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Seepage Analysis of Satpara Dam; A Case Study in Pakistan

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ABSTRACT **Satpara is a rock fill dam having an earth core and located in Skardu. The dam has a length of 1400 ft and a maximum height of 128 ft, built on ground moraines and alluvial soil. Due to the porous nature of strata, serious seepage problems arose, among them, one major concern is embankment breaching. To rectify these problems, the upstream side is provided with a blanket that is almost 600 ft long and a cut off which is 25 ft in the foundation. This study analyzed the seepage through the dam using SEEP/w and studied the numerical value regarding the effect of seepage on the production of electricity during the whole year. It was found that significant amount of seepage is taking place, but the phreatic line indicates that the seepage water is exiting through chimney drain posing no serious threat to stability of dam. Consequential effect of seepage on power generation were observed**

Keywords: Satpara Dam, Alluvial Soil, Seepage, SEEP/W.

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1. INTRODUCTION

Satpara dam was made by the combined contribution of Govt. of Pakistan and the United States Agency for International Development (USAID). It is a project of 2090 million Pak Rupees [1]. The construction started in April 2003 and was planned to complete up till November 2011. It is located on Satpara Nullah downstream of Satpara lake, about 6 miles south of Skardu Town [2].

Seepage is a phenomenon related to every embankment and leads further to many other problems like piping, chocking of filter, particles migration, and so on. Seepage cannot be eliminated, as the impounded water seeks paths of least resistance, but can be reduced and controlled. Seepage of water through, around, or under the dam is expected in all embankment dams and even in concrete dams. The quantity of seepage, the flow path of seeping water, and its velocity are of great concern in analyzing the structural behavior and performance of a dam and pose a large threat to the dam’s stability. Moreover, the magnitude of seepage also affects the purpose of the construction of the dam, directly and indirectly [3]–[7].

Satpara Hydropower Project is located on Satpara Nullah in the Northern area of Pakistan. Satpara Nullah is the left tributary of the Indus River. It flows from south to north, and its confluence with River Indus is near Skardu, having a total mainstream length of 34.5 km. It has a natural lake, about 06 km south of Skardu Town along the access road to Deosai plain. Satpara village is situated upstream of Satpara lake along the left bank of Satpara Nullah. The dam site is about 06 miles south of Skardu Town, which is located at 226 km and 760 km from Gilgit and Islamabad, respectively.

Satpara Dam is a multipurpose rockfill and earth dam. Not only it will enlarge the size of Satpara Lake, but it will also produce 17.36 MW of hydroelectricity, and supply water to 30,000 houses in Skardu Valley, irrigates 15,536 acres (62.87sq. km) of land, and supply 3.1 million gallons of drinking water to Skardu city [8]. The geology of the dam is such that, the most area is covered with moronic deposits and colluvial/alluvial material [9]. Thick moronic material is lying throughout the area. These deposits are loose to semi-consolidated having steep slopes and slides are common on both banks of the Nullah. Detailed information about Dam is listed in Table 1.

Table 1. Details of Dam

River	Name	Satpara Nullah
	Catchment Area	274.5 sq.km
	Avg. Annual Flow	114,610 Aft
	Maximum Estimated Flood	10,000 cubic ft/s
Reservoir	Storage Capacity Gross	93,385 Aft
	Dead	41,901 Aft
	Live	51,484 Aft
	Surface area Dead	690.16 Acres
	Live	299.21 Acres
	Length (approx.)	14,000 ft
Dam	Type	Clay core earth-filled
	Dam length(crest)	560 ft
	Maximum Height	128 ft
	Crest Width	29.53 ft
	Crest Elevation	8750 ft
	Lowest Foundation	8622 ft
	Free Board	10 ft
Energy Output	Design Capacity(2 Plants)	13.2 MW
	Mean Annual Peak Energy	80 GWh/a
	Plant Factor	70%

2. SCOPE of WORK

In this study effect of seepage on the stability and performance of Satpara dam is dam is being studied and analyzed. Data of different heads was collected from various piezometers and was then analyzed using SEEP/W. In the end it was expected to quantify the amount of seepage through dam and analyze it's effects on the production of electricity.

3. RESULTS and ANALYSIS

A typical dam cross-section was selected, and the seepage analysis was performed by modeling the dam's cross-section in SEEP/W for the seepage quantification. SEEP/W provides the properties and the figures at each point in the dam's cross-section. So, the primary purposes for using SEEP/W were, Seepage quantification and determination of the phreatic line, for the estimation of the pore water pressures

For the analysis of seepage through and under earth dams, flow is considered two-dimensional, and the Laplace equation is given in Equation 1:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \qquad (1)$$

This equation forms the basis of SEEP/W software. The results are plotted in the form of a Flow net. The lines joining the points having equal potential heads are the 'Equipotential lines'. The direction of seepage is always perpendicular to the equipotential lines and the path of seepage is shown by lines called the ‘Flow lines’. From Darcy’s equation the total flow between two points is calculated by using Equation 2.:

$$Q = kA\frac{\Delta H}{l} \qquad (2)$$

SEEP/W can compute the seepage quantity that flows across a user-defined section. The imaginary flow lines from one side of the section to the other side are known as sub-sections. SEEP/W identifies all subsections across a user-defined flux section, computes the flow for each subsection, and then sums the subsection flows to obtain total flow across the flux section.
Theoretically, from Cedregren (1989) [10] and Casagrande (1940) [11], after the flow net is drawn the rate of seepage can be computed from the geometry of the seepage pattern with equation 3.

$$Q = kh\frac{N_f}{N_d} \qquad (3)$$

Where:
k= Coefficient of permeability(ft/sec)
h= total pressure head loss (ft.)
N_f= Number of flow channels
N_d= Number of equipotential drops
Q= Rate of seepage (ft^3/sec)
The above equation applies to isotropic soil conditions. So, it can be modified to be used for anisotropic conditions by using, $k = \sqrt{k_n k_v}$. Therefore, the equation becomes Equation 4.

$$q = \sqrt{k_n k_v}\, h\frac{n_f}{n_d} \qquad (4)$$

The first attempt was made on the Maximum Conservation Level. The overall step-wise process is as explained below:

a. The first step was to sketch the Dam’s cross-section according to scale as shown in Figure 1.

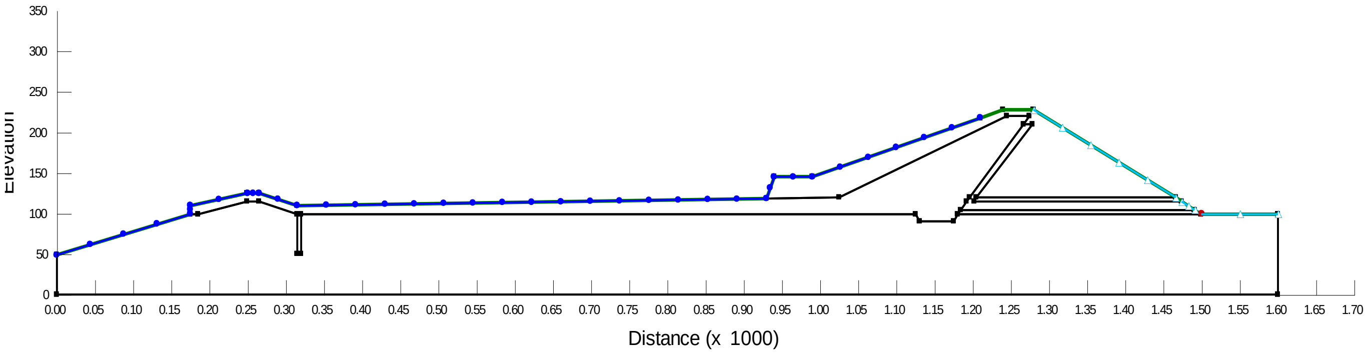

Figure.1 Simple sketch of Dams cross-section

As the 1st step of analysis dam cross-section was drawn according to scale and all known dimensions were used as input for this. The cut-off length, upstream blanket, core, shell, and other components of the dam were drawn in this step.

b. Then a finite element mesh was generated as shown in Figure 2.

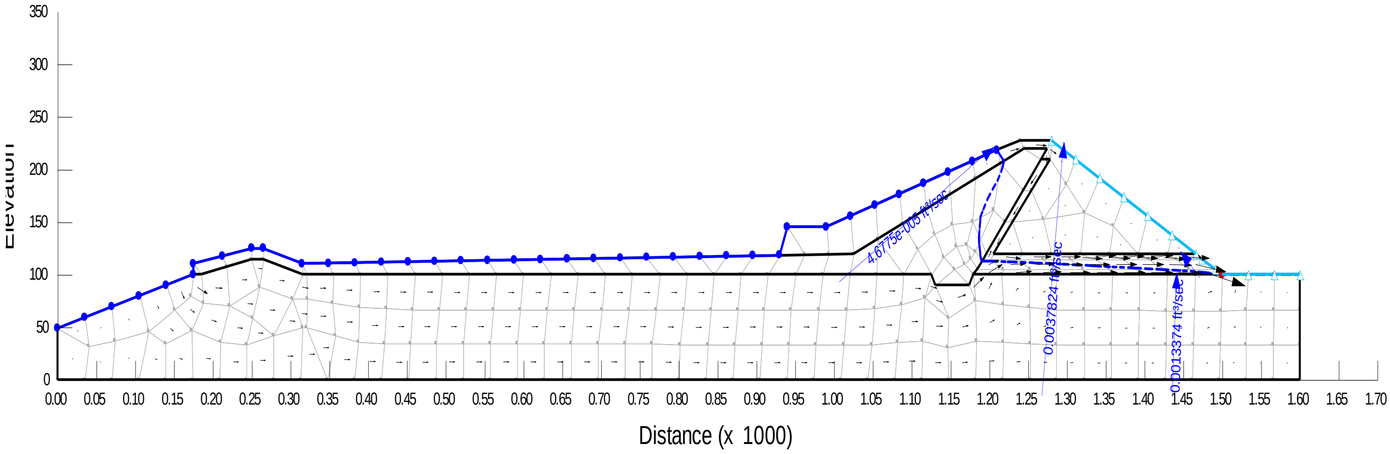

Figure. 2 Finite Element Mesh

c. Material properties were assigned, and distinct colors were given to each of them.

After drawing the cross-section of the dam, the next step is to generate the finite element mesh and assign properties to the materials as shown in Figure 3 with Colors. To perform the analysis the mesh plays a significantly important role. As we increase the number of nodes in the mesh, the analysis becomes more rigorous but more time-consuming. Depending upon the nature and purpose of analysis the nodes and hence finite element mesh can be adjusted.
After that properties are assigned to the materials. Different components of the dam have different properties according to their particular nature. So to perform the seepage analysis it is very important to assign properties and parameters carefully to each material. Some of the material properties include permeability coefficient, material density, moisture content, specific gravity, soil category according to USCS or AASHTO classification, shear strength parameters (C and ϕ values).

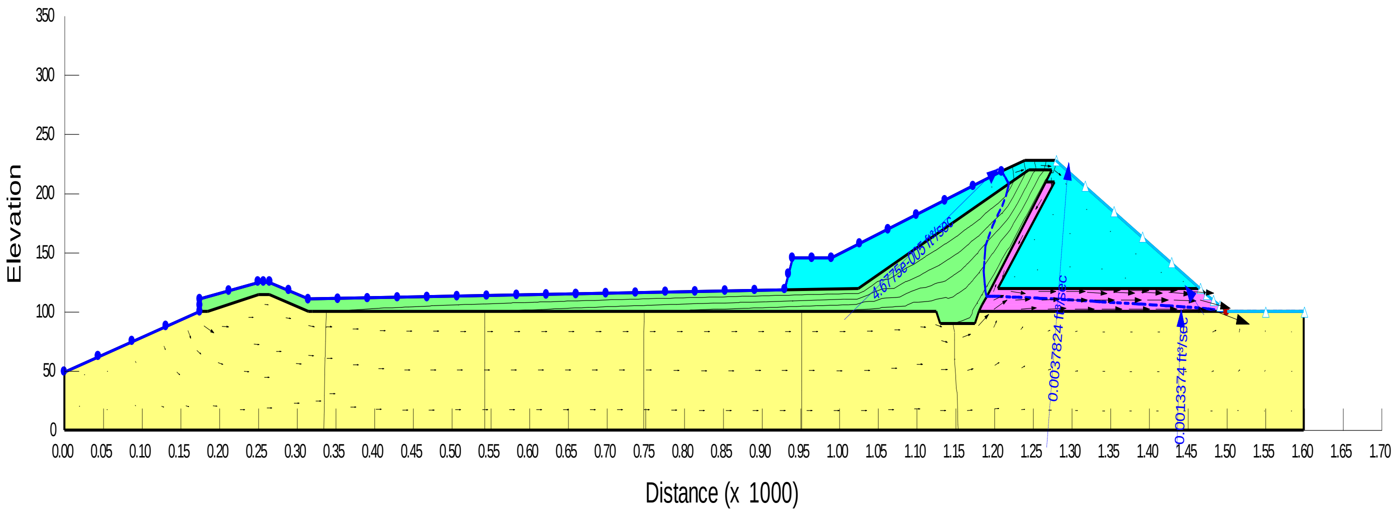

Figure. 3 Materials Properties with Colors

d. The problem was solved to obtain results shown by following Contours for Pore water Pressure, Pressure Head and Total Head Respectively as shown in Figure 4.

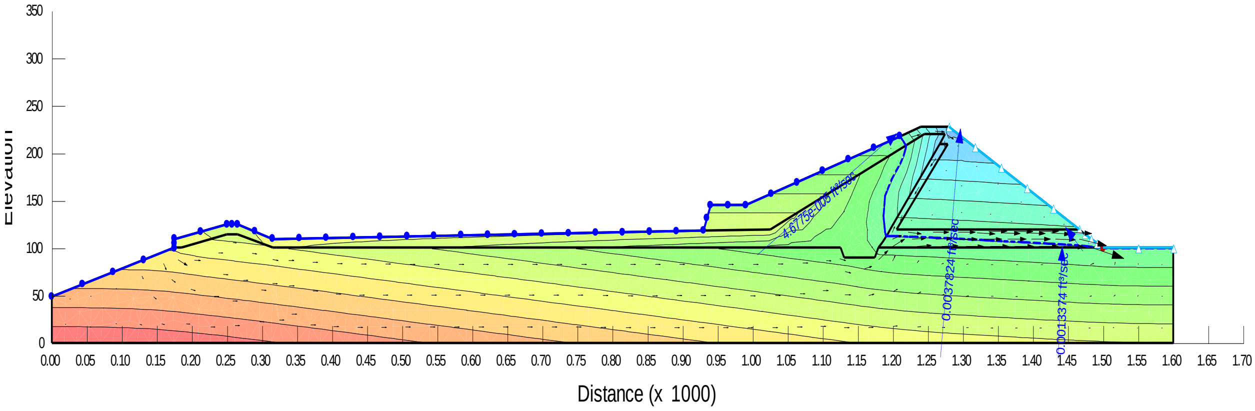

Figure. 4 Pore Water Pressure

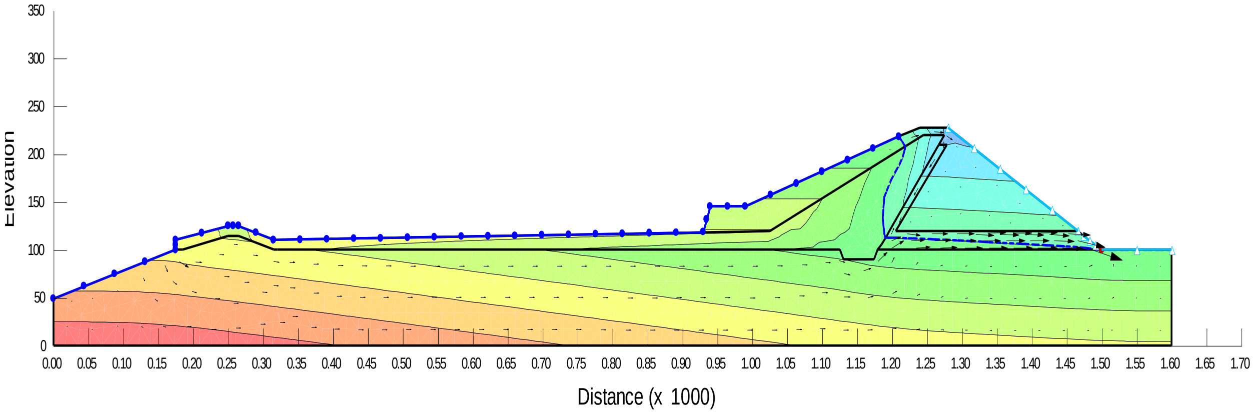

Figure. 5 Pressure Head

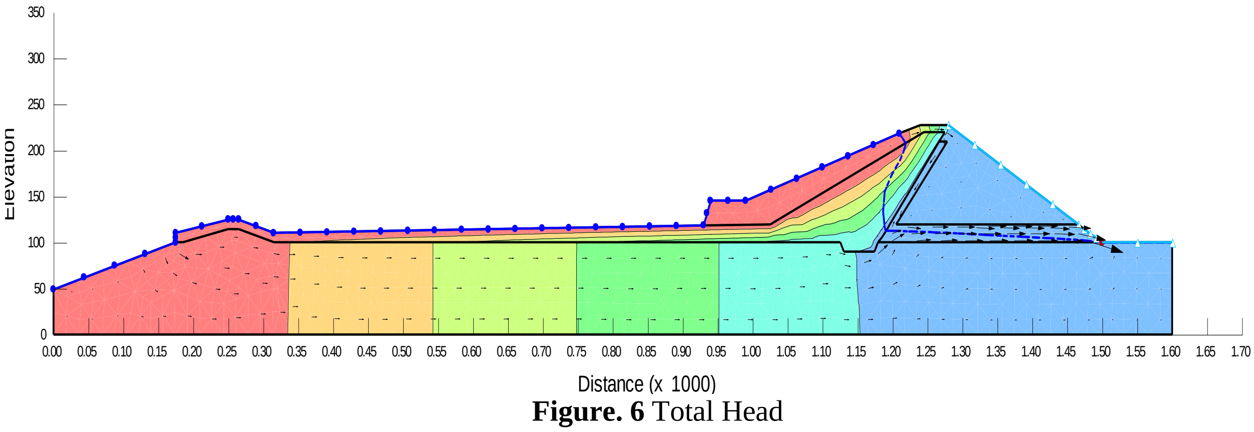

Figure. 6 Total Head

Figure 4, 5, and 6 depicts the distribution of pore water pressure, pressure head, and total head respectively, across the cross-section of the dam. It can be observed clearly with the help of contours that a significant amount of seepage is taking place from the dam, causing loss of head and hence affecting the electricity generation.

4. INFLUENCE of SEEPAGE on POWER PRODUCTION

Power and energy both are directly proportional to discharge; therefore, an increase is generally expected with any minor increment in discharge.

Table 2 is taken from the Satpara dam feasibility report by HEPO, WAPDA [12][13]. The value in the table shows general power and energy calculations without considering the seepage effects while Table 3 shows the amount of seepage taken as an incremental discharge; an apparent increase in power production and energy generation is indicated. Q_{Total} is found by using Equation 5.

$$Q_{Total} = Q_{Power} + \Delta Q_{Seepage} \quad (5)$$

Table 2. Calculation Sheet for Discharges Excluding Seepage

Months	Days	U/S Level (ft)	D/S Level (ft)	Gross Head (ft)	Net Head (ft)	Discharge (cusecs)	Power (MW)	Energy (GWh)
January	31	8740.50	8427.96	276.54	273.54	158.21	3.30	2.45
February	28	8693.18	8427.96	265.22	262.22	168.45	3.36	2.26
March	31	8677.76	8427.96	249.80	246.80	155.03	2.91	2.17
April	30	8661.76	8427.96	233.80	230.80	138.43	2.43	1.75
May	31	8646.93	8427.96	218.97	215.97	140.20	2.31	1.72
June	30	8650.64	8427.96	222.68	219.68	172.34	2.88	2.08
July	31	8721.22	8425.50	295.72	292.72	121.48	2.71	2.01
August	31	8733.26	8425.50	307.76	304.76	119.01	2.76	2.05
September	30	8735.66	8425.50	310.16	307.16	153.27	3.58	2.58
October	31	8731.82	8425.50	306.32	303.32	158.56	3.66	2.72
November	30	8724.73	8426.32	298.41	295.41	160.33	3.61	2.60
December	31	8715.71	8426.32	289.39	286.39	159.62	3.48	2.59
					Total=		37.00	26.98
Max. Conservation Level		8740.00	8427.96	312.04	309.04	211.89	4.89	3.59

Table. 3 Calculation Sheet for Discharge Including Seepage.

Months	Days	U/S Level (ft)	D/S Level (ft)	Gross Head (ft)	Net Head (ft)	Discharge (cusecs)	Seepage (cusecs)	Total Discharge (cusecs)	Power (MW)	Energy (GWh)
January	31	8704.5	8427.96	276.54	273.54	158.21	3.22	161	3.36	2.5
February	28	8693.18	8427.96	265.22	262.22	168.45	3.09	172	3.43	2.3
March	31	8677.76	8427.96	249.8	246.8	155.03	2.99	158	2.97	2.21
April	30	8661.76	8427.96	233.8	230.8	138.43	2.94	141	2.48	1.79
May	31	8646.93	8427.96	218.97	215.97	140.2	2.88	143	2.35	1.75
June	30	8650.64	8427.96	222.68	219.68	172.34	2.89	175	2.93	2.11
July	31	8721.22	8425.5	295.72	292.72	121.48	3.15	125	2.78	2.07
August	31	8733.26	8425.5	307.76	304.76	119.01	3.19	122	2.84	2.11
September	30	8735.66	8425.5	310.16	307.16	153.27	3.2	156	3.66	2.63
October	31	8731.82	8425.5	306.32	303.32	158.56	3.19	162	3.74	2.78
November	30	8724.73	8426.32	298.41	295.41	160.33	3.17	164	3.68	2.65
December	31	8715.71	8426.32	289.39	286.39	159.62	3.13	163	3.55	2.64
						Total=			37.76	27.54
Max. Conservation Level		8740	8427.96	312.04	309.04	211.89	3.22	215.11	5.06	3.64

Table 4 shows a comparison of monthly power production and energy generation respectively, with and without incremental seepage. The influence of seepage on power and energy is indicated as the differences.

The annual difference in power is 0.77 ≈ 0.8 (approx. 800 KW), and in energy, it is 0.56 ≈ 0.6 GWh (approx. 600GWh).

Table 4 Comparison Sheet for Power and Energy with and without Incremental Seepage.

Month	POWER (MW)			ENERGY (GWh)		
	Without Seepage	With Seepage	Difference	Without Seepage	With Seepage	Difference
January	3.3	3.36	0.06	2.45	2.5	0.05
February	3.36	3.43	0.07	2.26	2.3	0.04
March	2.91	2.97	0.06	2.17	2.21	0.04
April	2.43	2.48	0.05	1.75	1.79	0.04
May	2.31	2.35	0.04	1.72	1.75	0.03
June	2.88	2.93	0.05	2.08	2.11	0.03
July	2.71	2.78	0.07	2.01	2.07	0.06
August	2.76	2.84	0.08	2.05	2.11	0.06
September	3.58	3.66	0.08	2.58	2.63	0.05
October	3.66	3.74	0.08	2.72	2.78	0.06
November	3.61	3.68	0.07	2.6	2.65	0.05
December	3.48	3.55	0.07	2.59	2.64	0.05
Total	37	37.76	0.76	26.98	27.54	0.56
	% Increase		2.07	% Difference		2.07

5. CONCLUSIONS

- The Dam was encountering serious seepage problems and the remedial measures were good enough.
- The seepage analysis in SEEP/W revealed that all the seepage water was exiting the dam through the filter
- The provision of concrete lining was useful in reducing the seepage through the embankment which saved it from breaching.
- The effect of seepage on power production was as expected, indicating a difference of 2.07%.

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