Geotechnical Assessment of Seepage and Rainwater Harvesting Feasibility at Beit Al Rush Earth Dam, Southwest Bank, Palestine

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***Abstract*— Water scarcity in Palestine is becoming increasingly severe, as massive areas face semi-arid conditions due to extended droughts in the eastern Mediterranean region and limitations on water access. With limited surface and groundwater availability, earth dams have been considered a practical solution for water harvesting and have gained a mitigation strategy. This study presents a comprehensive geological and geotechnical evaluation of the Beit Al Rush earth dam, located in the southern West Bank in the Hebron Governorate. Despite initial expectations of storing 130,000 m³ of water annually, the dam failed shortly after construction due to complete water loss within days. To assess its feasibility for rainwater retention, integrated geotechnical fieldwork and laboratory analyses were conducted, including borehole drilling, trial pits, infiltration testing, and soil classification. GIS techniques were used to create spatial maps of geological features, watershed boundaries, and topographic elements. The geological review revealed that the dam site is located within karstified carbonate rock formations that are underlain by fractured marly limestone and covered by highly permeable alluvial soils. Hydrologically, the region receives an average annual rainfall of about 350 mm. The steep, rugged topography facilitates rapid surface runoff. Geotechnical results demonstrated high permeability rates (3.958 * 10^{-3} cm/sec) in surface soils and bedrock layers, confirming the site's unsuitability for effective water retention. The study recommends remedial measures, including grouting fractured zones, applying impermeable liners, and improving compaction to enhance storage capacity. These findings emphasize the critical role and importance of geological and geotechnical investigations for earth dam site selection, especially in semi-arid, structurally complex regions such as Palestine.**

I. Introduction

Water resources are among the most critical requirements for the development and sustainability of both urban and rural communities. The assessment and management of water resources hold significant strategic importance in planning for nations worldwide, particularly in arid and semi-arid regions [1-4], such as the southern areas of the West Bank [5-8]. In recent years, large parts of Palestine have been increasingly exposed to the risk of transitioning into semi-arid zones due to declining precipitation levels, irregular rainfall patterns, and poor spatial distribution, particularly in the early 21st century. This has led to a significant reduction in groundwater recharge [9].

Consequently, natural water reserves have been experiencing a continuous decline, exacerbating the already critical water crisis. For Palestinians, this crisis is particularly severe due to its geopolitical and security dimensions. The Israeli occupation exerts extensive control over water resources, restricting access and usage not only for Palestinian communities but also to benefit Israeli settlements in the West Bank and populations within the so-called "Green Line." It is important to note that many Israeli settlements are established in water-rich areas of the West Bank, further intensifying the disparity in water accessibility [10, 11].

As a result of the restrictive Israeli policies on both surface and groundwater resources in Palestine, there has been an urgent need to explore alternative water sources. Rainwater harvesting has emerged as one of the most effective and historically significant methods particularly in arid and semi-arid regions, where water scarcity poses substantial challenges.

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The effectiveness of rainwater and floodwater harvesting techniques varies depending on climatic conditions and geographical location, necessitating the selection of the most suitable approach based on technical, logistical, economic, and climatic factors specific to each region [12, 13]. In the context of initiatives of rainwater harvesting to develop the rural regions in Palestine, Beit Al Rush earth dam was designed in the Hebron Governorate, located in the southern West Bank "Fig. 1".

Earth dams are common water structures built across rivers and streams for a variety of purposes, including flood control, irrigation, human use, and the generation of electric hydropower [14, 15]. Compacted layers of soil particles make up earth dams. They are intended to be a non-overflow portion with a separate spillway for escaping any surplus water, and they often have a broad base and a typical trapezoidal shape [16, 17]. Seepage through the earth embankment is one of the major stability issues [18,19]. Since seepage has a major impact on the overall stability and safety of earth dams, it is a crucial design criterion. Uncontrolled seepage is responsible for about 30% of dam failures [20].

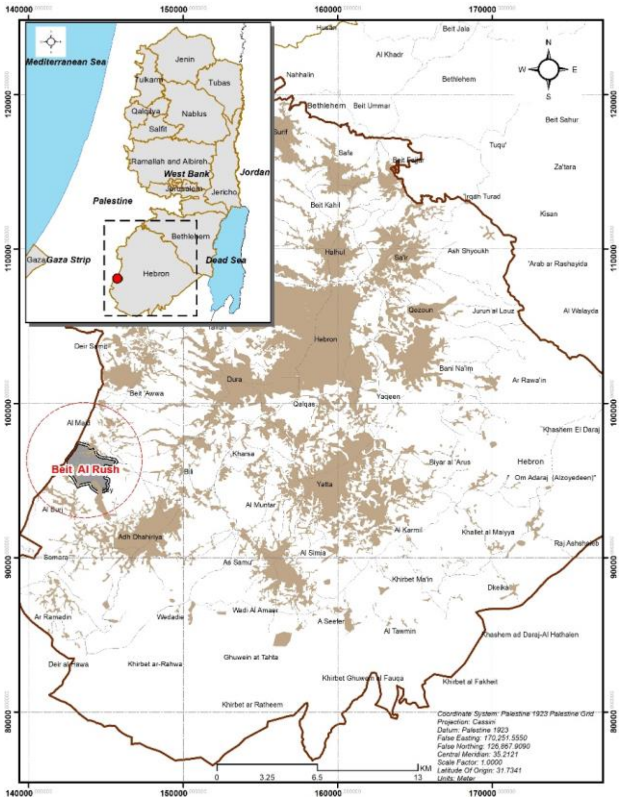

Figure 1. Location map [33]

In this paper, a case study has been conducted to assess the leakage problem in Beit Al Rush Earth dam, south West Bank, Palestine. This study underscores the necessity of sustainable water management strategies to address the ongoing water crisis in Palestine, with a particular emphasis on rainwater harvesting as a viable solution. Given the increasing water scarcity and geopolitical constraints, implementing efficient water collection and conservation techniques is crucial to ensuring long-term water security in the region.

II. Geological Setting

A. Stratigraphy

The study area is situated in the southern part of the West Bank, within the Hebron Governorate. Beit Al Rush lies near the Hebron-Dura Road. The geological formations of Beit Al Rush watershed primarily consist of Cretaceous-age sedimentary rocks, mainly limestone and dolomite, with occasional marl interbeds. These formations belong to the Judea Group "Fig. 2", which is widely distributed across the central and southern West Bank and serves as a major regional aquifer system [21].

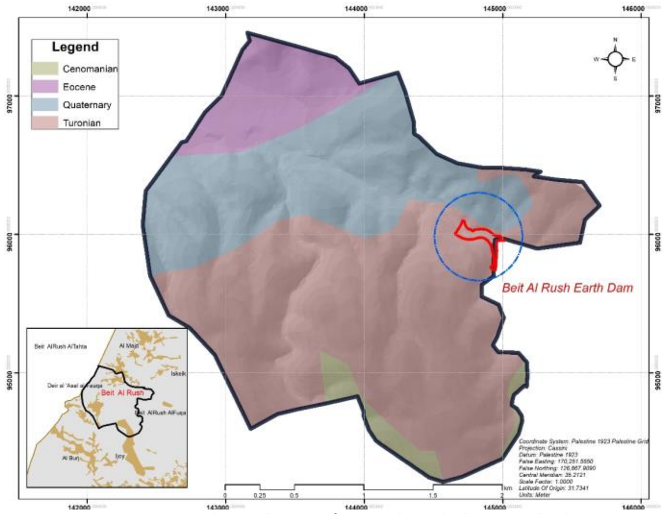

Figure 2. Geological map of Beit Al Rush dam site [33]

The Judea Group formations, particularly the Lower and Upper Cenomanian-Turonian limestones, are known for their high porosity and secondary permeability due to fracturing and karstification [21- 23]. This enhances their capacity to store and transmit groundwater, making them significant contributors to regional water resources. Additionally, the area exhibits structural deformations, including faults and joints, which further influence groundwater movement and storage. The presence of karstic conduits and fractures facilitates rapid infiltration but also poses challenges for water retention, making the implementation of rainwater harvesting techniques essential for sustainable water management. The structural geology of the region is influenced by the major fault systems associated with the Dead Sea Transform (DST), a strike-slip fault system that extends through the Jordan Rift Valley [24].

B. Topography and Hydrology

Beit Al Rush watershed is part of the southern West Bank mountainous terrain, with elevations ranging between 400 to 600 meters above sea level "Figs. 3 and 4". The landscape consists of rolling hills and depressions, which influence both surface runoff patterns and groundwater dynamics. The rugged nature of the terrain affects the hydrological behavior of the watershed, with precipitation being unevenly distributed across the slopes and valleys. Most of the annual rainfall occurs in the period from October to April, with an average of 350 mm/yr.

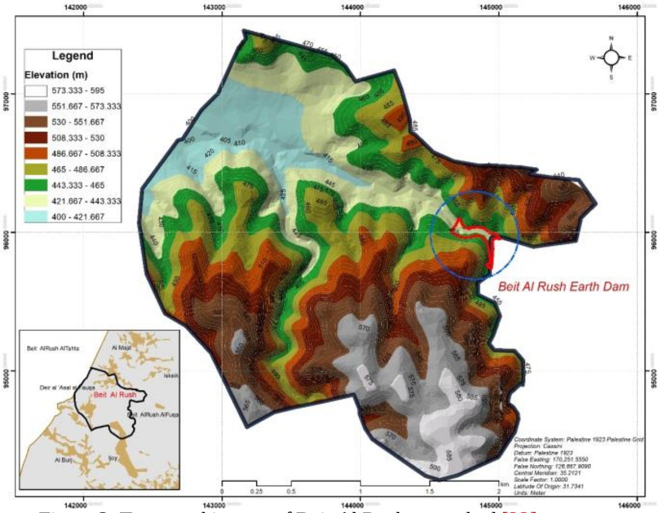

Figure 3. Topographic map of Beit Al Rush watershed [33]

Due to its karstic characteristics, the watershed has limited perennial surface water bodies, as most of the rainfall percolates quickly into the subsurface. However, during intense rainfall events, flash floods can occur in the valleys and low-lying areas, making the construction of Beit Al Rush dam "Fig. 4" and other rainwater harvesting structures strategically important. These interventions can help enhance water retention, mitigate water loss due to rapid infiltration, and support regional agricultural and domestic water demands.

III. GEOTECHNICAL ANALYSIS

Before Seepage through earth dams is a complex phenomenon influenced by factors such as stratigraphy, soil permeability, dam geometry, and water levels. Seepage estimation is crucial for the design and maintenance of earth dams to ensure their safety and longevity. Various methods have been developed to estimate seepage, including geotechnical, numerical, and probabilistic approaches [25-31]. In this work, geotechnical investigations used drilling of boreholes and laboratory soil tests to assess soil properties, permeability, and leakage risks, which are essential for

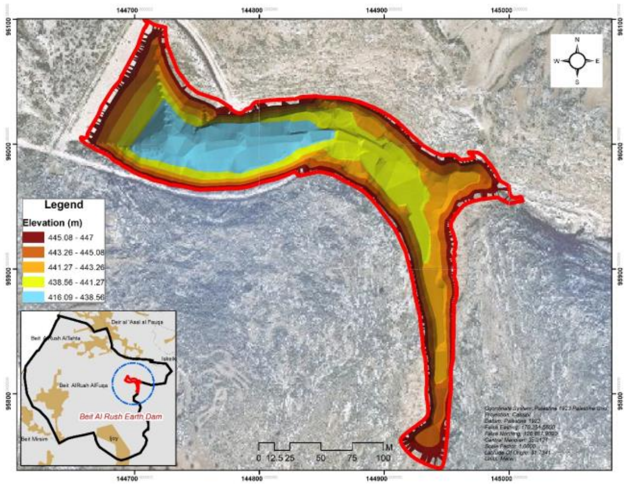

Figure 4. Location map and topography of Beit Al Rush dam

evaluating dam feasibility and suitability for rainwater harvesting in the study area [32].

A. Site Geotechnics

The surface and subsurface soil layers influencing water infiltration will be described from a geotechnical perspective, based on the results of tests conducted on samples obtained from trial pits and boreholes and in-situ testing. "Fig. 5" illustrates the locations of the trial pits, while "Fig. 6" shows the locations of the boreholes.

Figure 5. Locations of the trial pits

The trial pits and boreholes were not carried out directly beneath the riprap-covered lower slope due to a combination of safety/access constraints and the adopted phased investigation strategy. The decision was supported by (i) visual inspections that showed no signs of localized settlement or seepage, (ii) continuity with adjacent boreholes and available as-built/compaction records, and (iii) non-invasive geophysical surveys that indicated no significant anomalies beneath the riprap.

Based on the results obtained from the trial pits and borehole investigations, the geological cross-sections and geotechnical properties of the soil layers were identified. A surface layer of alluvial silty clay soil (CH) was observed, characterized by a high plasticity index and significant swelling potential. This layer, which has a thickness not exceeding 20 cm, was formed due to the deposition of clay and silt in the reservoir area as a result of stagnant water behind the dam. "Fig. 7" illustrates the appearance of this layer after the water in the dam lake dried up.

The geotechnical properties of this surface silty clay soil (CH) indicate a very high plasticity, with a liquid limit (L.L.) of 78, a plastic limit (P.L.) of 62, and a plasticity index (P.I.) of 16. Additionally, 90% of the soil particles pass through the sieve no. 200.

Figure 6. Locations of the boreholes

Figure 7. The surface silty clay layer

The second layer consists of Wadi soil (alluvial-colluvial soil), which is a silty clay soil (GC) mixed with a high proportion of sand and variously sized gravel and stones, as illustrated in “Fig. 8”. The thickness of this layer ranges between 2 and 4 meters.

The third layer encountered is a bedrock stratum composed of marly limestone, characterized by low strength, looseness, and significant fracturing. It contains cavities and voids, and its hardness was observed with depth, particularly 6 meters below the existing ground surface. Water infiltration tests conducted in the boreholes indicated that the rock is highly fractured and loosely compacted, resulting in rapid water seepage. “Fig. 8” presents one of the geological cross-sections within the dam lake and along the upper side slopes of the dam.

B. Field and Laboratory Tests

Field tests were conducted to obtain an approximate indication of the water seepage rate within the dam reservoir, with the primary goal of determining whether the underlying soil layers are capable of retaining water for a sufficient period of time, rather than precisely quantifying the seepage rate. In parallel, soil samples were collected from the trial pits and analyzed in the laboratory to determine the geotechnical properties of the soils within the reservoir area.

1. Trial Bits

Five trial pits were excavated within the dam reservoir area which presented in [34]. Table I below presents the dimensions of these excavations, while “Fig. 5” illustrates their locations. Laboratory soil samples were collected from these trial pits for further geotechnical testing.

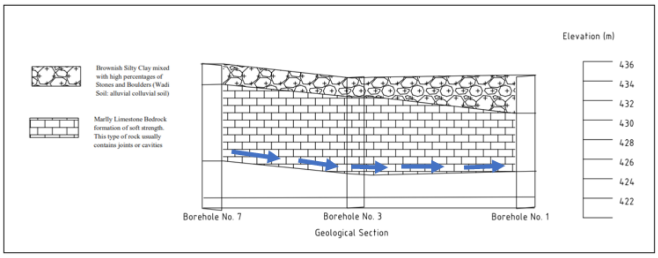

Figure 8. A geological cross-section between boreholes no. 1, 3, and 7

Infiltration tests were conducted on the surface layers of the reservoir at all trial pit locations on March 16 and 17, 2023. The test results are summarized in Table 1. Detailed information on both field and laboratory tests is provided in the appendices.

It is noteworthy that all trial pits lost the water introduced into them in less than 24 hours. Additionally, laboratory permeability tests were conducted on two soil samples collected from the trial pits. The results were as follows:

- Permeability coefficient of the first sample: 7.6×10^{-3} cm/sec
- Permeability coefficient of the second sample: 6.1×10^{-3} cm/sec

Further laboratory test results are presented in in Appendix A.

2. Boreholes

A total of ten boreholes were drilled to a depth of 10 meters below the existing ground surface, each with a diameter of 15 cm knowing that the minimum number of boreholes required is five [35]. “Fig. 6” illustrates the locations of the boreholes at the site, while Appendix B presents selected photographs documenting the drilling process, water filling of the boreholes, and the measurement procedures.

The boreholes were filled with water, and the rate of water infiltration was measured. The results indicated a very high infiltration rate in the upper layers, which consist of alluvial gravel. In contrast, the marl limestone layers exhibited variable infiltration behavior—ranging from an inability to retain any water to moderate infiltration rates. In some cases, water was retained, but only at greater depths, typically beyond 7 meters. The infiltration rates for each borehole, along with the detailed borehole logs describing subsurface stratigraphy, are provided in the appendices. Appendix C presents the laboratory test results for the samples obtained from the boreholes.

3. *Analysis of Tests Results*

Based on the results of the field and laboratory tests, the soil description of the dam lake area is characterized by alluvial soil, which is a mixture of silty clay (CH) with a high percentage of gravel of various sizes. The results of the water infiltration and permeability tests indicate very high permeability values, similar to those of coarse sandy soils, which do not meet the required criteria for water retention in the dame lake for an appropriate period. This implies that the floor of the dam requires special treatment to prevent water leakage from the accumulated water in the lake.

Regarding the sides of the dam, both the northern and southern sides, it was found that these sides consist of marly limestone with weak hardness. However, with increasing depth, the rock becomes moderately hard (i.e., more solid), but this type of rock (both weak and moderately hard) is fractured, contains cavities, voids, and fissures to a significant degree. Water infiltration tests conducted in the boreholes revealed that water permeates the rock very quickly due to the presence of cracks, voids, and cavities.

It is evident that the rocky sides of the dam need treatment due to the presence of fractures, voids, and cavities in the rock sections. However, due to the inclination of the rock layers towards the north, the movement of water leakage is predominantly directed towards the north. Therefore, the northern side of the dam, beneath the spillway, urgently requires treatment. In other words, the northern side of the dam needs to be treated to prevent the leakage of water accumulated in the dam lake.

IV. DISCUSSION

The feasibility of Beit Al Rush earth dam for rainwater harvesting must be evaluated by integrating geotechnical findings with the site's stratigraphic, structural, topographic, and hydrological characteristics. Stratigraphically, the area is underlain by Cretaceous formations of the Judea Group, predominantly composed of limestone and marl, which are known for their dual-porosity nature due to karstification and fracturing [21–23]. These formations, while serving as important regional aquifers, pose a substantial challenge to surface water retention due to the high secondary permeability associated with karst conduits and structural discontinuities. Structurally, the area is influenced by the tectonic dynamics of the Dead Sea Transform fault system, which has led to the formation of numerous faults and joints that act as conduits for rapid groundwater movement and potential seepage paths beneath and around the dam body [24].

The topography of the watershed, characterized by steep hills and depressions at elevations between 400 and 600 meters, naturally supports surface runoff collection during rainfall events. However, the rugged terrain and inclined rock layers, particularly dipping northward beneath the spillway, facilitate rapid water escape, especially through fractured northern slopes. Hydrologically, although the region receives an average annual precipitation of about 350 mm, the karstic nature of the subsurface and the limited surface water bodies results in most rainfall infiltrating quickly into the ground [9, 22, 23]. This renders the area inherently vulnerable to water loss unless properly engineered solutions are implemented to manage and retain surface runoff.

Geotechnical investigations reinforce these concerns. Laboratory and field tests revealed that the surface and subsurface soils are composed of silty clay (CH) mixed with gravel and sand, exhibiting high permeability rates consistent with coarse sandy soils. Permeability coefficients ranged from 6.1×10^{-3} to 7.6×10^{-3} cm/sec, with infiltration rates of up to 3.96×10^{-3} cm/sec, indicating a soil profile incapable of sustaining water retention for long durations. Furthermore, borehole logs confirmed the presence of marly limestone bedrock exhibiting substantial fracturing, voids, and cavities, all of which contribute to rapid seepage [25, 26].

These findings are consistent with broader literature highlighting the significance of geological and geotechnical factors in earth dam performance. For instance, similar challenges have been observed in other semi-arid regions where high infiltration rates and karstic formations required the application of seepage control measures such as grouting, impermeable linings, or cutoff walls [20, 27, 28]. In this context, Beit Al Rush dam remains a potentially viable water harvesting solution, but only if comprehensive remedial actions are taken. Grouting the fractured bedrock and northern spillway zone, applying geomembrane liners to the reservoir floor, or even considering the site for managed aquifer recharge rather than long-term surface storage could be practical and cost-effective interventions [2, 3, 4, 6, 7, 20].

Therefore, while the current geotechnical and hydrological profile indicates that the dam in its existing form is not adequately retaining water, the strategic location and rainfall patterns still justify efforts to rehabilitate the structure. Future projects in similar settings must emphasize detailed geotechnical and hydrogeological assessments during site selection and design phases, aligning with sustainable water management principles essential for addressing Palestine’s acute water scarcity [5–8].

V.GENERAL REMARKS

This study provided an in-depth geotechnical and geological assessment of Beit Al Rush earth dam in the southern West Bank, with a focus on diagnosing the causes of its failure to retain rainwater. Through the integration of field investigations, borehole data, and laboratory analyses, it became evident that the dam's inability to hold water stems primarily from the high permeability of its alluvial and colluvial surface soils, as well as the fractured marly limestone bedrock. These characteristics, which are associated with karstification and the complex structural setting of the Dead Sea Transform fault system, contribute to rapid seepage and loss of stored water.

Despite these limitations, the dam’s location within a catchment that receives adequate seasonal rainfall and is hydrologically conducive to runoff collection confirms the potential of the site for rainwater harvesting, provided that remedial measures are implemented. Such measures may include the application of impermeable liners, grouting of fractured zones. These interventions would align with best practices documented in similar arid and semi-arid environments, where geological and hydrological challenges have been mitigated through adapted engineering solutions.

Future research should focus on pilot-scale testing of proposed solutions and the development of predictive seepage models using numerical simulation to enhance the long-term viability and performance of similar projects. Ultimately, such efforts are vital for strengthening water security and supporting agricultural and domestic needs in regions facing chronic water scarcity.

TABLE I. RESULTS OF FIELD INFILTRATION TESTS AND SELECTED LABORATORY ANALYSES FOR SAMPLES COLLECTED FROM TRIAL PITS

Trial Pit No.	**Pit Dimensions (Width × Length × Depth) (m)**	**Infiltration Rate (cm/sec) *(cm/day)***	**Water Content (%)**	**Soil Description**	**Typical Classification Based on Infiltration Rate**
1	2.0 × 3.0 × 2.0	1.19×10^{-3} *(103)*	15	Gravel mixed with sand and fines (silt and clay); Fines content = 22%	Coarse Sand
2	1.3 × 2 × 1.2	1.42×10^{-3} *(123)*	21	Gravel mixed with sand and fines (silt and clay); Fines content = 42%	Coarse Sand
3	1.4 × 2.3 × 1.7	1.69×10^{-3} *(146)*	13	Gravel mixed with sand and fines (silt and clay); Fines content = 25%	Coarse Sand
4	1.4 × 2.4 × 2.0	3.96×10^{-3} *(342)*	18	Gravel mixed with sand and fines (silt and clay); Fines content = 35%	Coarse Sand
5	1.8 × 2.4 × 2.0	3.22×10^{-3} *(278)*	17	Gravel mixed with sand and fines (silt and clay); Fines content = 38%	Coarse Sand

VI. APPENDICES

Appendix A. Laboratory Test Results for Samples Collected from the Dry Surface Alluvial Layer and Trial Pits

SAMPLE NO.	**USCS CLASSIFICATION**	**AASHTO CLASSIFICATION**	**SOIL DESCRIPTION**	**MOISTURE CONTENT (%)**	**% PASSING SIEVE #200**	**ATTERBERG LIMITS**			**DEPTH (M)**
						LL.	PL.	P.I.	
1	CH	A-7-5	FAT CLAY (DRY SURFACE LAYER)	-	90	78	62	16	0.2
2	GC	A-2-6	CLAYEY GRAVEL WITH SAND	15	22	30	17	13	1.0
3	GC	A-6	CLAYEY GRAVEL WITH SAND	21	42	36	19	17	1.0
4	GC	A-2-6	CLAYEY GRAVEL WITH SAND	13	25	32	16	16	1.0
5	GC	A-6	CLAYEY GRAVEL WITH SAND	18	35	33	17	16	1.0
6	GC	A-6	CLAYEY GRAVEL WITH SAND	16	38	35	18	17	0.2

Appendix B. Boreholes Tests

Appendix C. Laboratory Test Results of Samples Collected from Boreholes

Borehole No.	Depth (m)	Description	Infiltration	Water Content (%)	Classification AASHTO	Classification USCS
1	0.0-2.0	Brownish Silty Clay mixed with high percentages of Stones and Boulders (Wadi Soil: Alluvial Colluvial Soil)	High like coarse sand >1x10^{-3} cm/sec	8	A-6	GC
	2.0-4.0	Brownish Silty Clay mixed with high percentages of Stones and Boulders (Wadi Soil: Alluvial Colluvial Soil)	High like coarse sand >1x10^{-3} cm/sec	8	A-2-6	GC
	4.0-10.0	Marly Limestone Bedrock formation of soft strength. This type of rock usually contains joints or cavities	High due to joints and cavities	3	Marlstone Bedrock formation	Marlstone Bedrock formation
2	0.0-2.0	Brownish Silty Clay mixed with high percentages of Stones and Boulders (Wadi Soil: Alluvial Colluvial Soil)	High like coarse sand >1x10^{-3} cm/sec	10	A-6	GC
	2.0-4.0	Brownish Silty Clay mixed with high percentages of Stones and Boulders (Wadi Soil: Alluvial Colluvial Soil)	High like coarse sand >1x10^{-3} cm/sec	7	A-2-6	GC
	4.0-10.0	Marly Limestone Bedrock formation of soft strength. This type of rock usually contains joints or cavities.	High due to joints and cavities	3	Marlstone Bedrock formation	Marlstone Bedrock formation
3	0.0-2.0	Brownish Silty Clay mixed with high percentages of Stones and Boulders (Wadi Soil: Alluvial Colluvial Soil)	High like coarse sand >1x10^{-3} cm/sec	7	A-6	GC
	2.0-10.0	Marly Limestone Bedrock formation of soft strength. This type of rock usually contains joints or cavities	High due to joints and cavities	1 0.4	Marlstone Bedrock formation	Marlstone Bedrock formation
4	0.0-4.0	Brownish Silty Clay mixed with high percentages of Stones and Boulders (Wadi Soil: Alluvial Colluvial Soil)	High like coarse sand >1x10^{-3} cm/sec	6	A-6	GC
	4.0-10.0	Marly Limestone Bedrock formation of soft strength. This type of rock usually contains joints or cavities	High due to joints and cavities	6 0.6	Marlstone Bedrock formation	Marlstone Bedrock formation
5	0.0-1.0	Brownish Silty Clay mixed with high percentages of Stones and Boulders (Wadi Soil: Alluvial Colluvial Soil)	High like coarse sand >1x10^{-3} cm/sec	10	A-6	GC
	1.0-4.0	Marly Limestone Bedrock formation of soft strength. This type of rock usually contains joints or cavities	High due to joints and cavities	4	Marlstone Bedrock formation	Marlstone Bedrock formation
	4.0-10.0	Marly Limestone Bedrock formation of soft strength. This type of rock usually contains joints or cavities	High due to joints and cavities	3 1	Marlstone Bedrock formation	Marlstone Bedrock formation
6	0.0-1.0	Brownish Silty Clay mixed with high percentages of Stones and Boulders (Wadi Soil: Alluvial Colluvial Soil)	High like coarse sand >1x10^{-3} cm/sec	10	A-6	GC
	1.0-10.0	Marly Limestone Bedrock formation of soft strength. This type of rock usually contains joints or cavities	High due to joints and cavities	2 1	Marlstone Bedrock formation	Marlstone Bedrock formation

7	0.0-2.0	Brownish Silty Clay mixed with high percentages of Stones and Boulders (Wadi Soil: Alluvial Colluvial Soil)	High like coarse sand $>1x10^{-3}$ cm/sec	7	A-6	GC
	2.0-10.0	Marly Limestone Bedrock formation of soft strength. This type of rock usually contains joints or cavities	High due to joints and cavities	2 1	Marlstone Bedrock formation	Marlstone Bedrock formation
8	1.0-10.0	Marly Limestone Bedrock formation of soft strength. This type of rock usually contains joints or cavities	High due to joints and cavities	6 4	Marlstone Bedrock formation	Marlstone Bedrock formation
9	0.0-10.0	Marly Limestone Bedrock formation of soft strength. This type of rock usually contains joints or cavities	High due to joints and cavities	3 1	Marlstone Bedrock formation	Marlstone Bedrock formation
10	0.0-4.0	Marly Limestone Bedrock formation of soft strength. This type of rock usually contains joints or cavities	High due to joints and cavities	8	Marlstone Bedrock formation	Marlstone Bedrock formation
	4.0-10.0	Marly Limestone Bedrock formation of soft strength. This typee of rock usually contains joints or cavities	High due to joints and cavities	1	Marlstone Bedrock formation	Marlstone Bedrock formation

VII. ACKNOWLEDGMENT

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