Mangla Dam Raising: Effectiveness of Seepage Reduction Measures for Sukian Dyke

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ABSTRACT: *Mangla Dam (Pakistan) is one of the largest Earth Core Rock fill Dam (ECRD) in the world in terms of volume of material used. The Sukian dyke of Mangla Dam Project is 5.33 km (17,500 ft.) in length and is founded on alternate beds of clay and weak (friable) sandstone. Raising of the dam subjected the project area including the dyke to an additional head of about 12.19m (40 ft.) in 2013. Before raising, the maximum seepage in the entire project was observed in the Sukian dyke area. An upstream blanket was selected to control seepage in this area after dam raising. FEM analyses were carried out to determine the efficiency of the upstream blanket in controlling seepage. After raising and impoundment, the FEM results were compared with instrumentation readings and seepage measurements and close agreement was observed.*

KEYWORDS: Mangla Dam, Sukian dyke, Sandstone, Seepage, Upstream Blanket, FEM analysis

SITE LOCATION: http://casehistories.geoengineer.org/geodatabase/IJGCH-database.kmz

INTRODUCTION

Mangla Dam is one of the major multipurpose dam projects of Pakistan. It is located on river Jhelum near Jhelum city (Figure 1). The project was completed in 1967. The main components of the project include the Main Dam, Intake Embankment, Sukian Dyke, Jari Dam, Main and Emergency Spillway, Powerhouse and New Bong Escape (Figure 2).

At the time of its construction, provision was made in the design for ultimate raising of the dam and associated structures. After more than 35 years of operation and depletion in reservoir capacity due to sedimentation, from the original 7.25 x 10^9 m^3 (Billion Cubic Meter) (5.88 Million Acre Feet) to 5.83 x 10^9 m^3 (Billion Cubic Meter) (4.73 Million Acre Feet) which amounts to about 20% reduction in capacity, a decision was made to raise the dam and associated works by 9.10 m (30 ft.) (El. 376.12 m/1234 ft. to El. 385.27m/1264 ft.) and to increase the reservoir level by 12.20 m (40 ft.) (El. 366.37 m/1202 ft. to El. 378.56 m/1242 ft.).

During the operation of the project since 1967, seepage was observed in the downstream area of all project components, as is normal for all dams, but it was highest in the Sukian dyke area and caused "boil" formation in the downstream. Raised reservoir level would subject all components of the project to higher water heads, including the Sukian Dyke. Therefore this area was studied in greater detail to analyze the extent of the problem and design measures to control seepage within safe limits after raising of the dam.

THE SUKIAN DYKE

The dyke's vertical core has been constructed by rolling weak and friable sandstone type-B (finer sandstone containing more than 17% silt fraction). The upstream shoulder has been constructed by rolling weak and friable sandstone type-A (coarser sandstone containing less than 17% silt fraction). The design for raising of the dyke included widening both the upstream and the downstream shoulders.

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The height of Sukian dyke was 43.90 m (144 ft.) (Crest El. 376.12 m/1234 ft.) before raising. After raising by 9.10 m (30 ft.), its height now is 53.00 m (174 ft.) (Crest El. 385.27 m/1264 ft.). Layout Plan and typical cross-sections of the dyke before and after raising are shown in Figures 3, 4 and 5 respectively.

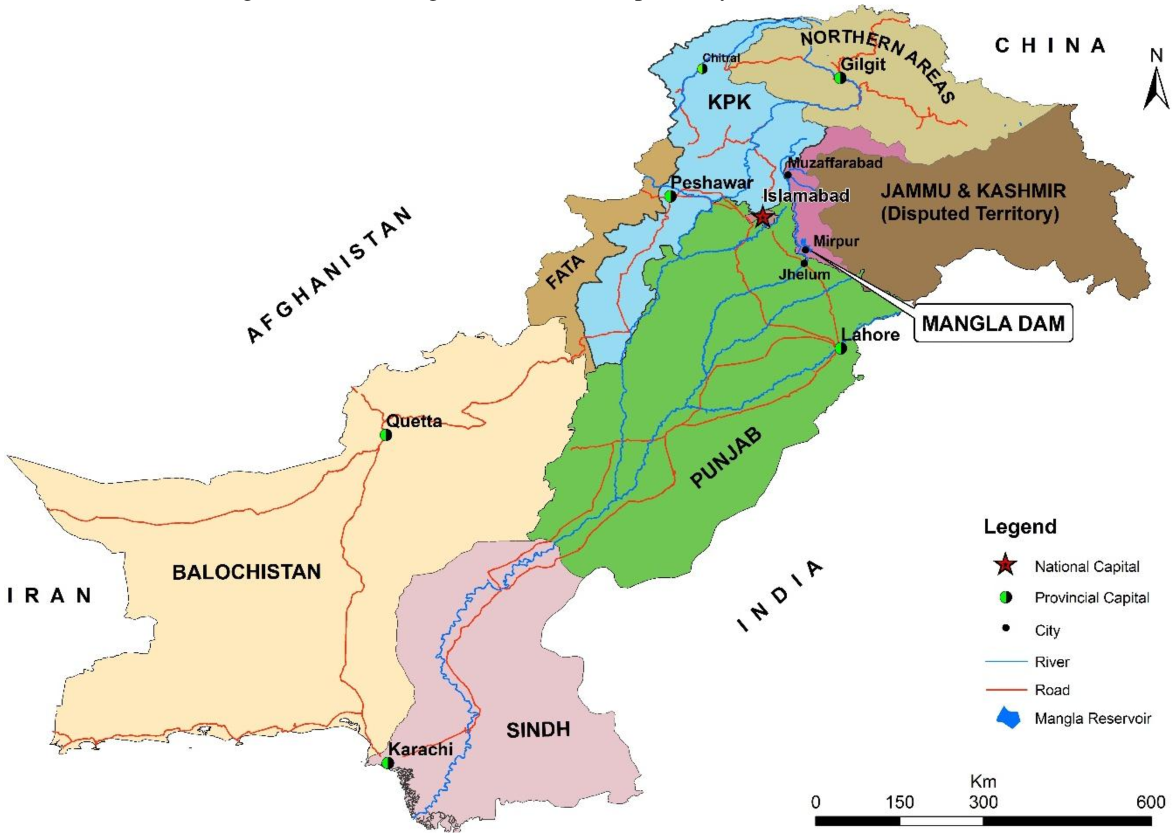

Figure 1. Location map of the project.

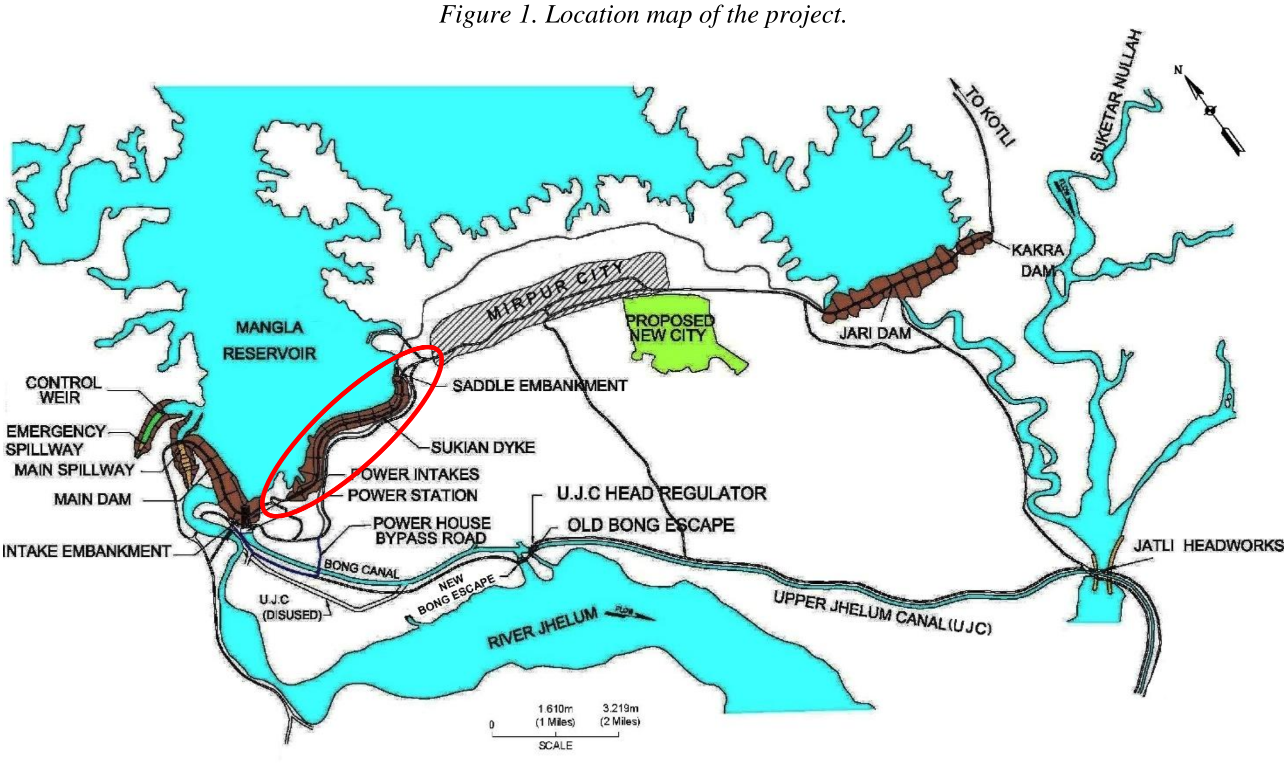

Figure 2. General layout of the project.

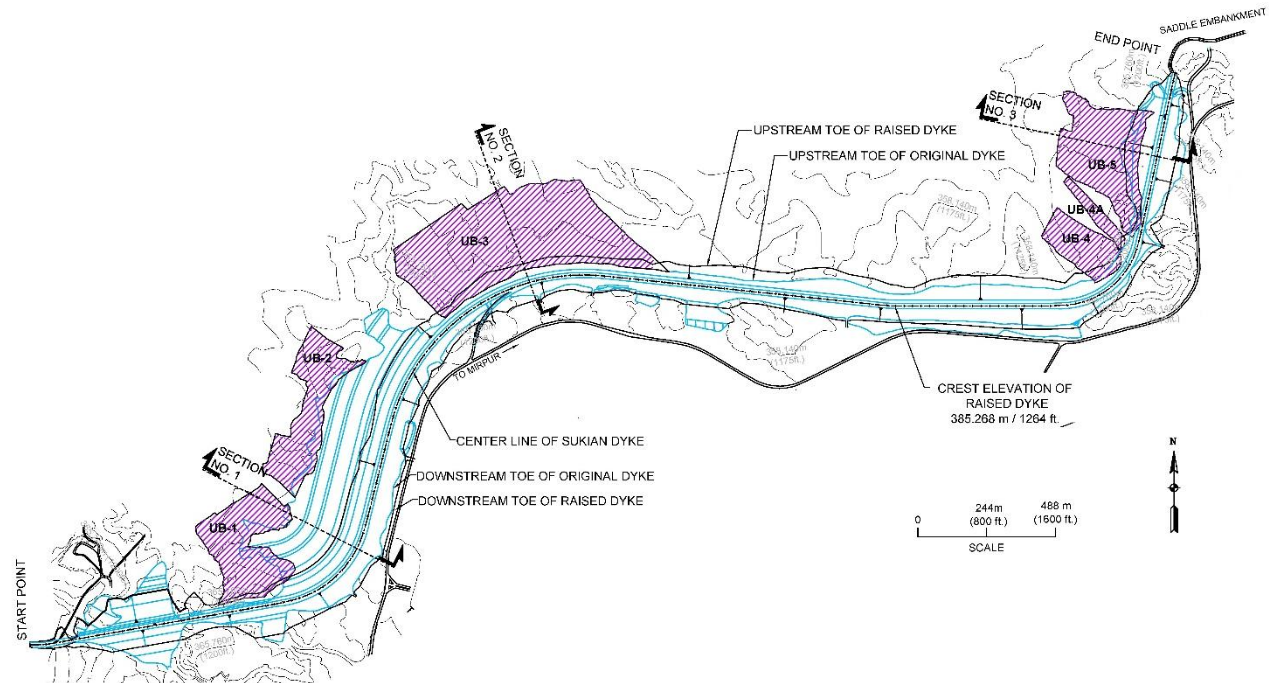

Figure 3. Layout plan of the Sukian dyke showing cross-sections analyzed and placement of upstream blankets (UB-1 to UB-5).

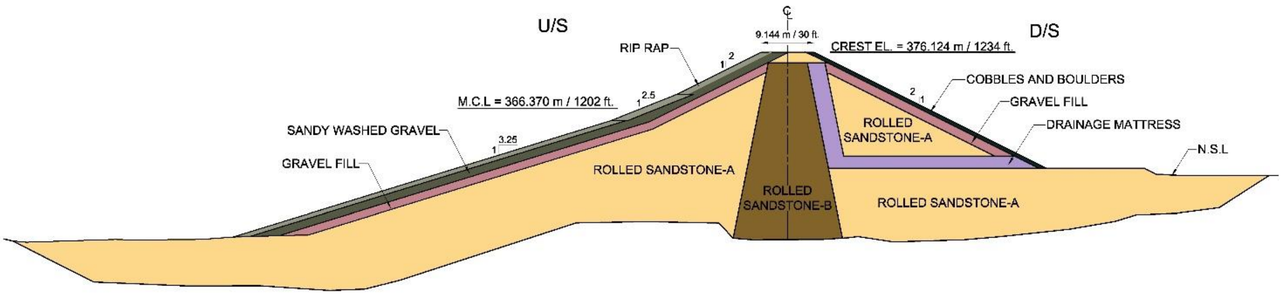

Figure 4. Typical cross-section of the dyke before raising.

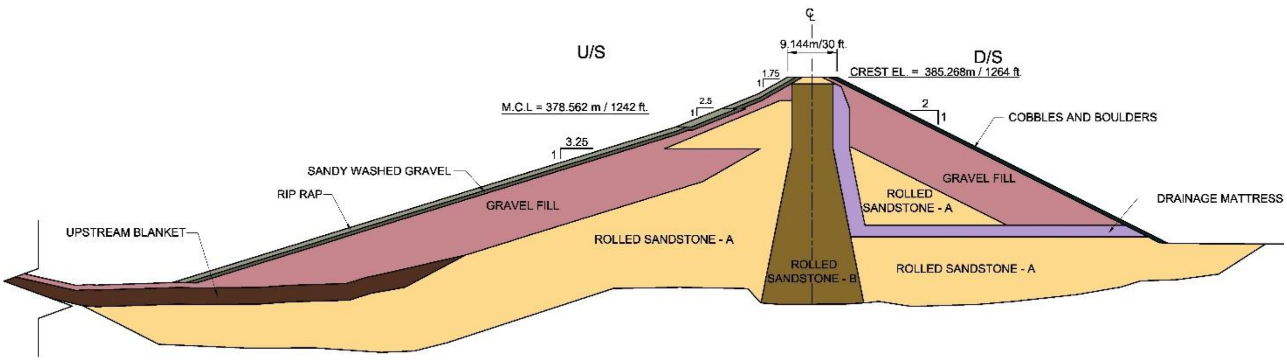

Figure 5. Typical cross-section of the dyke after raising.

The Sukian dyke was raised symmetrically about the center line of the existing dyke. Limited excavation of the existing dyke was carried out in order to raise the core vertically so that it would have sufficient thickness at the top. The construction sequence was such that the top layers were first removed completely from the upstream and downstream shoulders. These included removal of rip-rap and sandy washed gravel from the upstream shoulder and cobbles and boulders from the downstream shoulder. Upstream and downstream shoulders were then constructed using gravel fill, tying to the originally placed layer maintaining the designed thickness/width as shown in Figure 5. After achieving the designed thickness, the top layers including rip-rap were reconstructed. The foundation of Sukian dyke comprises of intercalated clay and weak sandstone beds of Siwalik Formation (Mangla 1967) as shown in Figure 6 (geological cross-section along the center line of the dyke). It can be observed from this figure that there are 30 sandstone beds present in the foundation beneath the Sukian dyke marked as 1 to 30. These beds are dipping towards downstream at an angle of almost 12^0. Soon after the completion of the Mangla Dam project, heaviest seepage was reported at Sukian dyke. The seepage associated with the foundation of Sukian dyke was about 80% of all measured seepage loss from the reservoir and measured 0.61 m^3/sec (22 ft^3/sec). Water seeped mainly through the sandstone beds and its contact with clay beds and created issues downstream of the Sukian dyke including "boil" formation. This tied with the observation of extensive pressure heads that developed beneath the Sukian dyke as observed in piezometer readings and seepage in downstream nullahs (streams). The boils were located in the sandstone beds no. 6, 12, 24 and 27. There was no significant amount of erosion of bed material as suspended solids were in the order of 40 ppm which is negligible. Boils through sandstone beds no. 6 and 12 were emerging about 1371.60 m (4500 ft.) and 579.10 m (1900 ft.) from downstream toe of dyke respectively. The boil through sandstone bed no. 4 was emerging at a distance of about 609.60 m (2000 ft.) from the downstream toe of Sukian dyke. The boil through sandstone bed no. 27 was emerging at a distance of about 396.24 m (1300 ft.) from the downstream toe of Sukian dyke. Seepage quantities were expected to increase when the reservoir level would be raised by some 12.20 m (40 ft.) after dam raising and could be adversely affecting the overall safety of the project. Thus effective measures to mitigate seepage were required.

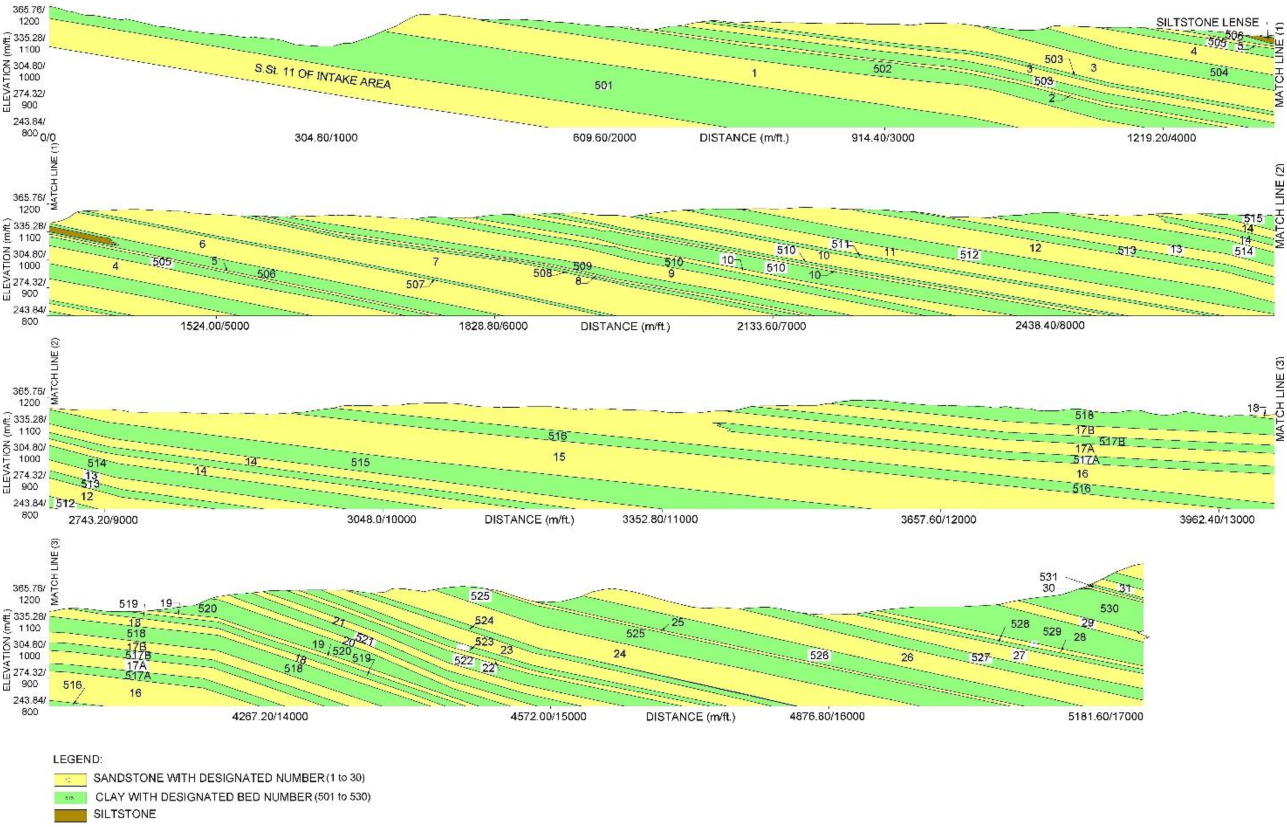

Figure 6. Geological cross-section along center line of the dyke.

METHODOLOGY

The initial work started by collection of all available information including as-built drawings and geological cross-sections of the Sukian dyke area. Historical seepage and instrumentation data was also collected and analyzed.

The result of this study indicated that out of the some thirty (30) sandstone beds under the dyke foundation, seepage was mainly concentrated in fourteen (14) beds. Thus it was concluded that effective measures to mitigate seepage would only be required for these fourteen (14) beds of sandstone i.e. 3 to 7, 12 to 15 and 24 to 28.

SEEPAGE CONTROL MEASURES

Various techniques for controlling seepage such as grouting, slurry walls and impervious blankets have been reported for dams (Turkmen, 2003; Uromeihy and Barzegari, 2007; Khan et al., 2011). Of the available techniques, an impervious blanket was considered the most suitable due to construction reasons. For about six months in a year, the area required for upstream blanket placement remained above water during low reservoir period. Analysis showed that it was manageable to complete the construction of the blankets within the low reservoir period.

Since the data analysis showed that fourteen beds of sandstone were involved in seepage, it was decided to concentrate the efforts on these particular beds. Five (5) impervious blankets (Figure 3) named as UB-1, UB-2, UB-3, UB-4 and UB-5 were constructed to cover these 14 sandstone beds (Mangla, 2004). Impervious blankets and corresponding sandstone beds are given in Table-1. The surface width (along the axis of the dyke) of these blanketed beds ranged from 304.80 m (1000 ft.) to 762.00 m (2500 ft.).

During the detailed design stage, sensitivity analyses were carried out to optimize the length of the blanket and it was found that a 2.40 m (8ft.) thick and 304.80 m (1000 ft.) long blanket would be sufficient to substantially reduce the seepage quantity in the downstream area of the dyke. Therefore, a 2.40 m (8 ft.) thick impervious blanket, 304.80 m (1000 ft.) long perpendicular to the upstream toe of the dyke, was designed. Locally available silty clayey material was selected for the blanket which yielded a permeability of 1.02E-6 cm/sec (3.35E-8 ft/sec) in laboratory tests, very similar to the dam core material. The blanket was designed such that selected sandstone beds would be covered with it and the blanket would be tied to the adjacent clay beds on both sides, as the sandstone beds were inter-bedded with clay (Figure 7).

Table 1. Blanketed sandstone beds.

Blanket No.	Sandstone Bed No.
UB-1	3
UB-2	4,5,6,7
UB-3	12,13,14,15
UB-4/4A	24,25
UB-5	26,27,28

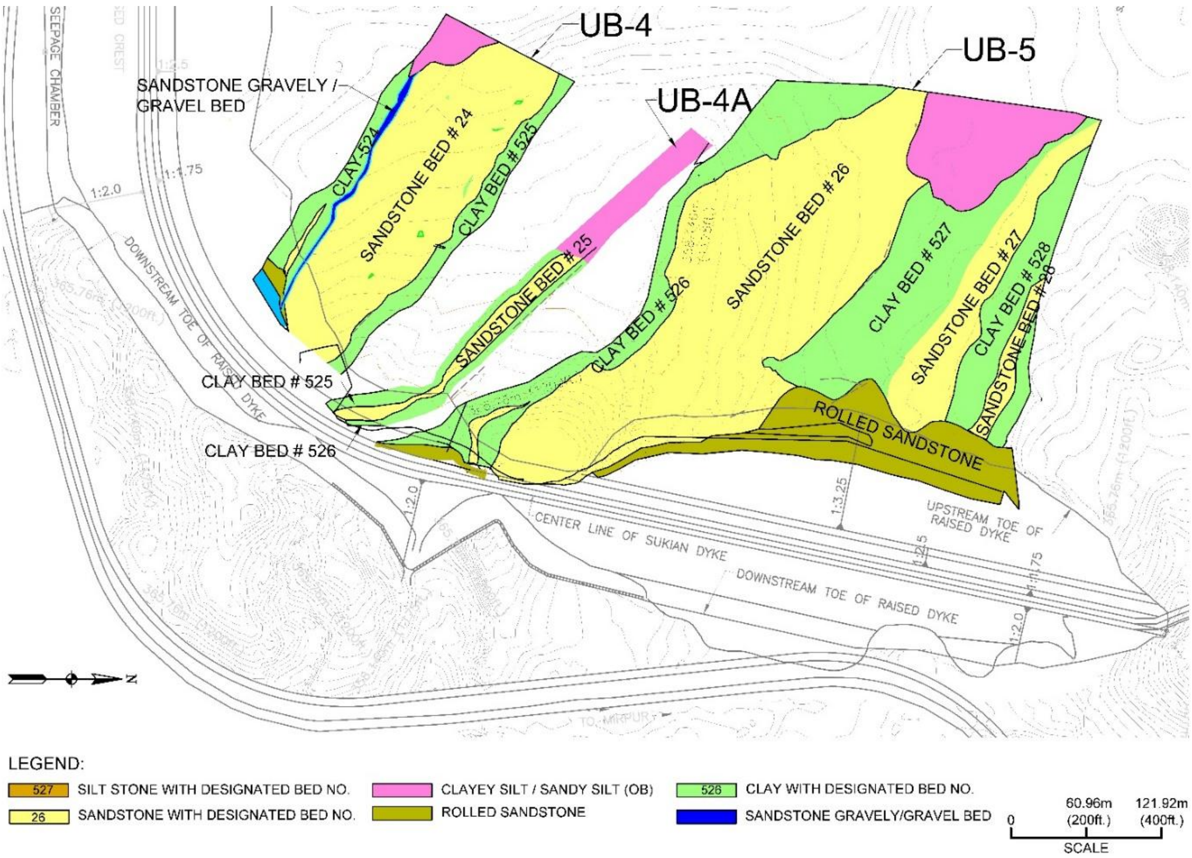

Figure 7. Sandstone beds covered with impervious blankets UB-4/4A and UB-5 (coloured portion is basically the limits of the blankets).

SEEPAGE ANALYSIS

Two FEM based software were used for the seepage analysis of Sukian dyke i.e.

- SEEP/W (Version 2007)
- SLIDE (Version 6.0)

The seepage quantities at Sukian dyke before raising were gathered from the available instrumentation data when the reservoir levels were between El. 359.70 m (1180 ft.), 362.70 m (1190 ft.), 365.80 m (1200 ft.) and 366.40 m (1202 ft.). Because, the Sukian dyke is constructed on a ridge which has an average crest elevation of about 359.70 m (1180 ft.), seepage measuring devices installed to measure the seepages from the body of the dyke, usually showed readings when the reservoir attained this or higher level. These historic reservoir levels were used to perform the seepage analyses in both software for the "before raising" condition (original condition). For the "after raising" scenario (raised condition) seepage analyses for every 3.05 m (10 ft.) increment (in general) in the reservoir level from 359.70 m (1180 ft.) up to 378.60 m (1242 ft.) were performed. Separate flux sections were incorporated in the software models, one for the dyke body (passing through the core only) and the other through the foundation, to calculate the seepages through these separately. Table-2 shows the reservoir levels for which seepage analyses were performed.

Table 2. Reservoir levels for which seepage analyses performed.

Scenario	Reservoir Level in meter (ft.)
Before Raising	359.70(1180) 362.70(1190) 365.80(1200) 366.40 (1202)
After Raising	359.70 (1180) 362.70 (1190) 365.80 (1200) 366.40 (1202) 368.80 (1210) 371.90 (1220) 374.90 (1230) 377.80 (1239.60) 378.60 (1242)

Three sections (Section No. 1, Section No. 2 and Section No. 3) as shown in Figure 3 were selected for the seepage analysis for both scenarios i.e. before raising and after raising. These sections were selected as these were generally representative of their respective reaches. The seepage quantities calculated from these cross-sections were extrapolated throughout the length of the dyke to obtain total seepage. The extrapolation was carried out such that results of cross section 1 were used for the reach to the right of this section; average of the results of cross sections 1 and 2 were used for the reach between these two sections; average of the results of cross sections 2 and 3 were used for the reach between these two sections; and results of cross section 3 were used for the reach to the left of this section, looking downstream (Fig. 3). The seepage quantities determined after the extrapolation of all the sections at a particular reservoir level were then added to determine the total seepage passing through the body and foundation of the dyke at that particular reservoir level.

The details of the analyzed cross-sections are given in Figures 8 to 13.

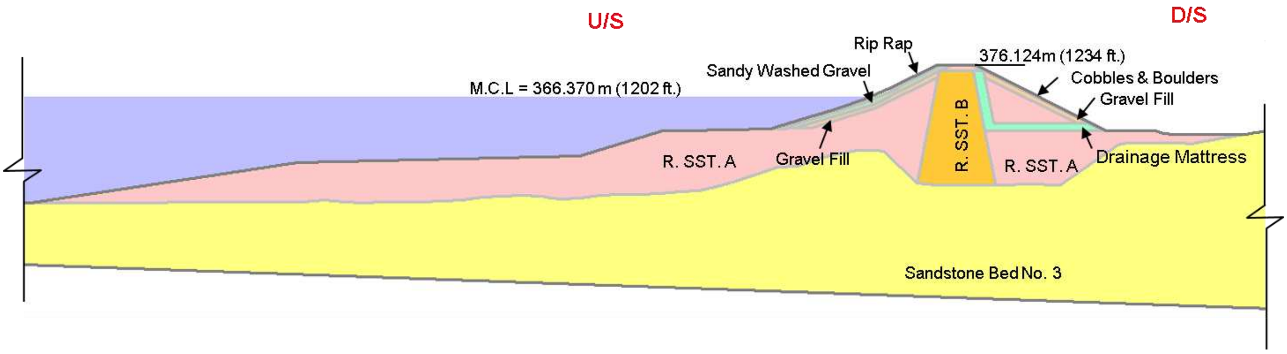

Figure 8. Cross-section detail of section no. 1 before raising.

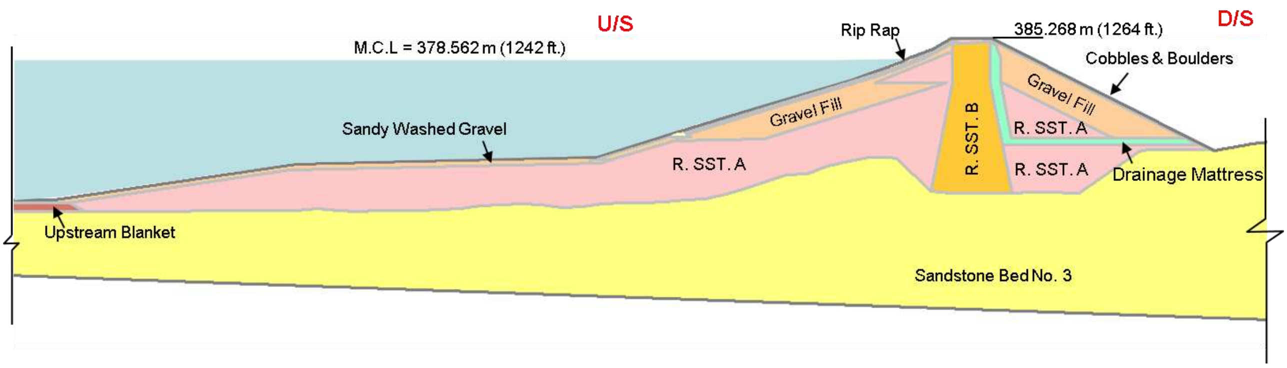

Figure 9. Cross-section details of section no. 1 after raising.

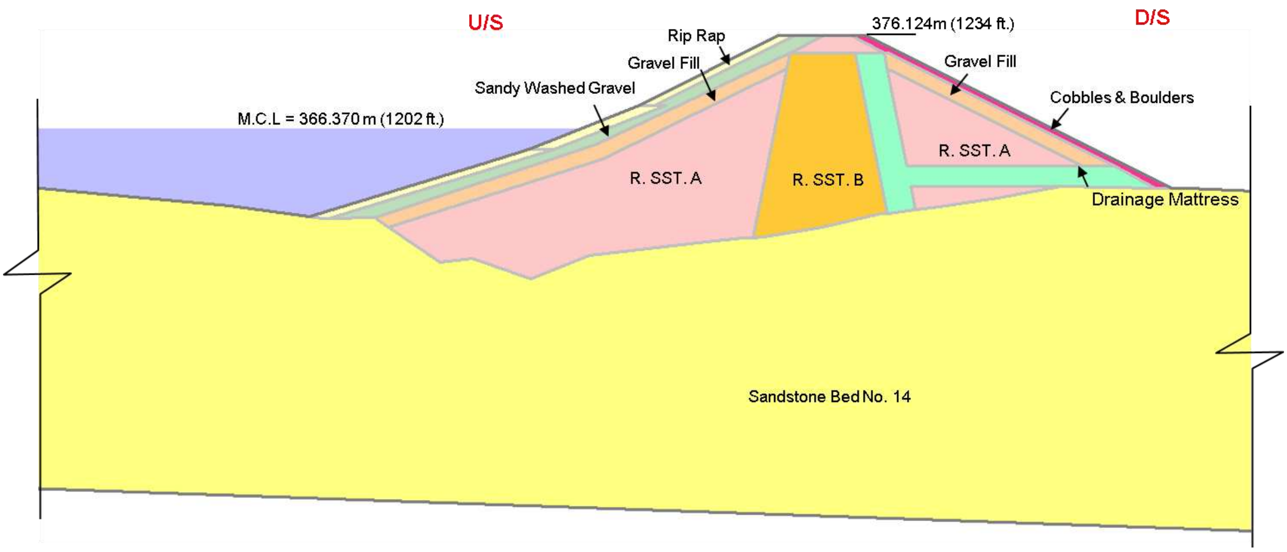

Figure 10. Cross-sections detail of section no. 2 before raising.

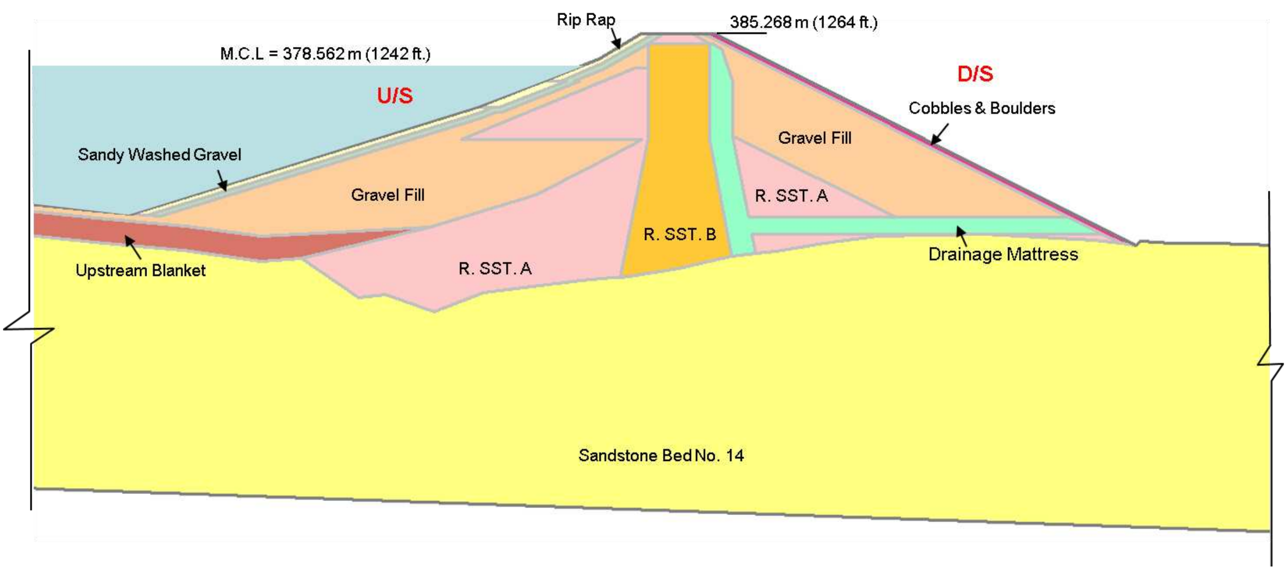

Figure 11. Cross-sections detail of section no. 2 after raising.

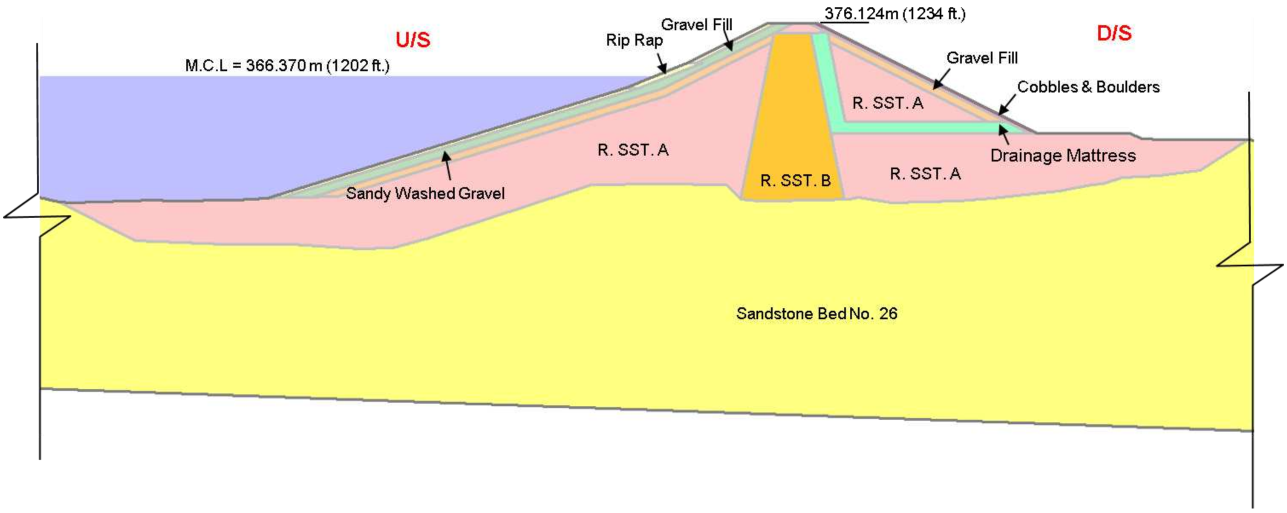

Figure 12. Cross-section details of section no. 3 before raising.

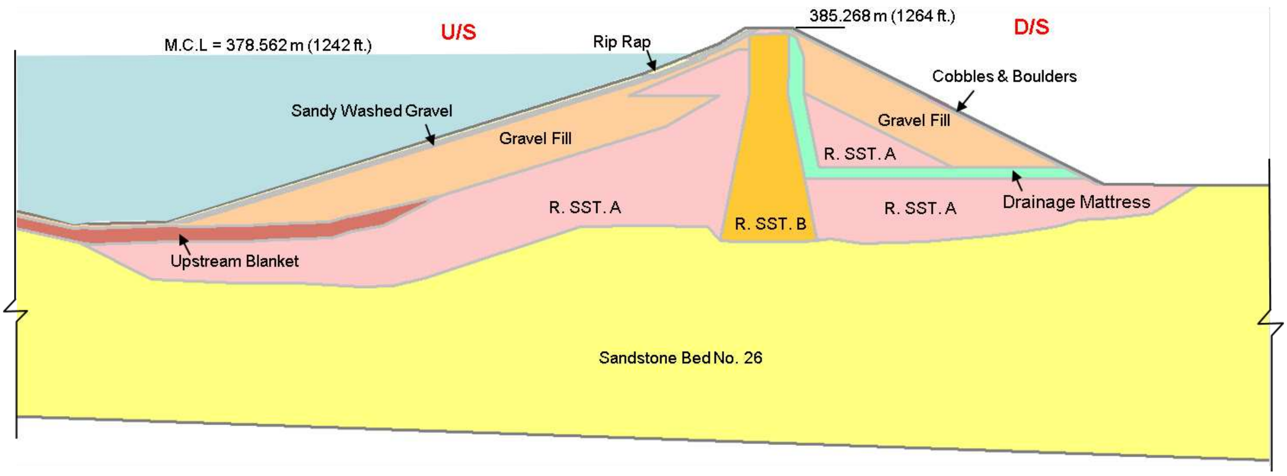

Figure 13. Cross-section detail of section no. 3 after raising.

MATERIAL PROPERTIES

The permeability values of various materials were taken from the design report of Mangla Dam Project (2004). However, the permeability value of the blanket material was also determined in the laboratory. For the purpose of analysis, the clay beds were considered impermeable. Table 3 provides the permeability values of various materials of the Sukian dyke and its foundation and the corresponding ratio of K_h/K_v used in this study.

Table 3. Permeability values of different materials.

Material	K_h in cm/sec (ft./sec)	K_h/K_v
Rip-Rap	8.84 (2.9E-1)	1
Sandy Washed Gravel	1.00E-02 (3.28E-4)	1
Gravel Fill	1.00E-03 (3.28E-5)	1
Rolled Sandstone-A	1.00E-04 (3.28E-6)	9
Rolled Sandstone-B	5.00E-05 (1.64E-6)	9
Drainage Mattress	9.14E-02 (3.0E-3)	1
U/s Blanket	1.02E-06 (3.35E-8)	9
Sandstone Bed (Foundation)	9.14E-03 (3.0E-4)	1

FIELD SEEPAGE MEASUREMENTS

- Measurement of seepage through body of dyke

Seepage measurement chambers constructed at the downstream toe of sukian dyke intercept the flow of the drainage mattress which is the seepage from the body of the dyke (core).

- Measurement of seepage through the foundation of dyke

A vast network of trench drains was constructed in the beds of various nullahs (natural streams) intersecting sandstone and clay beds. Seepage measurement chambers equipped with v-notches were provided at the beginning and end points of the sandstone beds. The difference between the readings of the 1st and last v-notch in a specific nullah gave the total seepage of sandstone beds intersecting the respective nullah as the first v-notch measures the natural flow and the last one measures the natural flow plus seepage. The cumulative seepage measured in all the nullahs was taken as the total seepage through the foundation of the dyke.

RESULTS & DISCUSSIONS

The seepage quantities determined after the extrapolation of all the sections at a particular reservoir level were then added to determine the total seepage passing through the body and foundation of the dyke at that particular reservoir level and are tabulated in Table 4. However the measured quantities have been obtained as explained in the previous section. The graphical representation of the Table-4 is shown in Figure 14 and 15.

The results provided in Table 4 clearly show that the seepages measured in the field are less than those determined through analyses. This is mainly due to the continuous fluctuation in the reservoir levels during operation due to which steady state was not achieved at any particular reservoir level in the field whereas the seepage analysis was performed for the steady state condition. The data provided in Table 5 shows that steady state condition has not yet reached the core (rolled sandstone-B). Four hydraulic piezometers (Nos. HP-18, HP-19, HP-24 & HP-26) are installed in the core since original construction of the dyke completed in 1967. Yearly maximum piezometric levels in the core for the year 2008 to 2013 are given in Table 5. All four hydraulic piezometers have consistently been reading approximately their respective tip levels from year 2008 to 2012, indicating development of almost no pore pressures in the core. This is probably due to relatively low permeability of rolled Sandstone-A placed in the upstream shoulder associated with very short periods of high reservoir level, not long enough to establish steady state seepage through the upstream shoulder and then through the core. This is also clear from the piezometric readings that except for slight changes in HP-24 and HP-26, these have hardly responded to the reservoir level raising by almost 10 m in 2013.

Total seepage quantities determined through analyses and measured in the field passing through the body and foundation of dyke against corresponding reservoir levels are shown in Table 4 and their graphical representation is shown in Figures 14 and 15 respectively. The seepage passing through the dyke is the body seepage and that passing through the sandstone beds underneath is the foundation seepage. SLIDE software gave slightly higher values than SEEP/W; SEEP/W software gave values that were more closer to the field measured values.

Table 4. Total seepage (through foundation and body of dyke).

Scenario	Reservoir Level in meter (ft.)	Foundation Seepage (m^3/sec)			Body Seepage (m^3/sec)		
		SLIDE	SEEP/W	Measured	SLIDE	SEEP/W	Measured
Before Raising (Without Blanket)	359.70 (1180)	2.32E-01	2.24E-01	1.97E-01	6.42E-04	6.28E-04	4.25E-04
	362.70 (1190)	4.03E-01	3.87E-01	3.66E-01	1.64E-03	1.50E-03	1.22E-03
	365.80 (1200)	6.03E-01	5.97E-01	5.44E-01	3.62E-03	3.58E-03	3.06E-03
	366.40 (1202)	6.52E-01	6.45E-01	6.10E-01	4.00E-03	3.97E-03	3.40E-03
After Raising (With Blanket)	359.70 (1180)	1.31E-01	1.24E-01	1.12E-01	3.48E-04	3.27E-04	2.55E-04
	362.70 (1190)	2.06E-01	1.86E-01	1.74E-01	6.14E-04	5.91E-04	2.83E-04
	365.80 (1200)	2.80E-01	2.38E-01	2.19E-01	1.27E-03	1.06E-03	8.21E-04
	366.40 (1202)	2.96E-01	2.50E-01	2.29E-01	1.39E-03	1.15E-03	9.91E-04
	368.80 (1210)	3.54E-01	3.11E-01	2.82E-01	2.35E-03	2.20E-03	1.70E-03
	371.90 (1220)	4.39E-01	3.82E-01	3.50E-01	4.82E-03	4.04E-03	3.11E-03
	374.90 (1230)	5.24E-01	4.55E-01	4.17E-01	7.99E-03	6.83E-03	5.09E-03
	377.80 (1239.60)	5.84E-01	5.20E-01	4.91E-01	1.12E-02	8.79E-03	7.08E-03
	378.60 (1242)	6.19E-01	5.34E-01	*	1.18E-02	9.12E-03	*

* Until year 2013 this level was not achieved in the field.

Table 5. Maximum piezometeric levels in core (rolled sandstone-B).

Year	Maximum Reservoir Level (m)	Piezometer HP-18		Piezometer HP-19		Piezometer HP-24		Piezometer HP-26	
		Tip Elevation (m)	Reading (m)	Tip Elevation (m)	Reading (m)	Tip Elevation (m)	Reading (m)	Tip Elevation (m)	Reading (m)
2008	365.80	353.70	352.80	352.70	352.80	361.90	361.00	367.20	366.20
2009	366.70		352.80		352.80		361.00		366.20
2010	367.60		352.80		352.80		361.00		366.20
2011	368.80		353.10		353.10		361.20		366.20
2012	367.60		353.10		353.10		360.90		366.20
2013	377.80		353.10		353.10		361.80		367.70

From Table 4 and Fig. 14 and 15, it can be observed that the total seepage from the body of the dyke does not exceed 2% of the seepage from the foundation, at any given reservoir level. This minute quantity of seepage through the dyke corresponds well with the observation from the piezometers that hardly show any change, except reading almost the tip elevation. Similarly, it has also been stated previously that the dyke is built on natural ridge which has an average crest elevation of 359.70 m, and the seepage from the body of the dyke was only observed when the reservoir attained this or higher elevation.

It can be observed from Figure 14 that despite the increase in height of the dyke and higher water head, seepage through the dyke body decreased at reservoir levels ranging from 359.70 m (1180ft.) to 366.40 m (1202 ft.). Since the raising of the dyke was accomplished by widening both the upstream and downstream shoulders and the shoulder material also has low permeability, the longer seepage path is considered sufficient to cause significant reduction (up to 30%) in the seepage through the dyke body.

The seepage quantities through the body of the Sukian dyke measured in the field at various reservoir levels are lower than the values determined through the analyses. This indicates that the dyke performance under raised condition is satisfactory.

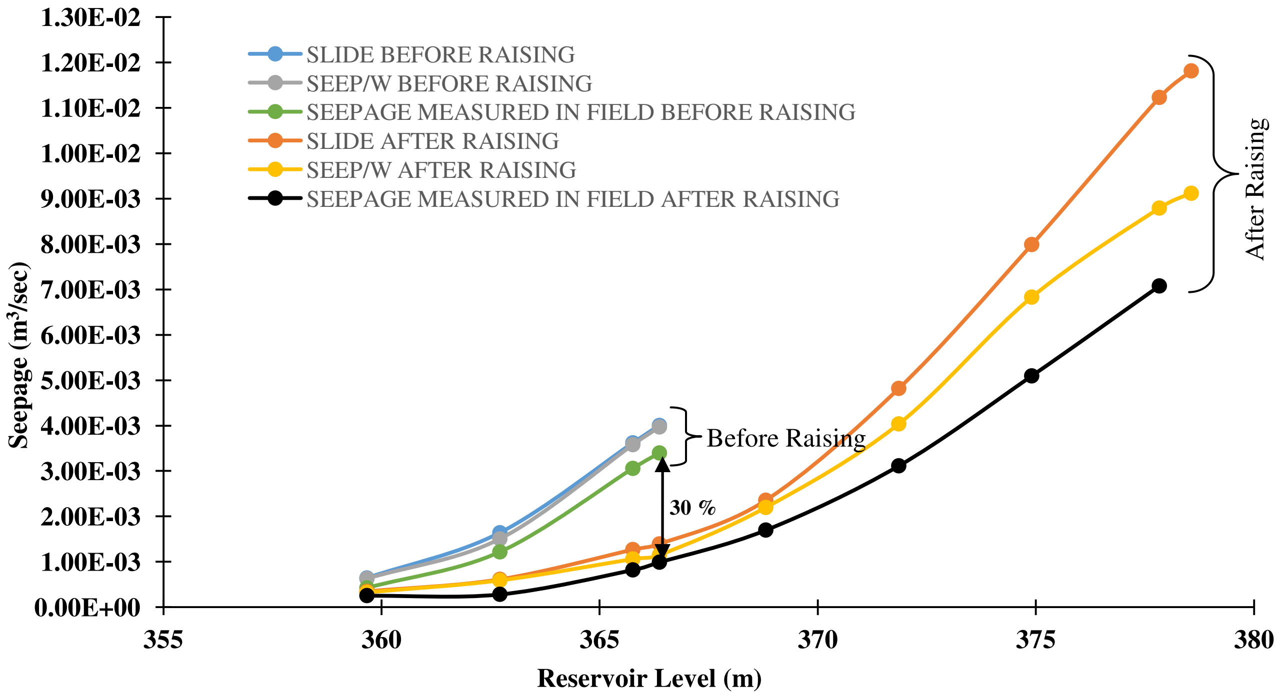

Figure 14. Total seepage through body of dyke.

The effectiveness of the upstream blanket can be gauged from the data provided in Table 6 and Figure 15, which gives the seepage through the foundation for various conditions.

Table 6. Effectiveness of upstream blanket based on seepage reduction through foundation.

Reservoir Level in meter (ft.)	SEEP/W			SLIDE			Measured		
	Seepage without Blanket (m^3/sec)	Seepage with Blanket (m^3/sec)	% Reduction	Seepage without Blanket (m^3/sec)	Seepage with Blanket (m^3/sec)	% Reduction	Seepage without Blanket (m^3/sec)	Seepage with Blanket (m^3/sec)	% Reduction
359.7 (1180)	2.24E-01	1.24E-01	44	2.32E-01	1.31E-01	41	1.97E-01	1.12E-01	41
362.7 (1190)	3.87E-01	1.86E-01	52	4.03E-01	2.06E-01	49	3.66E-01	1.74E-01	52
365.8 (1200)	5.97E-01	2.38E-01	60	6.03E-01	2.80E-01	53	5.44E-01	2.19E-01	59
366.4 (1202)	6.45E-01	2.50E-01	61	6.52E-01	2.96E-01	54	6.10E-01	2.29E-01	62

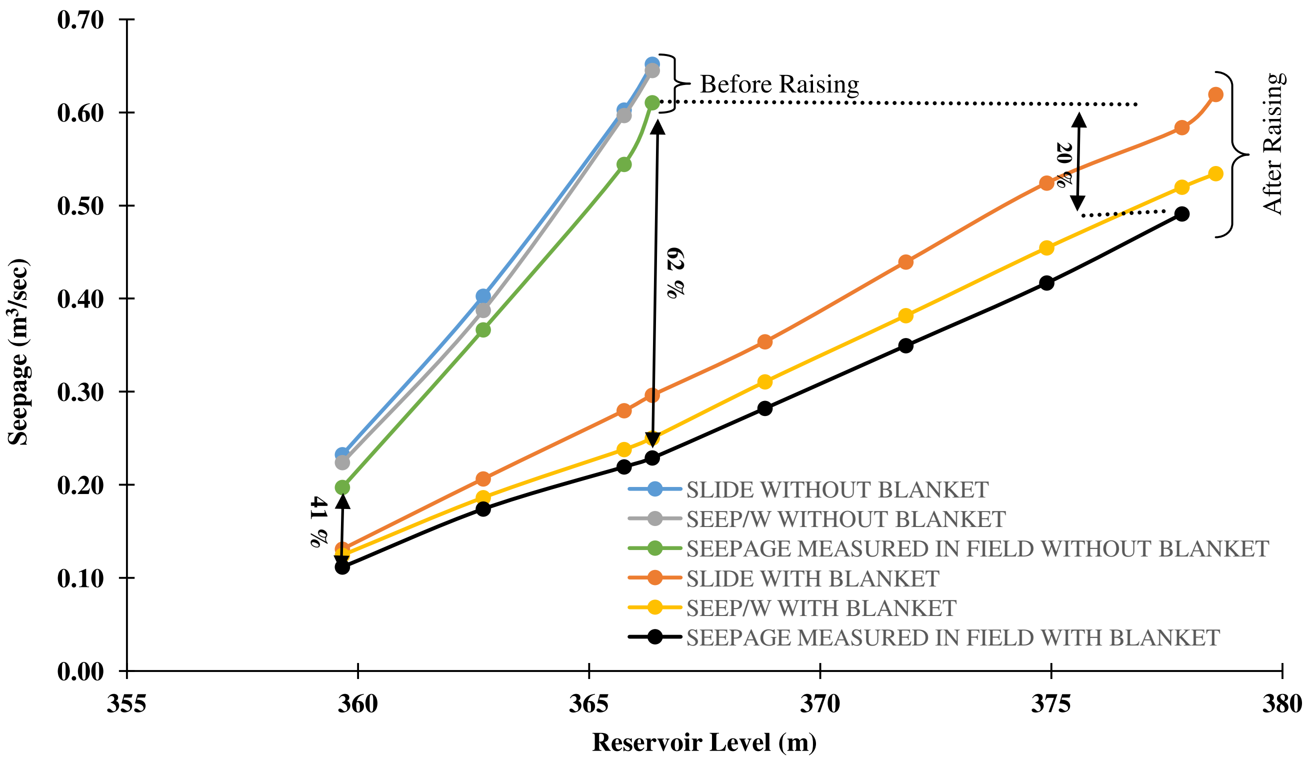

Figure 15. Total seepage through foundation of dyke.

Table 6 shows that the seepage through the foundation reduced by 40 to 60% for comparable reservoir levels. As per observed field data, peak seepage discharge through the foundation measured before the construction of blanket was 0.61 m^3/sec against the maximum reservoir level of 366.40 m (1202 ft.). After placing the impervious blanket, the peak seepage discharge reduced to 0.23 m^3/sec against the same reservoir level. Thus overall reduction of 62% in seepage discharge was achieved by placing the impervious blankets. Almost same percentage reduction was calculated through the software analyses as well.

It can be observed from Figure 15 that before raising (original condition), the observed peak seepage discharge at maximum conservation level of 366.40 m (1202 ft.) was 0.61 m^3/sec. After raising, which subjected the Sukian dyke foundation to an additional head of about 12.20 m (40 ft.) i.e. El 377.80 m (1239.60 ft.) in 2013, the observed peak seepage discharge through the foundation was 0.49 m^3/sec. Therefore after dam raising and with a higher head (reservoir level) of about 12.20 m (40 ft.), the seepage was 20% less compared to the before raising condition when the maximum reservoir level was 12.20 m (40 ft.) lower. This indicates the effectiveness of the blanket in controlling seepage against the raised reservoir levels.