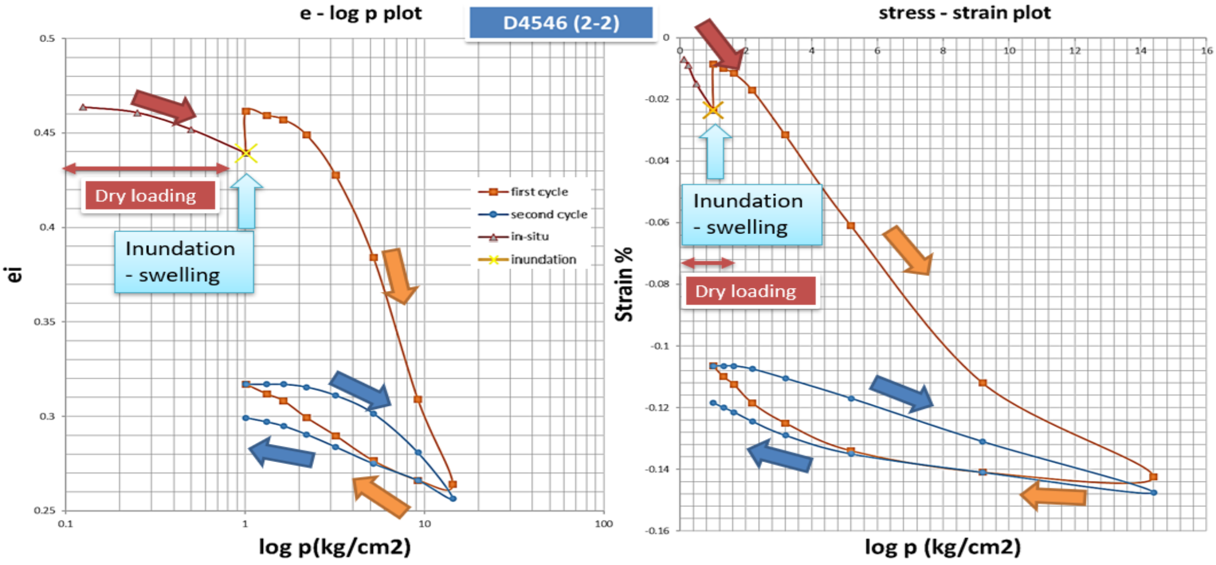


Fig (18) consolidation test of sample (2-2).

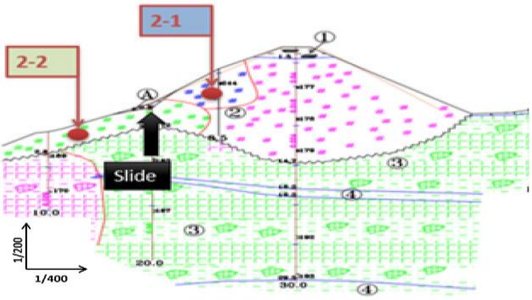


Fig (19) location of samples 2-1 and 2-2

Comparing the swelling percentage during saturation (first reservoir filling) shows that the swelling percentage in zone (2-1) is (0.15%), that is lower than zone (2-2) (1.5%), illustrating that the differential swelling percentage between adjacent zones reaches 90%, Fig.20. Furthermore, comparing the compression index (Cc) values between the first loading cycle (initial filling), of samples (Cc 2-1 = 0.23) and (Cc 2-2 = 0.27), Fig.21, and the second loading cycle (Cc 2-1 = 0.09) and (Cc 2-2 = 0.13) , Fig.22, demonstrates that the compressibility of the zone represented by sample (2-2) is higher than that of the overlying zone, which correlates with higher percentage of clay, Fig.7, This explains the development of the slip surface at the interface between these two zones, Fig.19.

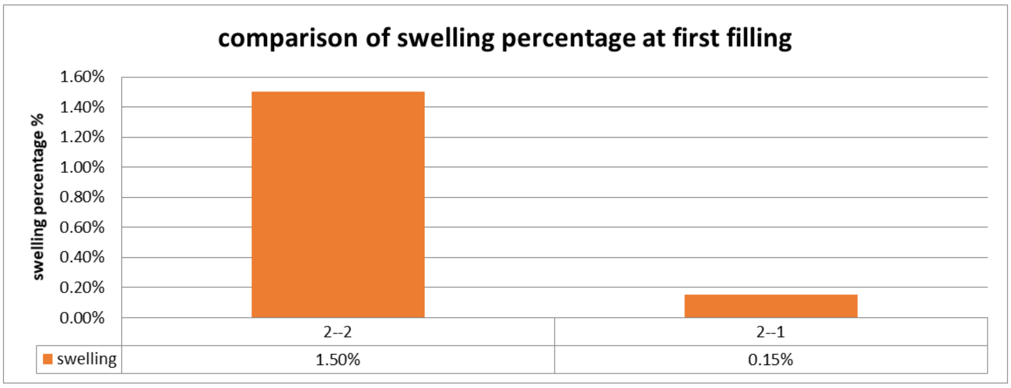


Fig (20) comparison of the swelling percentage between samples 2-1 and 2-2.

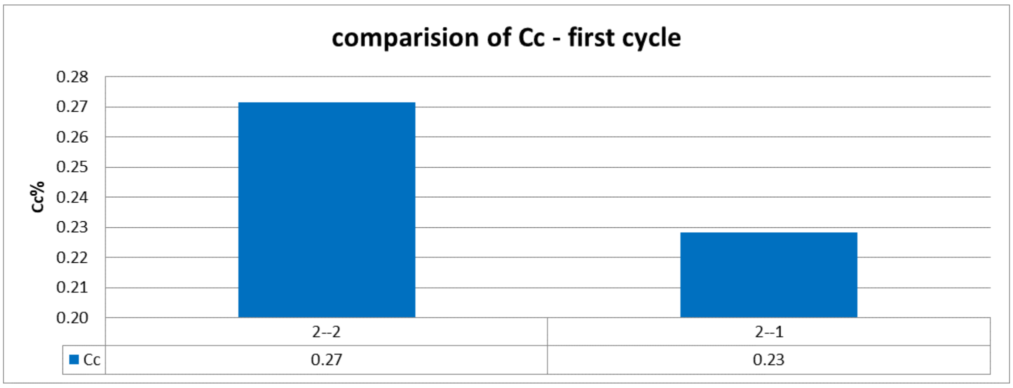


Fig (21) comparison of the compression index (Cc) between samples 2-1 and 2-2- first cycle.

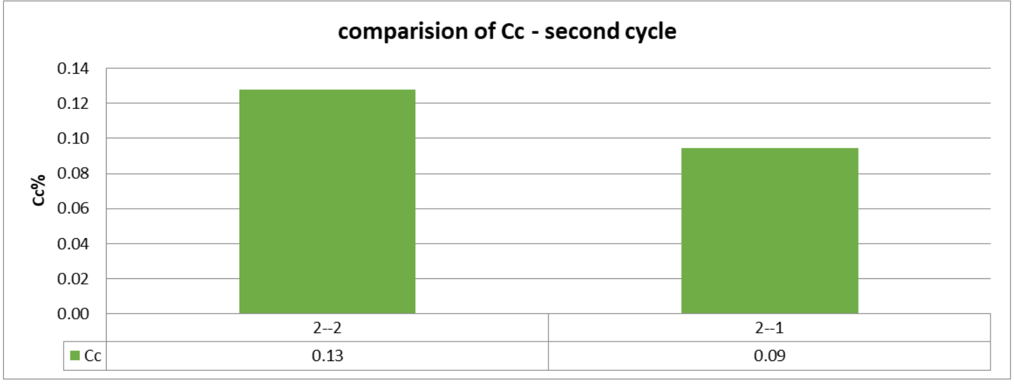


Fig (22) comparison of the compression index (Cc) between samples 2-1 and 2-2- second cycle.

A comparison of the results from the first set of oedometer tests establishes a correlation between samples (3-1), (3-2), and (3-3), Fig.23, Fig.24, Fig.25, situated on the same cross-sectional plane at the slip surface, Fig.26. Analysis of the swelling percentage during saturation (initial reservoir filling) indicates that the swelling percentage in zone (3-1) is (0.2%), while zones (3-2) and (3-3) exhibit deformation in the compression direction, Fig.27, that is correlated with higher value of swelling index of zone (3-1), Fig.31. Furthermore, comparing the compression index (Cc) values between the first loading cycle (initial filling), of samples (Cc 3-1 =0.245), (Cc 3-2 =0.342) and (Cc 3-3 =0.31), and the second loading cycle, of samples (Cc 3-1 =0.119), (Cc 3-2 =0.135) and (Cc 3-3 =0.137), Fig.28, reveals that the compressibility of the zone represented by sample (3-1) is lower than that of zones (3-2) and (3-3). This differential compressibility explains the formation of the slip surface at the interface between these zones, Fig.26.

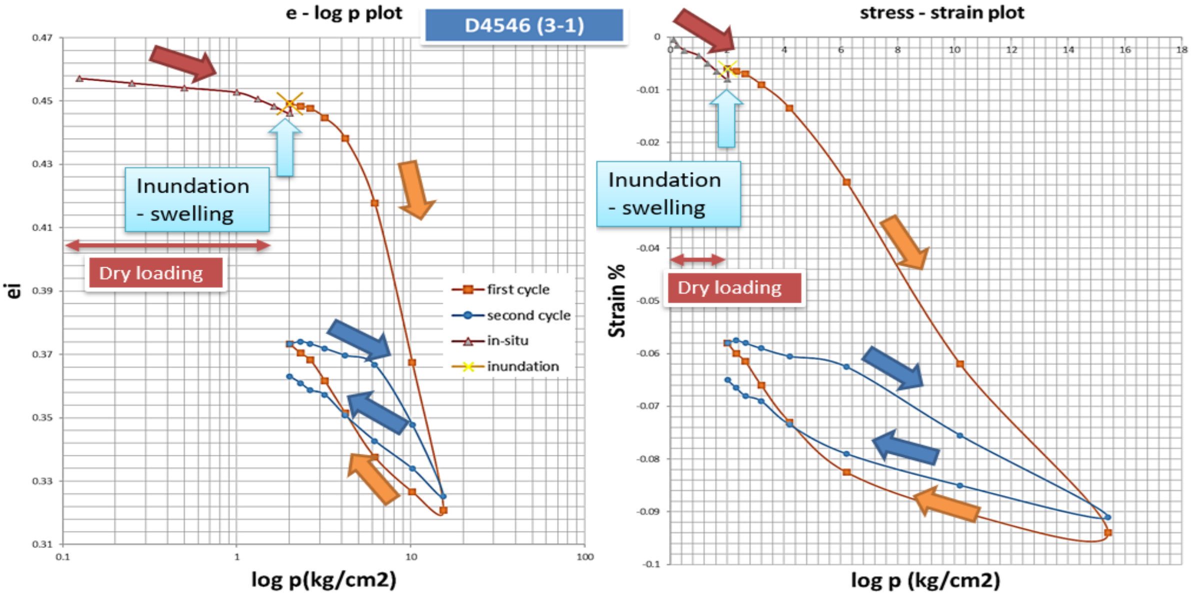


Fig (23) consolidation test of sample (3-1).

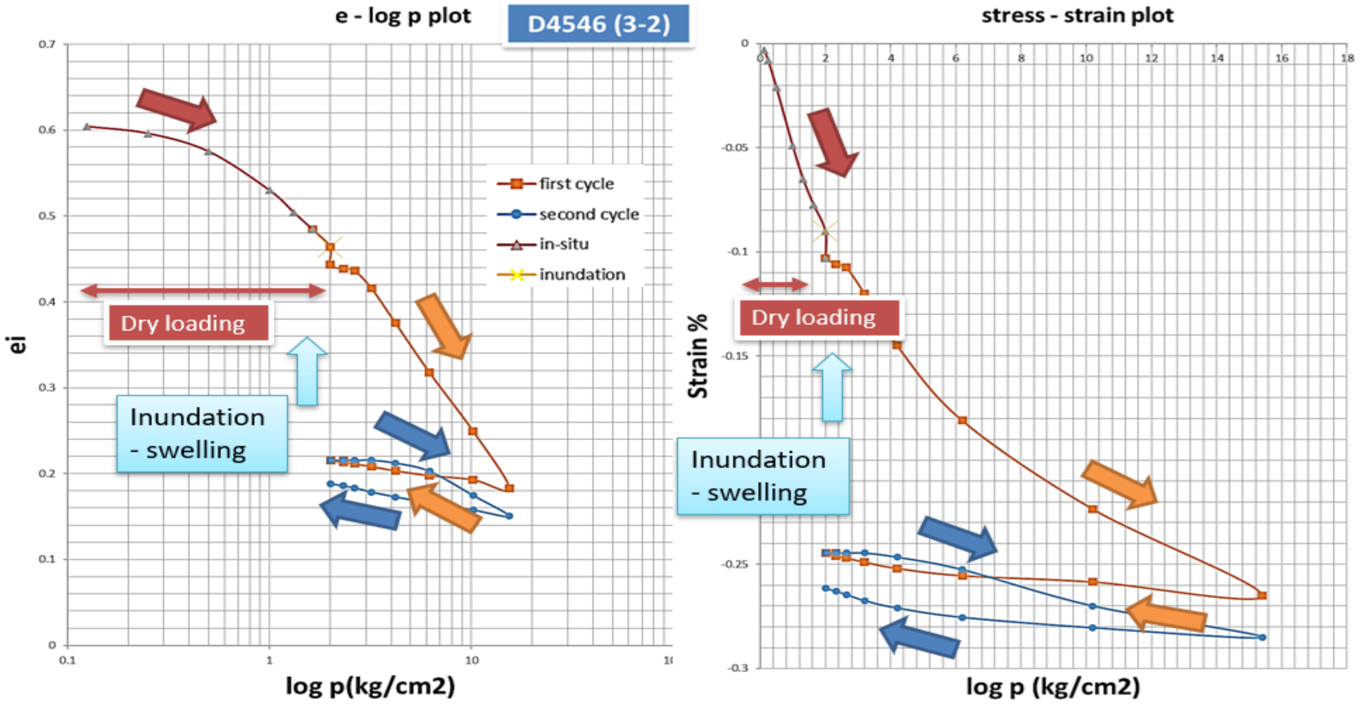


Fig (24) consolidation test of sample (3-2).

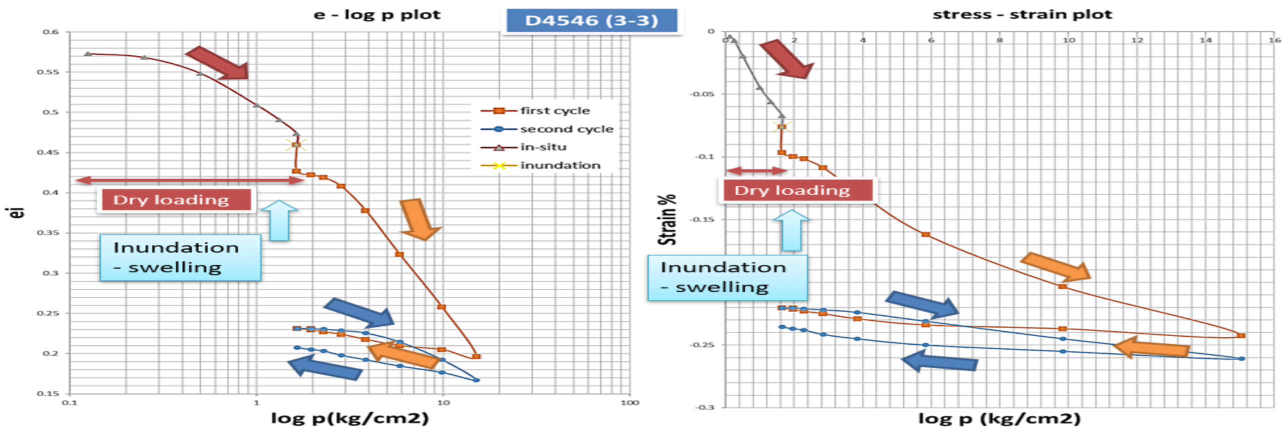


Fig (25) consolidation test of sample (3-3).

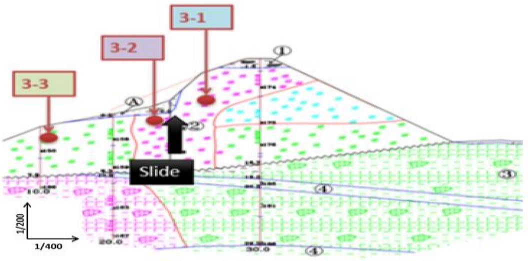


Fig (26) location of samples 3-1, 3-2 and 3-3.

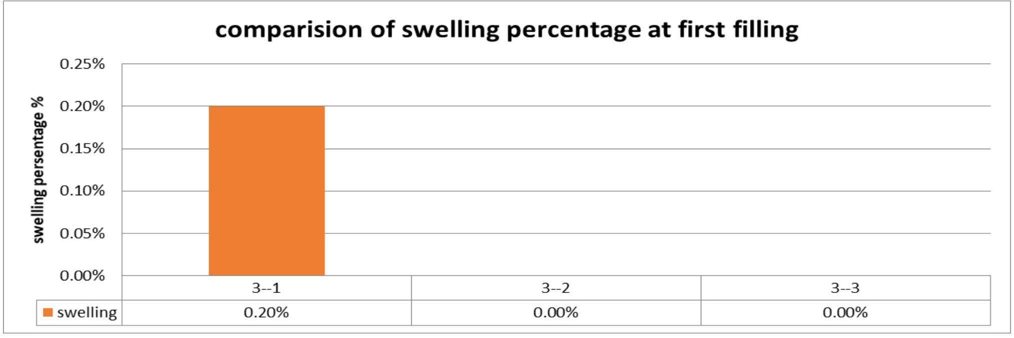


Fig (27) comparison of the swelling percentage between samples 3-1, 3-2 and 3-3.

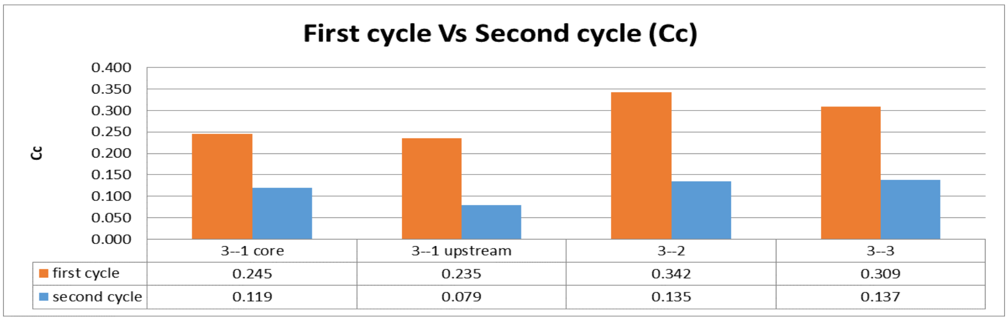


Fig (28) comparison of the compression index (Cc) between samples 3-1, 3-2 and 3-3. first and second cycle.

In addition to variations in the geotechnical properties of samples based on the zone they represent, the spatial variability of these samples significantly influences their swelling and compressibility behavior. This is reflected in parameters such as the indexes of compressibility and swelling. The most pronounced changes occur in samples extracted from upstream face of the dam, Fig. 29, amplifying inconsistencies in swelling behavior between adjacent zones and even within a single zone. El-Shami et al [15].

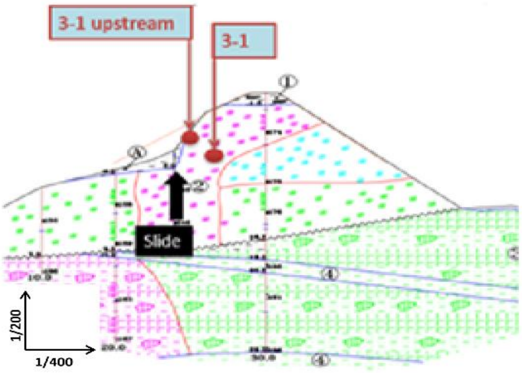


Fig (29) location of samples (3-1) and (3-1 upstream).

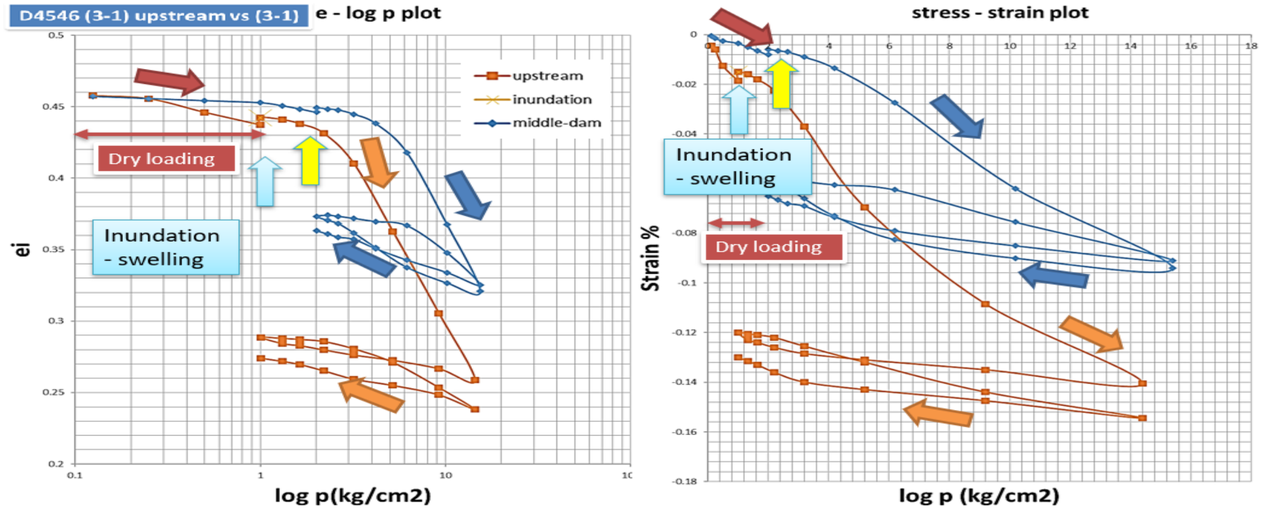
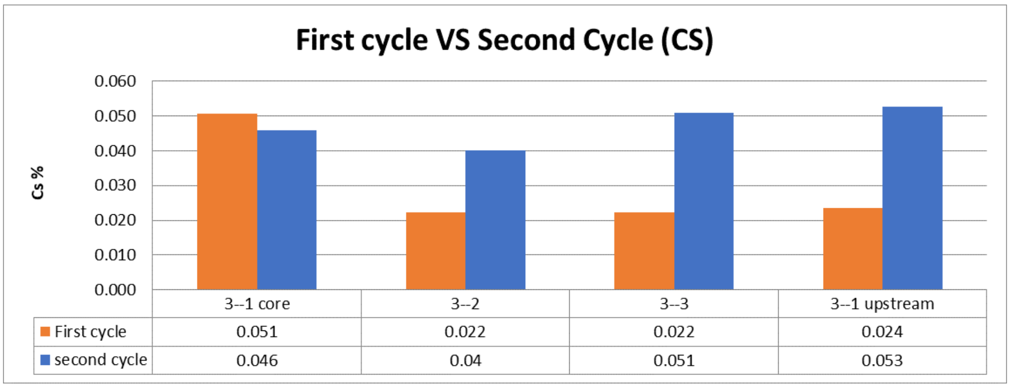


Fig (30) comparison of consolidation test of samples (3-1) and (3-1 upstream).

The figure above demonstrates that the sample corresponding to the upstream soil undergoes the swelling percentage during saturation (first reservoir filling) shows that the swelling percentage in zone (3-1 core) is (0.2%), that is lower than that in zone (3-1 upstream) (0.3%), Fig.30. Furthermore, comparing the compression index (Cc) values between the first loading cycle (initial filling), of under-crest sample (Cc 3-1 core =0.25) and upstream sample (Cc 3-1 upstream =0.24), and the second loading cycle (Cc 3-1 core =0.12) and (Cc 3-1 upstream =0.08), demonstrates that the compressibility of the zone represented by sample (Cc 3-1 core) is higher than that of the adjusting zone (Cc 3-1 upstream), Fig.28. A comparison of the swelling index (Cs) for the two samples, reveals that during the first loading cycle, (Cs 3-1 core =0.051) and upstream sample (Cs 3-1 upstream =0.024), and the second loading cycle (Cs 3-1 core =0.046) and (Cs 3-1 upstream =0.053). This indicates that the spatial positioning of the samples (and consequently the applied weight of the overlying soil weight) leads to distinct mechanical behavior during the initial filling-drawdown phase and the second filling-drawdown phase, Fig.31.



	3--1 core	3--2	3--3	3--1 upstream
🟧 First cycle	0.051	0.022	0.022	0.024
🟦 second cycle	0.046	0.04	0.051	0.053

Fig (31) comparison of the swelling index (Cs) between samples 3-1, 3-2 and 3-3. first and second cycle.

Consolidation tests, revealed adaptation of swelling potential over multiple wetting cycles, demonstrating that initial inundation exerts greater influence than later saturation events, that emphasized nonlinear response in the zones of dam, illustrating how repeated saturation events influence soil stabilization rates, a factor that is critical for predicting long-term dam performance.

The good correlation ($R\ s$ =0.632) observed between specific gravity (Ys) and second cycle swelling index (Cs) across samples in the same section, particularly 3-1 core, 3-1 upstream, 3-2, and 3-3, highlights the significant influence of mineral density on soil compressibility trends. This relationship was evaluated using Spearman's Rank Correlation formula, equation (1), which is particularly useful for nonlinear statistical analysis in geotechnical assessments. Unlike traditional linear regression, Spearman's method ranks values and measures monotonic relationships, making it ideal for soil behavior studies where compressibility patterns may not follow strict linear trends, table.2.

$$R_s = 1 - \frac{6\Sigma\, d_i^2}{n(n^2-1)} \qquad \text{equation } (\mathbf{1}).$$

d_i^2: the sum of squared rank differences.
n: number of observations (samples)

The results indicate that samples located on same section tend to exhibit good correlation for the second loading cycle relating the second filling of dam. These findings emphasize the necessity of incorporating rank-based correlation approaches in dam rehabilitation studies, ensuring a more comprehensive evaluation of material variability and settlement risks. Lizarraga-Sanchez et al [7]. Sanchez H et al [8].

Table (2) Spearman's method ranks values.

Sample	Ys	Cs	Rank clay	Rank Cs	di	di^2
3-1 core	2.69	0.046	2.5	3	-0.5	0.25
3-1 upstream	2.69	0.053	2.5	1	1.5	2.25
3---2	2.7	0.04	1	4	-3	9
3---3	2.62	0.051	4	2	2	4

4. Conclusions:

The findings of this study underscore the critical role of geotechnical irregularities in earth-fill dam embankments, particularly in regions with high seepage exposure and environmental fluctuations.

The combined findings on moisture content, density variations, grain size distribution, Atterberg limits, and specific gravity highlight the complexity of material heterogeneity within earth-fill dam embankments. The loss of fine clay particles, alongside density reductions, indicates progressive material variability, particularly in zones with high seepage exposure. Analyzing the bulk unit weight of old and new specimens reveals an increase, averaging 6%, attributed to a notable reduction in soil void ratio. In contrast, the newly extracted soil samples exhibited lower specific gravity values compared to historical records, indicating material degradation and particle loss, particularly within zones exposed to seepage. The largest reduction (up to 23%) was observed in samples collected from the upstream toe, where fine clay particles were washed out due to persistent seepage effects that weakens soil density and permeability characteristics, further impacting soil classification and long-term consolidation trends. Soil behavior under field-realistic loading and wetting conditions, as modeled in ASTM D4546, differs substantially from ASTM D2435 results. In ASTM D4546, the specimen remains under the effective overburden stress, keeping it within the compression domain. In contrast, under ASTM D2435, due to the high swelling potential of the soil, the sample enters the compression stage prematurely, within only a fraction of the loading-unloading cycle. The most significant compression and settlement occur during the initial reservoir filling, shows that the differential swelling percentage between adjacent zones reaches 90% Subsequent wetting-drying cycles after filling and drawdown can induce additional expansion and compression, the maximum swelling-to-compression ratio is 10% for first cycle of loading, whereas it rises to 67% in the second loading cycle, that increases the likelihood of crack formation and propagation over time, reinforcing the need for probabilistic geotechnical assessments of earth fill dams. The spatial variability of soil samples significantly impacts their swelling and compressibility behavior. This variability is particularly pronounced for specimens from the upstream face toe, that indicates a higher compressibility than the overlying zone (sample 2-2), contributing to heterogeneous swelling responses within adjacent zones, which explains the formation of the slip surface at the interface between these two zones.

High correlation (Rs =0.8) implies that samples with lower specific gravity tend to exhibit higher compressibility, which aligns with fine particle loss due to seepage exposure. Spatial consistency between 3-1 core, 3-1 upstream, 3-2, and 3-3 further supports this, meaning soil behavior within this section is strongly affected by density variations. A key takeaway from the study is the importance of material selection criteria to ensure compatibility within the embankment, preventing potential stress concentrations, Wang et al. [6]. and instability at interface zones that should be confirmed by numerical analysis. Additionally, the documented fluctuations in compression indices and swell pressures highlight the limitations of traditional static stability analyses, emphasizing the need for improved numerical modeling methodologies to address large-scale geotechnical anomalies. The variations in void ratios and compressibility parameters that are observed across different embankment zones reveal an increased susceptibility to volumetric changes, which play a crucial role in dynamic dam analysis. These inconsistencies impact stress redistribution, cyclic loading responses, and overall structural resilience, emphasizing the necessity of incorporating geotechnical variability into advanced stability assessments. The study establishes a foundational dataset for future seismic and hydro-mechanical simulations, providing essential parameters for optimizing dam evaluation. These insights underscore the critical role of material compatibility in dam rehabilitation efforts. Future assessments should integrate specific gravity analysis alongside consolidation evaluations to refine predictive models for embankment stability, ensuring optimal structural and ensure long-term embankment resilience.

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