Understanding the Seepage Behavior of Nai Gaj Dam through Numerical Analysis

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Abstract—This study presents the seepage patterns of earth-fill dams, using critical situations by employing the finite element approach. The Nai Gaj dam is 65km northwest of Dadu city in Sindh Province, Pakistan. In this study, the seepage through the main dam body and foundation is computed and simulated for different scenarios, i.e. maximum, normal, and minimum reservoir level. Seepage analysis was conducted by using the SEEP/W sub-program of GEO-SLOPE software. Dam design parameters and dam geometry data were used as input data to compute the unknown seepage. The seepage behavior of the Nai Gaj dam is shown in terms of net flow which consists of equipotential lines, streamlines, velocity vectors, and phreatic lines. The results show the seepage flux, maximum seepage, and exit gradient at different reservoir levels. The results show that the average flow rate at normal, maximum, and minimum reservoir levels are 1.49×10^{-7}cumec/m, 3.38×10^{-7}cumec/m, and 2.108×10^{-8}cumec/m respectively. In addition, the overall stability of the side slope of the dam is discussed.

Keywords-seepage; earth fill dam; phreatic line; SEEP/W; finite element modelling

I. INTRODUCTION

Pakistan is basically an agricultural country. The agriculture in Pakistan depends mainly on water irrigation. In this regard, many dams have been constructed in the past and some others are planned to be constructed in the future. Embankment dams are important and costly civil engineering structures that provide an essential infrastructure for the management of water [1, 2]. One of the critical aspects of dam design is the analysis of stability and safety of the earth structure under various operating conditions. Dams are built for specific functions, i.e. storage of water for domestic use and irrigation, flood control, entertainment, fishing, and hydroelectric power generation. Design and construction of dams have to meet safety criteria and satisfy specific requirements. Stability of the dam against slope failure is an essential component for the design, operation level under all flood and drought circumstances [3, 4]. The estimated number of the earth fill dams around the world is 11192 [5, 6]. A review of historical dam failures indicates that nearly half of all failures of embankment dams have occurred due to seepage induced internal erosion. Detailed studies of seepage analysis through and beneath the dam body need to be parts of design, construction, and maintenance of any dam component. Most geotechnical studies related to dams involved seepage and stability analysis considering the pore pressure variations in unsaturated soil conditions. Seepage failures occur by rainfall or water infiltration that changes the distribution of pore water pressure. This effect leads to changes in the stress and affects the seepage process of the soil. An analyst must have a good understanding of seepage, its solutions, and the preventive measures for its monitoring. Finite element analysis is extensively used in the geotechnical studies for seepage and stability analysis considering the pore pressure variations. In case of dam seepage, failures occur by rainfall or water infiltration that changes the distribution of pore water pressure. This effect leads to changes in the stress and affects the seepage process of the existing soil. To make the dam safe, it is important to take great care on stability and seepage control

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while designing embankment dams. Embankment dams are generally constructed with various zones of materials such as two permeable shells and impermeable core in the middle [7].

The main reasons behind embankment dams' failures are seepage, hydraulic failures, piping through the dam body, and structural damage due to earthquakes [8]. Permeable materials such as gravel or coarse sand when used in dam foundation lead to heavy seepage [5, 9-11]. In the past, embankment dams mostly faced seepage problems. As water in the reservoir seeks the paths of least resistance through the dam body and its foundation, it may pose some hazards on the dam safety. Excessive seepage may lead to dam failure if it is not treated and controlled properly. If seepage flow can continue unhindered in appreciable quantities, then the seepage force may erode fine soil particles and wash them out causing piping failure of the dam or create uplift problems. Seepage, therefore, may be considered as one of the most common safety hazards for embankment dams. The basic problem the designers and operators face are to discern how seepage is affecting a particular dam and what measures, if any, must be taken to ensure that the seepage does not unfavourably affect the safety of the dam. This paper presents a case study of the Nai Gaj Dam and highlights the probability of pre and post seepage issues. The SEEP/W GEO-SLOPE software was utilized. It can work quite well on seepage analysis in homogenous and non-homogenous embankment dams [12]. Slope stability analysis confirms the safety of the embankment dam. Different loading conditions can be studied, for example end of construction, steady state, rapid draw down, and the earthquake loading scenario.

The aim of this study is to analyze the steady state seepage behavior of the dam foundation of the Nai Gaj Dam for various scenarios, namely normal, maximum, and minimum reservoir level conditions. In addition, the stability of the dam was analyzed.

II. Description of the Study Area

Nia Gaj Dam is located on the Gaj river in the Kirther mountain range. It is located 65km north-west of the Dadu city, Sindh province. The purpose of the Dam Project is to provide irrigation to agriculture lands downstream of the dam. The foundation rocks of this dam project are generally weak and fragile. Sandstone and silty sandstone beds encountered at the core trench are weak and friable with jointings and open bedding planes [13, 14]. These rock characteristics may indicate poor rock conditions, low shear strength, and probability of increased seepage through the foundation [15].

III. Materials and Methods

Initially, the cross section of the dam was drawn in CAD format and imported in SEEP/W as shown in Figure 1. The material zones in the dam are sandy gravel, random fill, central impervious clay core, sand filter, coarse filter, and drainage blanket. The foundation of the dam mainly consists of sandy siltstone. The dam is 59m high, 1137m long, having a maximum design water level of 56.6m with 10m crest width. The core has an upstream side slope of 1H:3V, and a downstream slope of 1H:4V. The upstream and downstream shoulders have slopes 1V:2.5H. Drainage features, including a chimney drain and horizontal drainage blanket below the downstream shell, have been incorporated in the design to relieve the pore water pressure within the dam body and to dispose the seepage water in a safe manner to prevent erosion and boiling. Numerical analysis was carried out on a typical section of the dam. A non- homogenous section is selected for the analysis of the response of complex materials by varying the water levels in order to understand and analyze the seepage phenomenon. The physical, mechanical and index characteristics of the materials were taken from the references mentioned in Table I. These material properties were assigned to the finite element model of the dam.

The generated FEM mesh is shown in Figure 2. Dirichlet and Neumann boundary nodes were assigned at the inlet and outlet boundary conditions [16, 17]. It was accepted that the discharge is gravity driven flow while the capacity changes due to water compressibility, soil structure compressibility, and changes in matric suction (i.e. drainage), in spite of the fact that soil structure compressibility is related to pore water pressure changes. Subsequently, all the stresses inside the domain are accepted as constant. No loading and unloading of soil mass is included. Once the required data were imported to the SEEP/W, it verified the mesh development (7047 nodes and 6913 elements). Therefore, now the model can be used for simulations and analysis of the results.

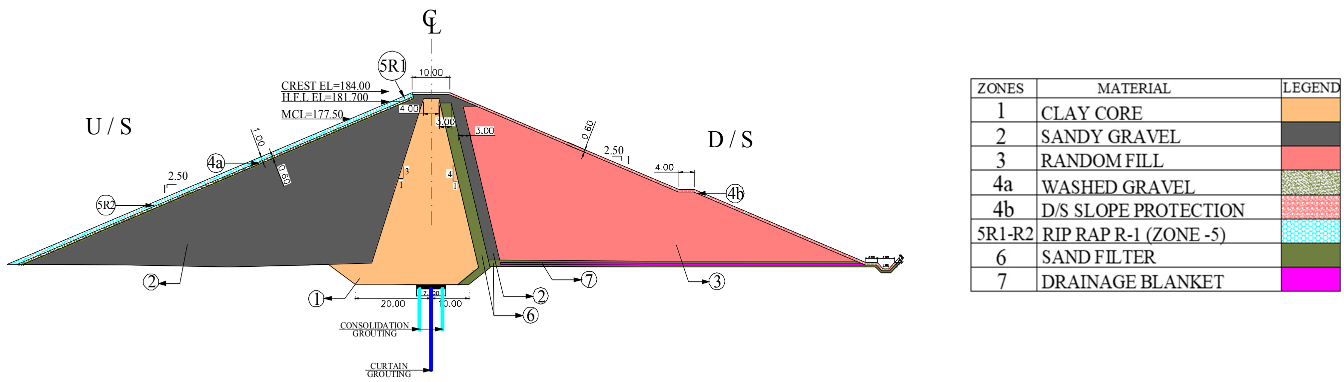

Fig. 1. X-section of th eNai Gaj dam.

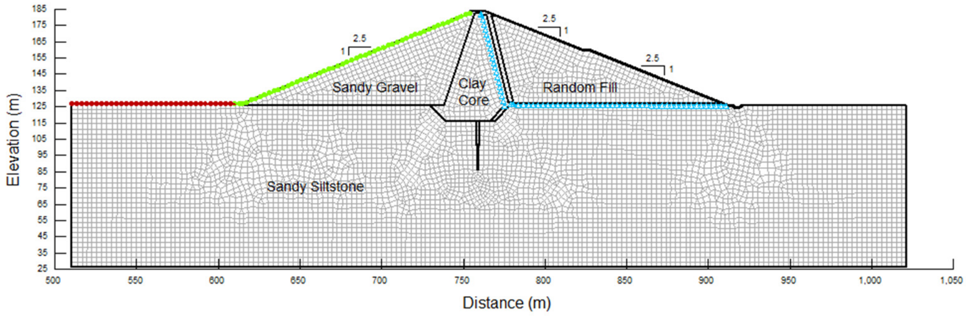

Fig. 2. Mesh formation for the selected non-homogeneous section.

Results are generated for the following scenarios: (i) normal reservoir level (150m), (ii) maximum reservoir level (177.5m), and (iii) minimum reservoir level (130m). The boundary conditions which are used in the analysis are:

- Dirichlet and Neumann boundary nodes are assigned at the inlet and outlet boundary conditions [17].
- Zero flux (Neuman) condition is considered as the boundary node at the bottom of foundation for the all the given conditions.

The results are analyzed in terms of development of net flows for different scenarios, along with velocity vectors, quantity of seepage value through the core and foundation of the dam for different scenarios, and exit gradient. In addition, the stability of the dam was determined based on slope stability analysis.

A. Fundamental Equations

In this study, finite element method is used for the modelling of the groundwater flow in porous media by utilizing the following differential equations to analyze the seepage through the body of the dam at its foundation. Equations are derived on the principle of mass conservation law [17, 18]. The partial differential equation (1) is used in SEEP/W:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial H}{\partial Y}\right) + Q = \frac{\partial Q}{\partial t} \quad (1)$$

where H is the hydraulic head, K_x and K_y are the horizontal and vertical hydraulic conductivity respectively, Q is the discharge, t is the time θ-domain and volumetric water content.

The above equation is a two-dimensional and nonlinear 2nd order PDE and is used for transient flow. It is derived from Darcy's Law:

$$v = -K\,\nabla H \quad (2)$$

where:

$$\nabla H = \begin{bmatrix} \frac{\partial H}{\partial x} \\ \frac{\partial H}{\partial y} \end{bmatrix} \quad (3)$$

where v is the Darcian velocity, K is the hydraulic conductivity of the soil material, and ∇H is the hydraulic gradient.

Equation (1) is dependent on time, and tells that the flow that enters an elemental volume minus the flow leaving the elemental volume at a point is equal to the volumetric water content at that point. If the volume of water that enters is equal to the volume of water that leaves at steady state situations, then the right side of (1) becomes equal to zero.

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_x \frac{\partial H}{\partial Y}\right) + Q = 0 \quad (4)$$

IV. RESULTS AND DISCUSSION

The material properties which are used in the selected dam sections were taken from past studies and from a feasibility report on the Nai Gaj dam [19]. The inherent material parameters used in the dam are presented in Table I. The mesh was generated by SEEP/W and got a no error report for further computations. Also, the given up- and down-stream boundary conditions were assigned. The physical and mechanical parameters of the materials during the time of construction were adopted. SLOPE/W then verified the development model and found no error in the generation of the numerical model.

TABLE I. INHERENT MATERIAL PARAMETERS OF THE NAI GAJ DAM [1, 19-23]

Dam component	**Material**	**Unit weight (kN/m^3)**	**Cohesion (kPa)** C	**Friction angle (deg)** φ	**Hydraulic conductivity (m/day)**
Foundation	Sandy siltstone	20.4*	12	29*	0.00063*
Upstream	Sandy gravel	21.5**	0	37*	86.4***
Downstream	Random fill	18.85*	0	34*	0.0263*
Downstream shell	Riprap	19.5*	0	34*	8640***
Core	Clay	18.85*	9.57	30*	0.000263*
Filter blanket	Sand filter	18.85*	0	36*	26.33*

The seepage analysis of the Nai Gaj dam and its foundation at different reservoir levels was conducted with the use of the SEEP/W. It is assumed that the downstream drain will drain out the seepage and no seepage will develop downstream. For this purpose, flow net has been drawn as shown in Figures 3-5 for the selected dam sections. It was found that if the reservoir is kept at 150m and 130m there is no pronounced seepage observed.

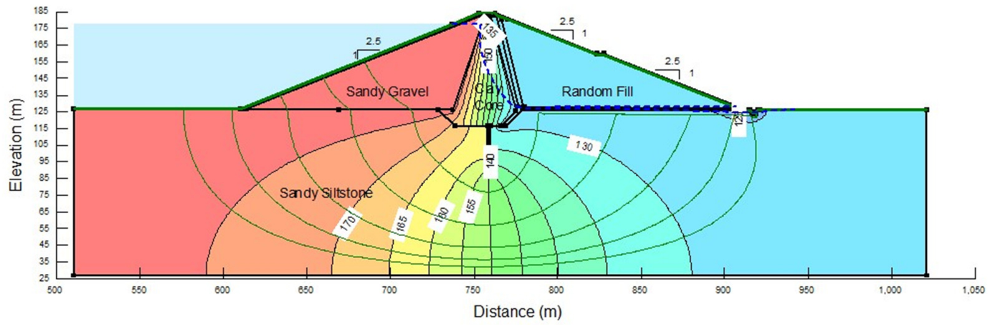

Fig. 3. Flow net of the selected section at maximum reservoir level (177.5m).

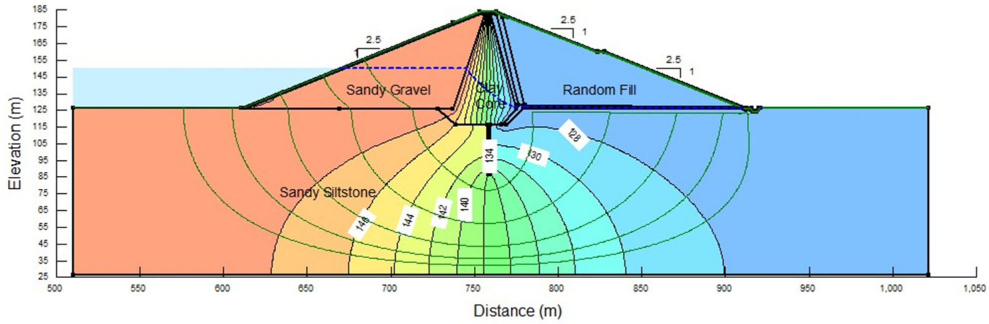

Fig. 4. Flow net of the selected section at normal reservoir level (150m).

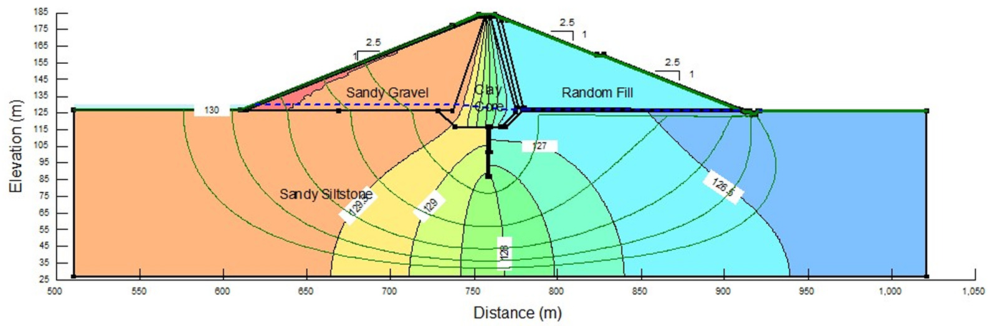

Fig. 5. Flow net of the selected section at minimum reservoir level (130m).

TABLE II. CALCULATED SEEPAGE FLUX AND EXIT GRADIENT

	Upstream reservoir level (m)	Water head (m)	Seepage flux (cumec/m)
Foundation	177.5 (max)	177.5	1.29×10^{-7}
	150 (normal)	150	4.53×10^{-8}
	130 (min)	130	6.92×10^{-9}
Core	177.5 (max)	177.5	3.38×10^{-7}
	150 (normal)	150	1.49×10^{-7}
	130 (min)	130	2.106×10^{-8}

The exit gradient was calculated at the downstream toe of the dam for 3 reservoir levels, i.e. 177.5, 150, and 130 m (Table III). The factor of safety against piping is described as follows:

$$FS = \text{critical hydraulic gradient/exit gradient} \quad (5)$$

The value of the critical hydraulic gradient is taken as 1. A dam is considered as safe against piping, if the value of the factor of safety is between 4 and 5. The results indicate that the values of factor of safety for normal, average, and maximum water level are 7, 6, and 5 respectively. This shows that the dam is safe against piping failure even at the maximum reservoir level of 177.5m. Table III shows that the exit gradient of the selected section was mostly found less than 1 for all the water levels which conforms the safety criteria of the dam. It further support the current design of the dam. From Tables II and III, it can be observed that both the exit gradient and seepage flux are functions of water level.

Generally, the stability of a slope at the downstream embankment is critical at steady state seepage condition. It is assumed that the steady seepage condition may develop when the reservoir is full at maximum retention level, i.e. at EL 177.5m. The phreatic surface is estimated using the flow net development by the SEEP/W program. Furthermore, to support the outcomes, deterministic slope stability analysis was performed for different loading conditions, such as the end of construction and steady state seepage. The material properties used are mentioned in Table I and the results were discussed in terms of their factor of safety as shown in Table III. The computed FOSs at different loading conditions were further compared with the USACE standards [24]. It was noted that in slope stability analysis, the computed FOSs for different loading conditions are greater than the standard values which indicates safety of the side slopes of the dam as given in Table III.

TABLE III. EXIT GRADIENT AND FACTOR OF SAFETY AGAINST PIPING

Upstream pond level (m)	Exit gradient (m)	Factor of safety against piping
177.5 (max)	0.19	5
150 (average)	0.16	6
130 (normal)	0.14	7

TABLE IV. FACTOR OF SAFETY

Load	Slope	Static equilibrium condition	
		Required*	Computed
End of construction	Downstream	1.30	1.7
Steady state condition	Downstream	1.50	1.8

V. CONCLUSION

In this paper, seepage analysis of Nai Gaj dam was carried out with the sub program SEEP/W of the GEO-SLOPE software. The flow rates of the seepage computed at the core of the dam at maximum (177.5m), normal (150m), and minimum (130m) reservoir level were found to be 1.49×10^{-7}cumec/m, 3.38×10^{-7}cumec/m, and 2.108×10^{-8}cumec/m respectively. It was observed that as the reservoir level increased, the seepage quantity also increased. For the three tested scenarios of the reservoir level, the value of the exit gradient was found to be less than 1 which confirms that the dam is safe against piping due to seepage. In addition, slope stability analysis shows that the dam is stable at the end of construction and at steady state seepage condition.

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