Flow and stability of Al-Wand earth dam during rapid drawdown of water in reservoir

***Mohammed Y. Fattah*[1], *Hasan A. Omran*[2] and *Mohammed A. Hassan*[3]**

The rapid drawdown is known as one of the most dangerous conditions for the upstream slope. When the countervailing upstream water pressure is lowered, it results in distress to the upstream slope. Soils within the dam body remain saturated, and flow commences towards the upstream slope. Seepage in addition to hydrodynamic pressures generates downward forces that act on the upstream slope. These forces act adversely to the stability and generate a critical condition in the upstream slope.

In this study, the finite element method is used to study seepage through the body of an earthfill dam. For this purpose, the software Geostudio 2007 is used through its subprograms SEEP/W and SLOPE/W. The water levels on the upstream and downstream sides, the properties of materials and boundary conditions of the dam were input variables and the water flux, exist gradient, and pore water pressure were the target outputs. Al-Wand dam in Iraq has been chosen for analysis for the original period of emptying the dam reservoir and emergency periods.

It was concluded that when the reservoir is rapidly emptied and water is drawn down, pore water pressures in the dam body are decreased in two ways: the first way is through slow dissipation of pore water pressure due to drainage, and there is an immediate elastic effect due to the removal of the total or partial water head. During rapid draw down, the pore water pressure at all points within the dam body decreases linearly which indicates that steady state flow takes place. Some points in the dam downstream may be affected by negative pore water pressure during the period of water draw down which indicates that the water level becomes below these points.

Key words: *Earth dam, rapid draw down, finite elements, stability.*

Introduction

Engineering design of an earth dam is an important subject from the safety and economy of construction cost point of view. Evaluation of safety of a given design involves intensive computation. Despite the progress in soft computing and development of software for analysis of design safety, their utilisation in practical applications appears to be limited. Perhaps accessibility, cost considerations, understanding and user-friendliness can be some of the causes for the problem. Under the current practices, the concentration is directed more at ensuring safety, and the economic requirements are often given low or no consideration during the design of the dams. The concept of finding an optimal design itself seems to be a genuine idea for many designer engineers in practice (Murthy et al., 2013). About 30 % of dams had failed due to the seepage failure, viz piping and sloughing (Middlebrooks, 1953).

A dam may undergo damage or collapse when the occurring seepage exceeds the limit. Rapid rising of upstream water level may cause a significant seepage pressure inside the body of the dam and reduce the stability of the downstream slope. An earth dam becomes saturated when the water level in the upstream is high, or seepage occurs on the downstream slope. When rapid drawdown takes place, the soil stability is in critical condition; such condition may endanger the upstream slope of the dam (Fathani and Legono, 2010).

All embankment dams are subject to some seepage passing through, under and around them. If uncontrolled, seepage may be detrimental to the stability of the structure as a result of excessive pore water pressures, or by internal erosion.

Chahar (2004) showed that an earth dam can be protected from failure caused by seepage due to softening of the downstream slope through supplying a horizontal drainage blanket or rock toe. Analytical solutions are not existing for determination of the filtered drainage blanket length and downstream slope cover. Instead, graphical solutions are existing for these problems. Explicit equations were derived for calculation of the length of the downstream horizontal drain and the downstream slope cover in homogeneous isotropic and anisotropic earth dams. Similar expressions had also been obtained for maximum downstream slope cover and minimum and maximum effective length of the filtered drainage. These equations were nonlinear and representative graphs were plotted for them covering all the practical ranges of the dam geometry.

Berilgen (2006) studied the stability of slopes under drawdown conditions. Because of the rapid drawdown, there would be a decrease in the slope stability that might lead to instability in slopes that did not have sufficient

[1] *Mohammed Y. Fattah,* Professor, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq., myf_1968@yahoo.com
[2] *Hasan A. Omran,* Assistant Professor, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq. Email: hassan_ali7745@yahoo.com
[3] *Mohammed A. Hassan*, Formerly graduate student, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq

level of safety against failure. The paper presented a study on slope stability during drawdown taking into account the drawdown rate and drawdown ratio, the permeability of the soil, also considering the material nonlinearity and different loading conditions. For that goal, a coupled transient deformation and seepage analyses (that include consolidation), in addition to the stability analysis, were carried out by adopting the finite element method for submerged slopes. The nonlinear elastoplastic behaviour of the slope soil was taken into account while analysis of the generation and dissipation of pore pressure was carried out.

Abdul Hussain et al. (2007) developed a method for determination of an optimal design of a homogeneous earth dam constructed on an impervious foundation with the existence of a drain. The method is mainly dependent on saturated flow modelling, involving optimising a multi-objective function including a weighted superposition of four objective functions, which are the section area of the dam, seepage rate of flow, the dam section wetted area and the drain area. The variables considered in the design and the optimisation were the slopes of upstream and downstream and the dimensions of the drain. The optimisation was conducted with the constraints of maintaining safe slopes in the upstream and downstream and relevant distance between the free surface and the downstream face. Two of the controlling functions (which are the seepage rate of flow and the wetted area) and the constraints are implicit functions of the variables of the design. Their values were gathered by conduction of the two-dimensional numerical model (vertical plane) with the variable saturated flow in a homogeneous earth dam. Optimisation, carried out by technique procedure of the sequential unconstrained minimization, was conducted by several trials of the model for different combinations of the design variables.

Zomorodian and Abodollahzadeh (2010) investigated the influence of horizontal drains on upstream slope of earth fill dams in the condition of rapid drawdown using limit equilibrium and finite elements methods. Development of pore water pressure, outpouring rate of flow and safety factor were inspected. The amount of water leakage and seepage in the dam was investigated by using the SEEP/W software and the static slope stability analysis by using the SLOPE/W software.

Fredlund et al. (2011) compared the Duncan (1990) three-stage procedure for analysis of rapid drawdown conditions to a combined slope stability analysis and transient flow. Limit equilibrium methods was adopted in the analysis of slope stability taking into account saturated and unsaturated pore-water pressures. Analyses of some typical cross-sections were taken into consideration to determine the potential effect of geometry. The aim of the study was to prepare scenarios under which the Duncan (loc. cit.) procedure produces results similar to those of a more rigorous analysis.

Giglou and Zeraatparvar (2012) considered the physical and geometric factors of earth dam such as permeability, upstream and downstream slope of the dam in the analysis of saturated-unsaturated seepage problem. The seepage rate through homogeneous earth dam took into account saturated and unsaturated flow. The unsaturated flow is usually discounted but must be considered to determine the levels of the water table and the flow face that may progress either within the filter layer behind the core of a homogeneous earth or on the downstream slope of a homogeneous earth dam. Various homogeneous earth dams with heights of 5, 10, 20, 30, 40 and 50 m were analysed numerically using a two-dimensional finite element code. The cases studied included the most frequent types of homogeneous earth dams designed to retain municipal or industrial wastewater. Solutions were obtained to solve numerically two problems concerned with the consideration of saturated and unsaturated physical flow conditions.

Mansuri and Salmasi (2013) investigated the design of earth dams and their problems during construction and after it, because of their potential hazards and failure for the downstream population. The study focused on the effectiveness of using horizontal drain and cutoff wall in reducing seepage flow from an assumed heterogeneous earth dam. For this purpose, various horizontal drain lengths and cutoff wall depths were examined under the earth dam in different locations of the foundation. Seepage analysis, hydraulic gradient and uplift pressure, were computed by numerical simulation, using SEEP/W software. Results showed that increasing horizontal drain length causes slightly increasing in seepage rate and increasing hydraulic gradient. The optimum location of the cut-off wall for reduction of seepage rate and piping was in the middle of dam foundation. By increasing the cut-off wall depth, seepage from earth dam and its foundation is reduced. Different locations of the cut-off wall in the dam foundation have little effect on exit hydraulic gradient, and always it was less than unity. Installation of the cut-off wall in the middle of foundation resulted in 19.68 percent decreasing in hydraulic gradient with respect to the existence of cut-off wall in upstream of the dam.

The finite element method was utilised by Fattah et al. (2014) to solve the governing equations of flow through earth dams. The computer program Geo-Slope was used in the analysis through its sub-program named SEEP/W. Eight-node isoparametric elements were used to model the dam and its foundation, while mapped infinite elements were used to model the problem boundaries. A case study adopted was Al-Adhaim dam which is a zoned earthfill dam of 3.1 km length. The dam in its original design was analysed by adopting the SEEP/W program. After that, several scenarios were conducted to investigate the control of flow in the dam through investigating the effect of different parameters which included the hydraulic conductivity of the shell material and the construction of impervious core at different locations and thicknesses. It was found that the construction of clay core in the dam provides an important influence on decreasing the exit gradient, that could increase in the order of 300% when there is no core in the dam, and the safety factor may be critical when the level of water in the reservoir is at 143.5 m. The sloping core is the best design for core for Al-Adhaim dam than other choices because it produces the lowest values of rate of flow and exhibits the lowest exit gradients.

The conventional methods for evaluating the slope stability of earth dams during water drawdown depend on plane-strain two-dimensional (2D) condition. Three-dimensional (3D) effect is usually discounted in the evaluation of the safety of a slope bounded by rigid structures or a dam restricted by a narrow valley. Based on the kinematic principle of limit analysis, a three-dimensional rotational failure mechanism was adopted by Gao et al. (2014) to investigate the influence of water drawdown on the stability of 3D slopes. Several stability charts were presented to conveniently estimate the safety factor of 3D slopes under four different types of drawdown processes. An example was presented to illustrate the difference in the factors of safety calculated from 2D and 3D analyses. When a slope is restricted to a large width (the width to the height ratio $B/H \geq 10.0$), the three-dimensional influence can be neglected, and the plane-strain analysis is suitable to evaluate its safety.

Factor of Safety Criteria

For loading condition described previously, a recommended minimum factor of safety is provided. Deviations either higher or lower from these general criteria may be considered, but should be supported with appropriate justification. The specific values selected need to consider (Chugh et al., 2011):

a. The design condition being analysed and the consequences of failure.
b. Estimated reliability of shear strength parameters, pore pressure predictions, and other soil parameters.
c. The presence of structures within the embankment.
d. Reliability of field and laboratory investigations.
e. Stress-strain compatibility of embankment and foundation materials.
f. The probable quality of construction control.
g. Embankment height.
h. Judgment based on past experience with earth and rockfill dams.

For the aim of slope stability analysis, the safety factor is calculated as the ratio of the total available shear strength of the soil to mobilised shear stress to maintain equilibrium along a potential surface of sliding.

For loading condition at the end of construction, excess pore pressures may develop in impervious zones of the earth dam or its foundation since these soils cannot complete consolidation entirely during the period of construction. If effective shear strength parameters are adopted in the analysis, then excess pore pressures affect the factor of safety considerably. A minimum safety factor of 1.3 can be adopted to be adequate if pore pressures are controlled during construction. However, if the effective shear strength parameter is adopted without any field inspection of pore pressures, the minimum factor of safety must be 1.4 minimum to decrease uncertainties caused by excess pore pressures.

For the steady-state flow condition under active conservation pool, a minimum safety factor of 1.5 must be verified to account for the uncertainties implemented in material strengths, pore pressures in impervious material, and also in long-term loading. Additionally, the downstream slope failure under a steady-state flow condition is more likely to cause a catastrophic release of water; this definitely demands a higher margin of safety than for the end of construction or rapid drawdown conditions.

For the condition of the rapid drawdown from maximum reservoir surface (after a probable maximum flood) to active conservation pool, a safety factor of 1.2 is suitable taking into account the short period of the flood pool surcharge before the normal pool is maintained. For the rapid drawdown below the active conservation pool, a value of 1.3 is applied to the minimum factor of safety.

This work is devoted to studying the stability of a dam under the condition of rapid drawdown and its effect on the seepage through a zoned earth dam. The finite element method is used as a tool for analysis. The computer program Geo-Studio (2007) package is used for this purpose through its sub-programs named SEEP/W and SLOPE/W.

Al-Wand Dam – Case Study

Al-Wand Dam is an earth dam with clayey core located at 3 km south-east Khanakeen - Dayala at a distance of 6 km from Iraq-Iran borders. Al-Wand dam stores the water coming from the western mountains of Iran through the Wand River. The embankment dam length is 2.8 km, and the area of the reservoir is 3204 km^2 some of the storage lies in the Iranian lands.

For the agriculture, industrial and domestic use, the general institution for dams signed a contract with the Bulgarian's company "Acrocomplect" in 1975 to study the area and design of the dam including the irrigational project which stores water for (232480 acres) to execute the geological scan, site investigation and prepare the final design for the main dam and the secondary structures. The company finished the design in 1979 (Al-Simawee, 2008).

Figure 1 presents a typical cross section of Al-Wand dam showing its components and water elevation. The material properties of the zoned dam are listed in Table 1. According to Al-Simawee (2008), the properties of the dam are as summarised in Table 2.

In the following sections, the dam section is analysed for different conditions of rapid drawdown. The reservoir is assumed to be emptied within 11 days, 3 days and 1 day. The reservoirs period of evacuation have been chosen based on many cases which are:

1. The period of reservoir emptying of 11 days is the designed period.
2. The period of reservoir emptying of 3 days is the theoretical assumption for emergencies.
3. The period of reservoir emptying of 1 day is the theoretical assumption for emergencies.

Tab. 1. Material properties of Al-Wand dam (Al-Samawee, 2008).

Material	Permeability [m/s]	γ [kN/m^3]	c [kN/m^2]	ϕ, [degree]
Shell	0.001	18	0	25
Core	$4.8x10^{-9}$	18	210	10
Fine filter	0.07	18	0	30
Coarse filter	0.11	18	0	30
Upper layer	$8x10^{-5}$	20	30	30
Lower layer	$3x10^{-6}$	23	100	36

Tab. 2. Al-Wand properties (Fattah et al., 2015).

Property	Value
Length of dam	2800 [m]
Type of dam	earth fills with the clayey core.
Highest elevation of dam	605 [m]
Normal elevation	601[m]
Storage capacity at elevation (601 m)	216x 10^6 [m^3]
Height of dam	39 [m]
Outlet flow	200 [m^3/s.]
Spillway flow	2750 [m^3/s.]
Station flow.	12 [m^3/s.]

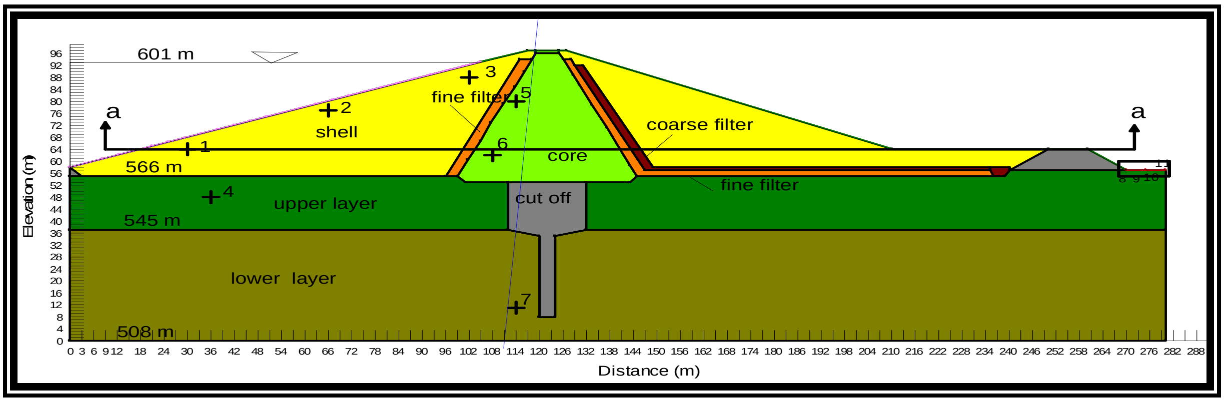

Fig. 1. Typical section of Al-Wand dam with the material details.

The Program Geo-Studio, 2007

Geostudio software is one of the geotechnical programs that is based on the finite element method and can carry out analysis such as stress-strain, flow, the stability of slopes, dynamic analysis and also rapid water drop in the reservoir. SEEP/W is part of the GeoStudio suite for analysing ground water and excess pore-water pressure dissipation problems in porous media. SLOPE/W was programmed and developed for the analysis of stability of earth structures.

Reservoir emptying within 11 days

According to the properties of each material, the phreatic line will be drawn as a case study for Al-Wand dam as shown in Figure 2 which illustrates the geometry of the dam and the path of the phreatic line through the shell, core and filters depending on the geometry and properties of materials. In addition, Figure 2 shows the distribution of the pore water pressure and the value of water flux through the flux section at time 0 for a period of reservoir emptying of 11 days.

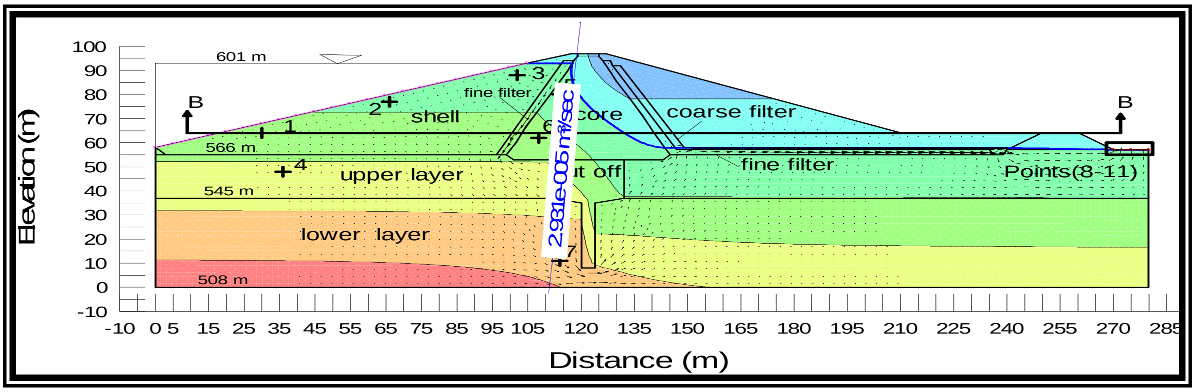

Fig. 2. Pore water pressure and the flux value immediately (0 hrs) after the start of rapid drawdown.

Table 3 presents the change of pore water pressure values at selected points shown in Figure 1 as a result of drawdown. The effect of rapid drawdown on the pore water pressure values at different locations is illustrated in Figure 3.

Tab. 3. Pore water pressure in (kPa) with time for a period of reservoir emptying of 11 days in Al-Wand dam.

Time [hr])	**Point 1**	**Point 2**	**Point 3**	**Point 4**	**Point 5**	**Point 6**	**Point 7**
0	288.16	158.25	58.12	444.70	83.30	276.20	719.22
24	256.95	127.05	27.01	413.51	64.29	248.95	695.79
48	225.75	95.86	-3.99	382.32	44.97	221.64	672.33
72	194.55	64.68	-34.86	351.14	25.66	194.41	648.91
96	163.35	33.62	-65.65	319.98	11.34	167.30	625.56
120	132.16	3.00	-96.31	288.86	3.28	140.47	602.30
144	101.01	-27.30	-126.69	257.87	-2.57	114.28	579.26
168	69.94	-57.49	-156.89	227.06	-7.89	89.01	556.37
192	39.34	-87.40	-186.80	196.64	-13.21	65.63	533.71
216	10.20	-116.69	-216.11	167.14	-18.58	46.03	511.52
240	-18.32	-145.18	-244.59	138.49	-24.01	33.36	489.94
264	-44.51	-171.67	-271.14	112.24	-29.35	26.19	469.87

When the reservoir is rapidly evacuated and drawn down, pore water pressures in the dam body are reduced in two ways. There is a slower dissipation of pore pressure due to drainage, and there is an immediate elastic effect due to the removal of the total or partial water load.

Figure 3 shows the variation of pore water pressure with time after the start of a drawdown in the reservoir at points 1 to 7 (Fig. 1). It can be seen that the pore water pressure at all points decreases linearly with time.

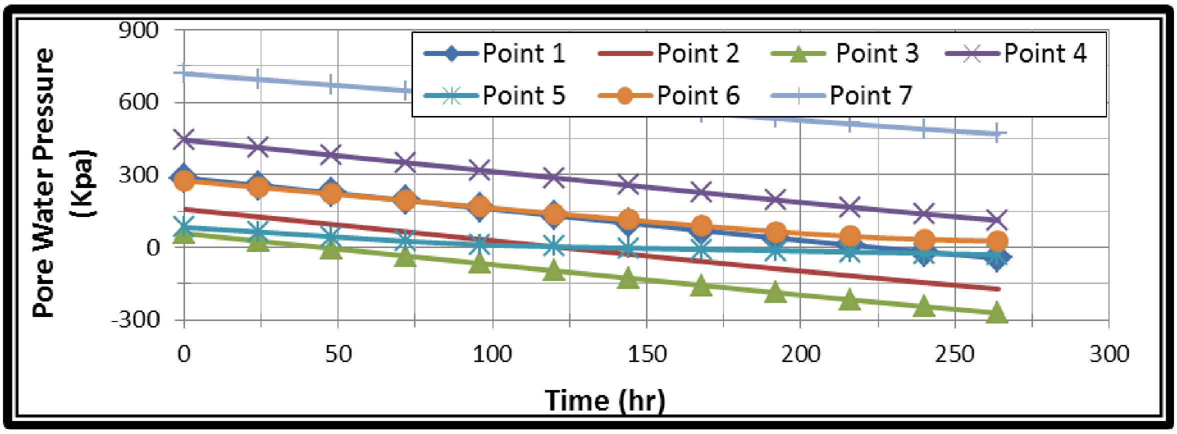

Fig. 3. Change in pore water pressure during rapid drawdown for a period of reservoir emptying of (11 days) of Al-Wand dam.

In order to trace the critical points in the dam, the xy-gradients have been estimated at points 8, 9, 10 and 11 (Fig. 1 and 2) at different times after the start of water drawn down as shown in Table 4 and Figure 4. In Table 5, the values of water flux for selected points (8-11) which are located in the downstream of the dam are presented.

Figure 5 reveals that the rate of flow at points 8, 9, 10 and 11 decreases with time; this is caused by the rapid flow of water caused by emptying the reservoir in a short period.

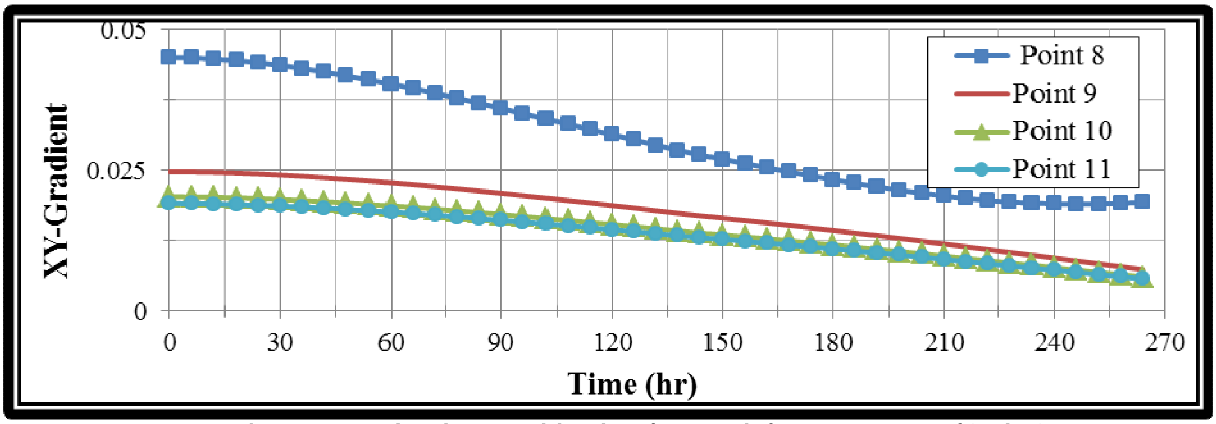

Fig. 4. Change in XY-gradient during rapid drawdown for a period of reservoir emptying of (11 days).

Tab. 4. Values of XY-gradient in Al-Wand dam at selected points for a period of reservoir emptying of 11 days.

Time [hr]	**Point 8**	**Point 9**	**Point 10**	**Point 11**
0	0.0450	0.0248	0.0203	0.0191
6	0.0450	0.0247	0.0203	0.0191
12	0.0448	0.0246	0.0202	0.0190
24	0.0441	0.0244	0.0200	0.0188
48	0.0418	0.0234	0.0192	0.0181
72	0.0387	0.0221	0.0181	0.0170
96	0.0351	0.0205	0.0168	0.0158
120	0.0313	0.0187	0.0154	0.0145
144	0.0277	0.0169	0.0139	0.0130
168	0.0247	0.0152	0.0125	0.0117
192	0.0220	0.0134	0.0110	0.0103
216	0.0200	0.0114	0.0094	0.0088
240	0.0190	0.0094	0.0077	0.0072
264	0.0193	0.0074	0.0061	0.0057

Tab. 5. Values of water flux in Al-Wand dam at selected points (m^3/day) for a period of reservoir emptying of (11 days).

Time [hr]	**Point 8**	**Point 9**	**Point 10**	**Point 11**
0	-1.156	-0.656	-0.492	-0.228
6	-1.155	-0.655	-0.491	-0.228
12	-1.151	-0.653	-0.489	-0.227
24	-1.138	-0.646	-0.484	-0.225
48	-1.094	-0.621	-0.465	-0.216
72	-1.032	-0.585	-0.439	-0.204
96	-0.958	-0.543	-0.407	-0.189
120	-0.876	-0.497	-0.372	-0.173
144	-0.790	-0.448	-0.336	-0.169
168	-0.712	-0.404	-0.302	-0.152
192	-0.625	-0.355	-0.266	-0.136
216	-0.534	-0.303	-0.227	-0.119
240	-0.440	-0.249	-0.187	-0.101
264	-0.346	-0.196	-0.147	-0.082

The exact mechanism of this phenomenon is as follows: It is assumed that the reservoir has been maintained at a high level for a sufficiently long time so that the fill material of the dam is fully saturated and steady seepage established. If the reservoir is drawn down at this stage, the direction of flow is reversed, causing instability in the upstream slope of the earth dam. The “instantaneous” drawdown is a hypothetical condition that is assumed, and pore pressures along the sliding surface are determined by inspection of “instantaneous” pore water pressure at different points in the finite element mesh. The most critical condition of sudden drawdown means that while the water pressure acting on the upstream slope at “full reservoir” condition is removed, there is no appreciable change in the water content of the saturated soil within the dam.

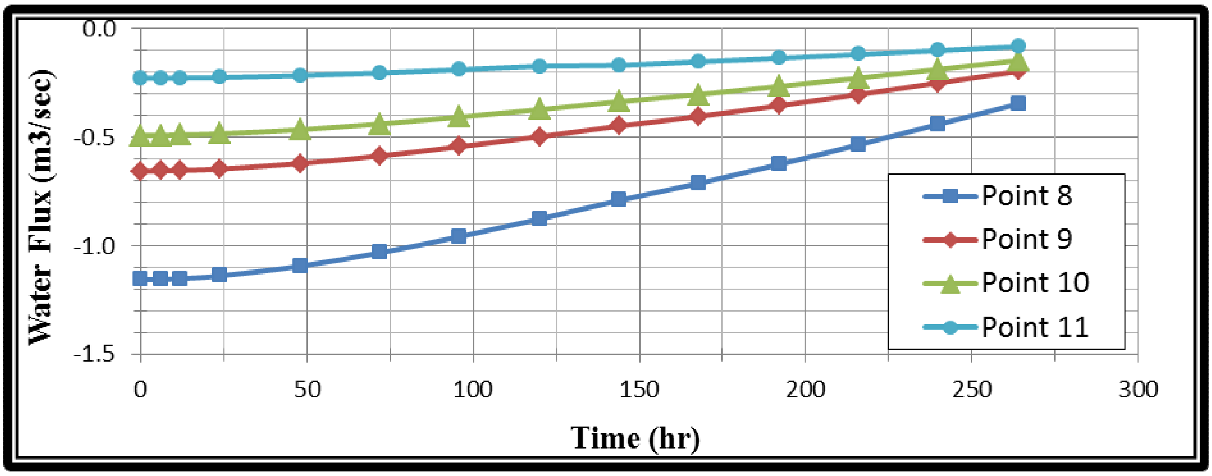

Fig. 5. Change in the quantities of water flux at points (8-10) during rapid drawdown for a period of reservoir emptying of 11 days.

The slope stability of the dam is one of the important elements that should be studied in analysing dams. Fluctuations in reservoir water level may cause the upstream face stability to become critical mainly due to the removal of the supporting water.

During the rapid drawdown, the stabilising effect of the water on the upstream face of the embankment is lost, but the pore-water pressures within the embankment may remain high. As a result, the stability of the upstream face of the dam can be much reduced. The dissipation of pore-water pressure in the embankment is largely influenced by the permeability and the storage characteristic of the embankment materials. Highly permeable materials drain quickly during the rapid drawdown, but low permeability materials take a long time to drain (GEO-SLOPE International Ltd, 2007).

In this section, the stability of upstream face of the dam during rapid drawdown condition is studied because it is the critical slope during the rapid drawdown. The results of this case are examined in Figure 6 which represents a section of Al-Wand dam after the analysis by the Program SLOPE/W using Bishop's method of slices. The critical sections were selected at the time of a minimum factor of safety for each method in case of reservoir emptying during 11days. The values of a factor of safety at different times estimated by three methods are listed in Table 6.

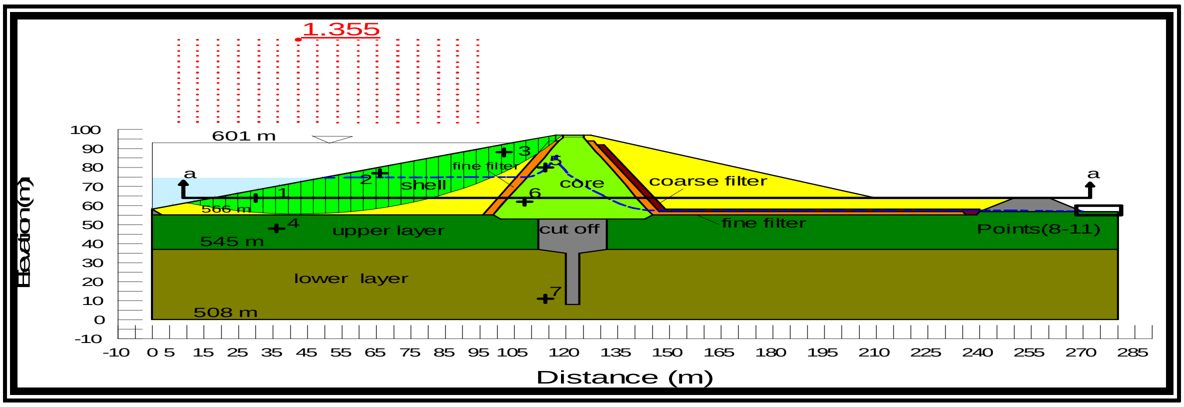

Fig. 6. The minimum factor of safety and slip surface in Al-Wand dam (at the time of 6 days) during rapid drawdown for a period of reservoir emptying of 11 days using Bishop's method of slices.

The saturated weight of the slope produces the shearing stresses while the shearing resistance is decreased considerably because of the development of the pore water pressures which do not dissipate rapidly (Gopal and Rao, 2005). Therefore, it was considered very important that such an analysis be carried out and included in this research.

Figure 7 traces the variation of the factor of safety with time. It can be noticed that the factor of safety decreases slightly during the first (120) hours after starting of reservoir emptying, then starts to increase rapidly. This is caused by dissipation of excess pore water pressure with time which leads to increase the effective stresses in the soil and hence increase its shear strength.

Tab. 6. Variation of the factor of safety with time during the rapid drawdown in Al-Wand dam for a period of reservoir emptying of 11 days.

Time [sec]	**Morgenstern-Price method**	**Bishop's method**	**Janbu's method**
0	1.404	1.403	1.399
12	1.404	1.403	1.399
24	1.392	1.39	1.393
48	1.402	1.402	1.398
72	1.416	1.415	1.405
96	1.416	1.388	1.362
120	1.376	1.36	1.246
144	1.36	1.355	1.348
168	1.361	1.357	1.356
192	1.388	1.385	1.378
216	1.392	1.39	1.382
240	1.49	1.488	1.473
264	1.68	1.68	1.574

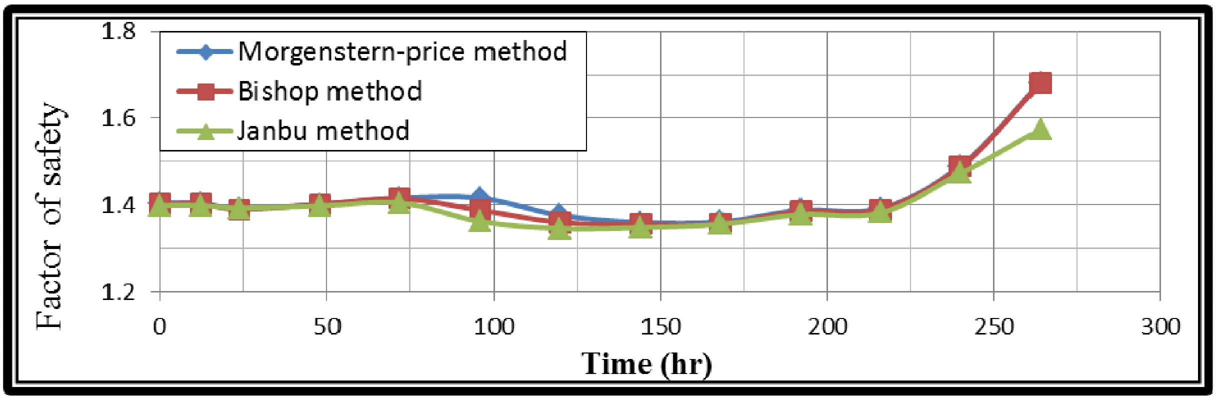

Fig. 7. Minimum values of a factor of safety during rapid drawdown for a period of reservoir emptying of 11 days in Al-Wand dam.

From Figure 7 and the values of Table 6, the minimum factor of safety in Morgenstern-Price method equals 1.36 which was achieved at time 6 days during reservoir emptying within 11 days and this result matches with the minimum factor of safety in Bishop's method which takes place at time 6 days and is equal to 1.355 but the minimum value is equal 1.246 in Janbu's method at time 5 days.

To illustrate the effect of rapid drawdown, section (a-a) shown in Figure 1 had been chosen to calculate the change in pore water pressure along the dam section for the period of reservoir emptying of 11 days. The results are shown in Table 7 and Figure 8.

Tab. 7. Values of pore water pressure (kPa) along the body of the dam for a period of reservoir emptying of 11 days in Al-Wand dam.

Distance [m]	**0 day**	**2 days**	**4 days**	**6 days**	**8 days**	**10 days**	**11 days**
0	278.21	215.80	153.40	90.99	28.58	-29.98	-56.06
25	286.05	223.65	161.30	99.27	38.80	-18.84	-45.17
49	280.99	218.65	156.57	95.39	35.30	-22.35	-48.82
78	277.50	215.35	153.64	92.64	32.59	-25.14	-51.69
99	152.31	123.70	94.57	67.59	46.43	31.71	26.18
122	-62.16	-62.62	-63.61	-64.83	-66.02	-67.36	-68.04
151	-59.92	-60.38	-61.37	-62.58	-63.78	-65.11	-65.79
172	-66.06	-66.52	-67.51	-68.72	-69.91	-71.25	-71.93
198	-60.32	-60.78	-61.77	-62.97	-64.16	-65.49	-66.17
216	-60.34	-60.79	-61.78	-62.98	-64.17	-65.50	-66.17
232	-60.34	-60.79	-61.78	-62.98	-64.17	-65.50	-66.17

The stability of slopes under drawdown conditions are usually analysed considering two limiting conditions, namely slow and rapid drawdown. In the slow drawdown situation, the water level within the slope is assumed to equalise the reservoir level at any time. In the case of rapid drawdown, which represents the most critical condition, it is assumed that the pore water pressure within the embankment continues to reflect the original water level. The lag of the phreatic line depends on factors such as permeability of soils, drawdown rate and slope gradient.

A minimum factor of safety of 1.3 would also be adequate when the analysis is carried out regarding undrained shear strength. However, if an undrained shear strength envelope is used, the laboratory testing performed to define the envelope must satisfactorily model the pore pressure behaviour and state of stress anticipated under field loading conditions.

Here in Figure 8, an important change in the behaviour of the pore water pressure line is noticed, the change starts at the time of 192 hr which represents the core effect on the velocity of water that came back to the upstream direction as shown in the last four curves.

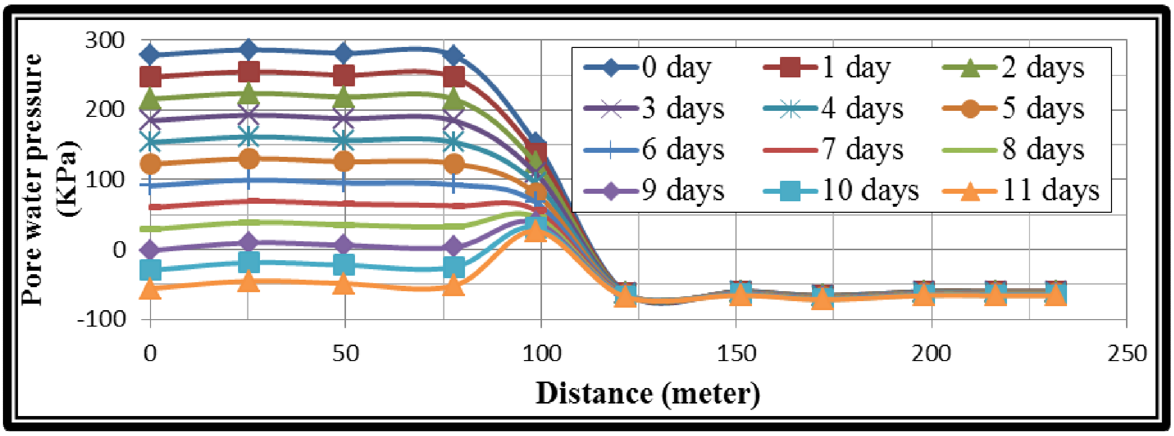

Fig. 8. Change in pore water pressure along the body of the dam for a period of reservoir emptying of 11 days in Al-Wand dam.

It can be noticed that the water flux decreases linearly with time and with the water level in the reservoir of Al-Wand dam which means that the rate of flow in the body of the dam is almost uniform change.

When the countervailing upstream water pressure has disappeared, it causes a danger to the upstream slope. Soils inside the dam body remain saturated, and seepage commences from it towards the upstream slope. Seepage and hydrodynamic pressures create downward forces acting on the upstream slope. Those are adverse to the stability and create a critical condition to the upstream slope. While the development of deep-seated failure surfaces is possible, the effect on earthen side slopes is most commonly seen in the form of relatively shallow slope failures, which if left unattended lead to the gradual deterioration of the whole dam (Reddi, 2003).

As a result of drawdown, the quantity of seepage will reduce, and the values of reduction of flow are shown in Figure 9.

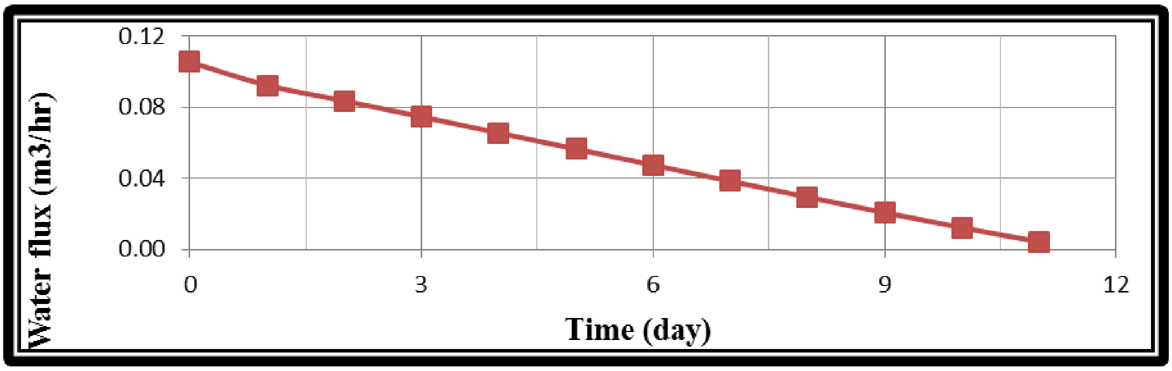

Fig. 9. Water flux for a period of reservoir emptying of 11 days in Al-Wand dam.

Reservoir emptying within 3 days

In this section, the reservoir emptying is considered to be conducted within 3 days. Figure 10 presents the change of pore water pressure values as a result of drawdown. Many points have been selected as history points to study the effect of rapid drawdown on the pore water pressure values, but in this case, the drawdown period is 3 days.

Figure 11 represents the reduction in the values of XY-gradient for the points (8-11) which are located in the downstream of the dam.

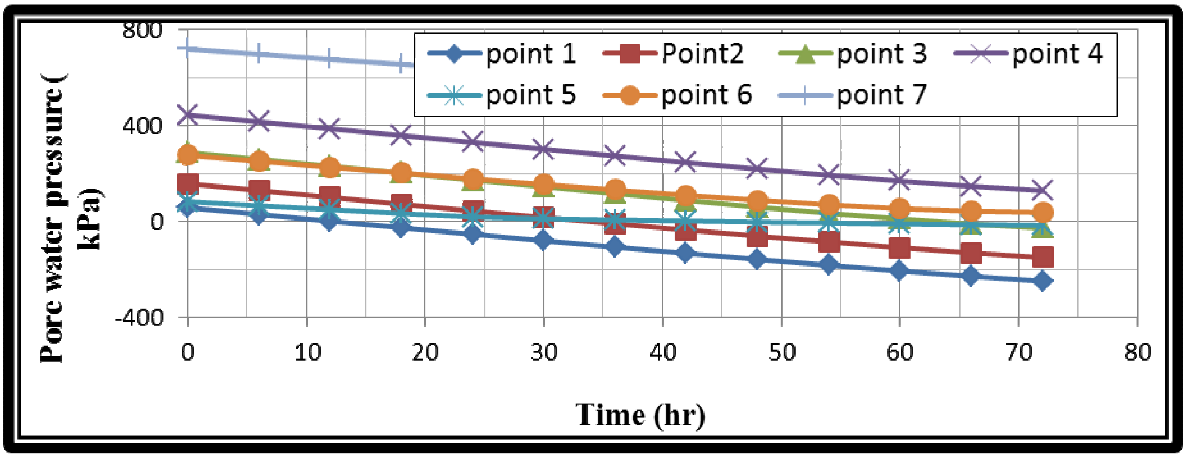

Fig. 10. Change in pore water pressure during rapid drawdown for a period of reservoir emptying of 3 days in Al-Wand dam.

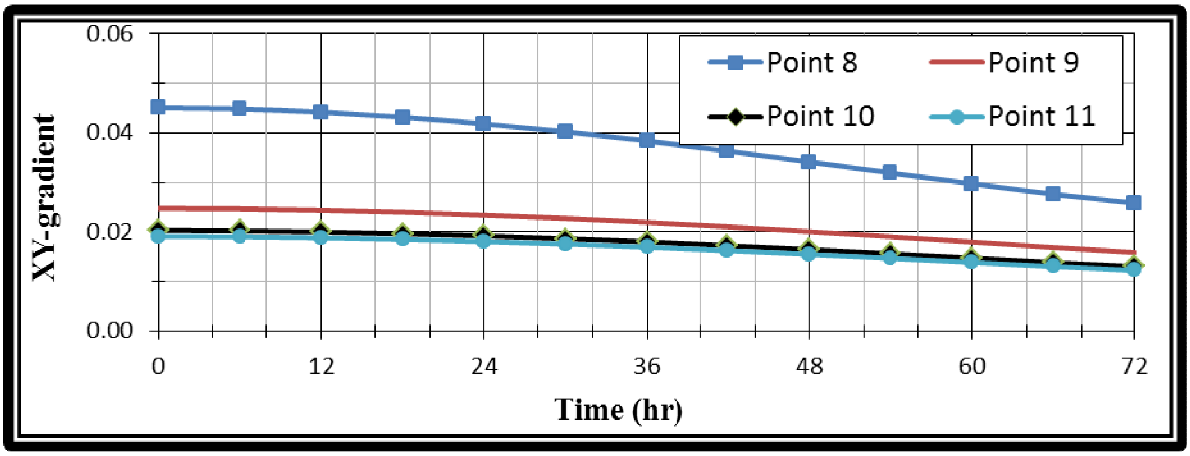

Fig. 11. XY-gradient during rapid drawdown for a period of reservoir emptying within 3 days in Al-Wand dam.

Figure 12 displays values of water flux at points (8-11) which are located in the downstream of the dam for a period of reservoir emptying of 3 days. A comparison between Figures 12 and 5 shows that when the period of reservoir emptying is long (11 days), the rate of flow is greater than that in the case of the 3-day emptying period.

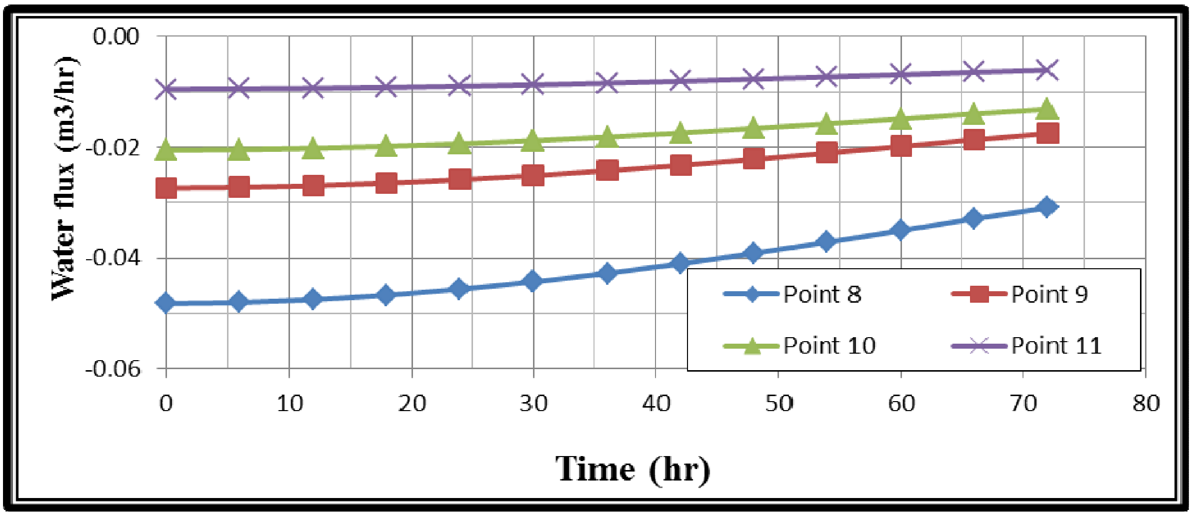

Fig. 12. Change in the quantities of water flux during rapid drawdown for a period of reservoir emptying within 3 days in Al-Wand dam.

Figure 13 presents a section of Al-Wand dam after analysis by the Program SLPOE/W using Bishop's method, selected at the time of a minimum factor of safety in case of reservoir emptying within 3 days.

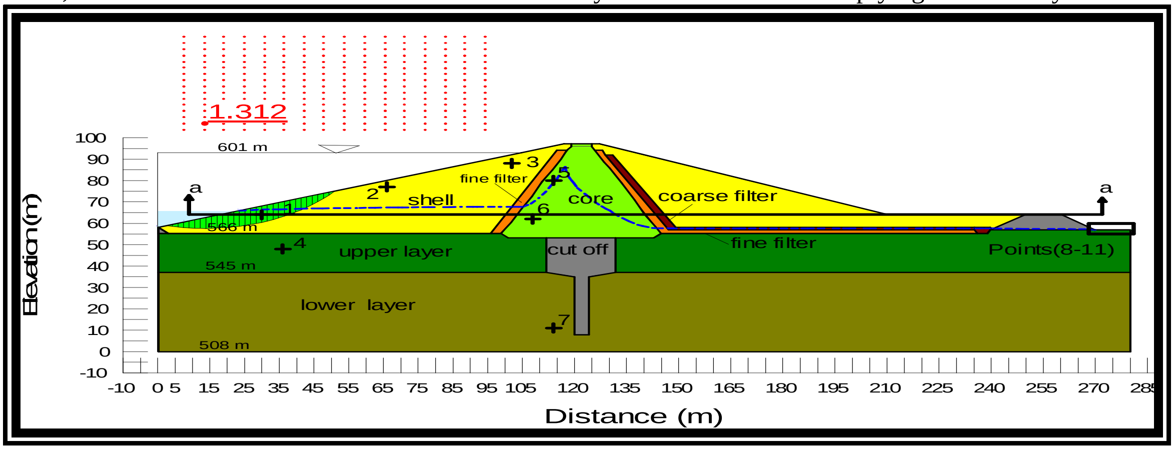

Fig. 13. A minimum factor of safety and slip surface (at hour 56) during rapid drawdown for a period of reservoir emptying of 3 days of Al- Wand dam using Bishop's method.

Table 8 summarises the values of the minimum factor of safety at different times during a period of 3 days for reservoir emptying.

Tab. 8. Minimum values of a factor of safety for a period of reservoir emptying of (3 days) in Al-Wand dam.

Time [hr]	**Morgenstern-Price method**	**Bishop's method**	**Janbu's method**
0	1.403	1.403	1.398
12	1.396	1.394	1.332
24	1.4	1.395	1.264
36	1.344	1.339	1.231
48	1.339	1.336	1.258
52	1.33	1.329	1.284
56	1.314	1.312	1.258
60	1.329	1.327	1.282
72	1.555	1.554	1.451

From Figure 14 and the values of Table 8, the minimum factor of safety in Morgenstern-Price method equals 1.314 which was calculated at time 56 hr during reservoir emptying of 3 days and this result matches with the minimum factor of safety in Bishop's method at time 56 hr which is equal to 1.312, but the minimum value equals 1.231 in Janbu's method at time 36 hr.

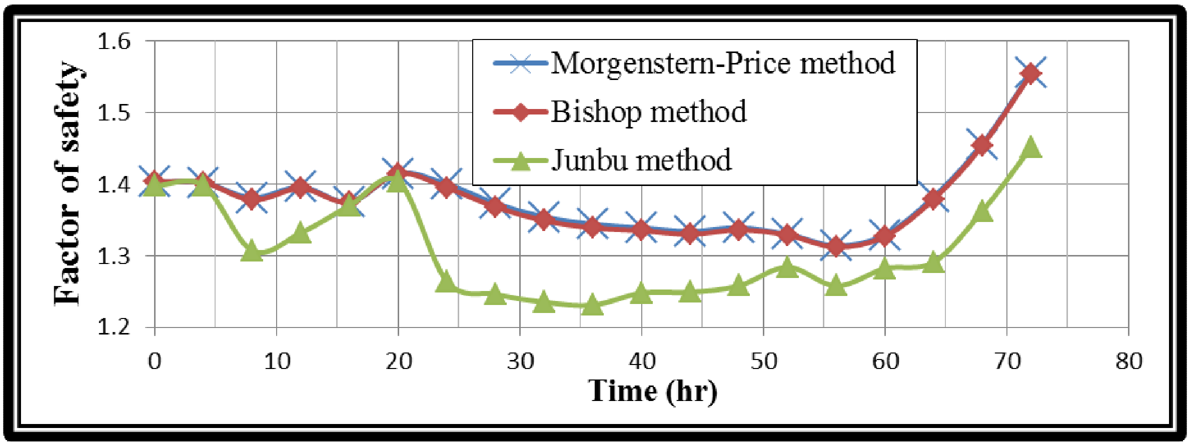

Fig. 14. Variation of the minimum factor of safety of the dam slope with time calculated by three methods for a period of reservoir emptying of 3 days in Al-Wand dam.

To discover the effect of rapid drawdown, section (a-a) has been chosen to calculate the change in the pore water pressure along the dam section for the period of reservoir emptying of 3 days as shown in Figure 15.

In Figure 15, a significant change in the pore water pressure curve starts at time 48 hr which represents the core effect on the phreatic line that came back to the upstream direction as shown in the last five curves.

The pore water pressure is constant at early times, and then at the time of 2 days, a decrease in water pressure takes place due to the effect of the core.

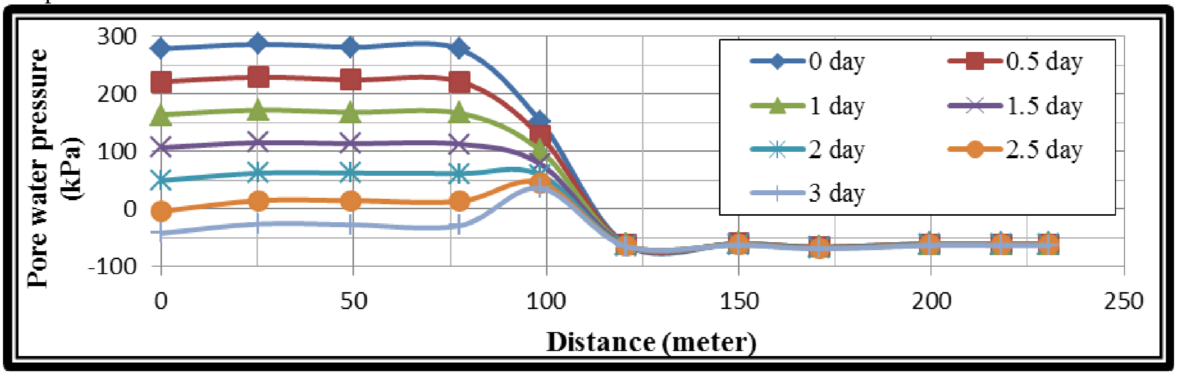

Fig. 15. Pore water pressure along the body of Al-Wand dam for a period of reservoir emptying of 3 days.

The drawdown results in a decrease of the quantity of seepage and the values of reduction are shown in Figure 16, since the reduction of water flux with a noticeable quantity is considered as an important point to study the effect of permeability of the shells of the dam.

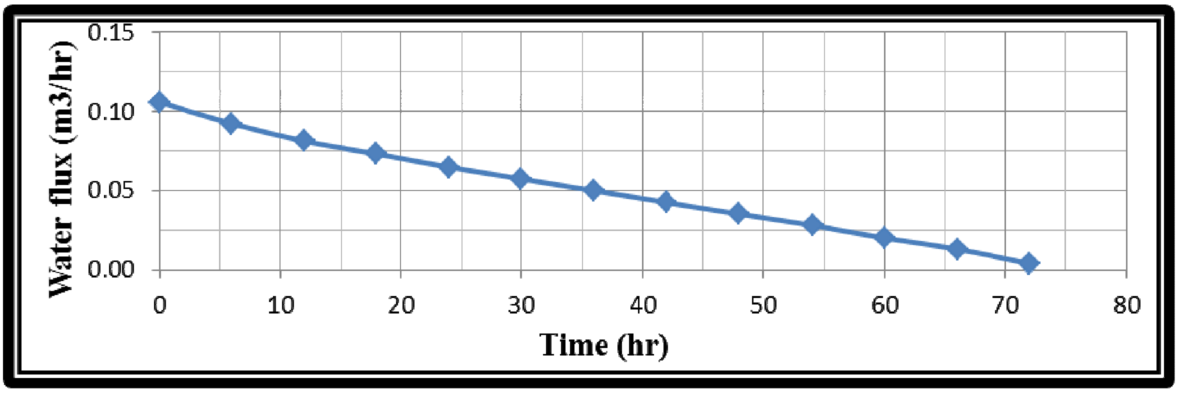

Fig. 16. Change in water flux for a period of reservoir emptying of 3 days in Al-Wand dam.

Reservoir emptying during one day

In this section, emergency period of 1day for rapid draw down is studied, also, the stability of the dam at this condition had been investigated. Figure 17 presents the change of pore water pressure values as a result of drawdown. It can be noticed that the pore water pressure at all points decreases linearly with time at the same rate. Figure 18 presents the reduction in the values of XY-gradient for the points (8-11) which are located in the downstream of the dam.

Figure 19 shows graphical representation at selected points for a period of reservoir emptying of 1 day. For this condition, the water flux decreases slightly during the period of rapid draw down of 24 hours due to low permeability of the core material. Figure 20 displays values of of factor of safety of the dam slopes for a period of reservoir emptying of 1 day.

From Figure 20, the minimum factor of safety in Morgenstern-Price method equals 1.178 which was calculated at time 20 hr during reservoir emptying of 1 day and this result matches with the minimum factor of safety in Bishop's method at time 20 hr which is equal to 1.177 but the minimum value equals 1.154 in Janbu's method at time 20 hr.

It can be noticed that the factor of safety decreases through the first (20 hours) from 1.4 to about 1.18 due to slow dissipation of pore water pressure compared with rapid lowering of water level. This leads to decrease the effective stresses and shear strength of the soil.

The change in the pore water pressure along the dam section for the period of reservoir emptying of 1 day is shown in Figure 21 in which, a significant change in the pore water pressure curve starts at 16 hr which represents the core effect on the phreatic line that came back to the upstream direction as shown in the last three curves. This means that during the period of reservoir emptying of 24 hours, no change in pore water pressure takes place.

After that, there will be negative values of pore water pressure which indicate an increase in the effective stress and shear strength of the soil.

As a result of the drawdown, the quantity of seepage reduces, and the values of reduction are shown in Figure 22, since the reduction of water flux with a considerable quantity is considered as an important point, a study of the effect of permeability of dam shells is required.

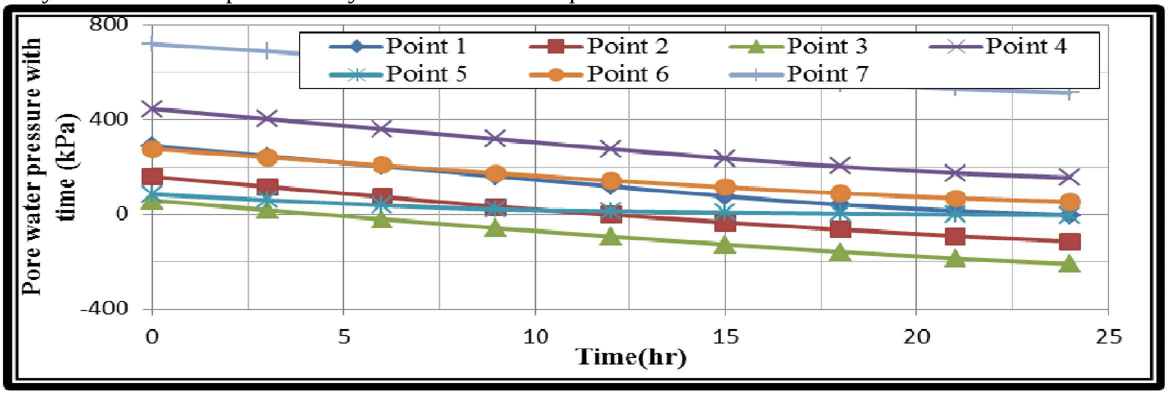

Fig. 17. Pore water pressure during rapid drawdown for a period of reservoir emptying of 1 day in Al-Wand dam.

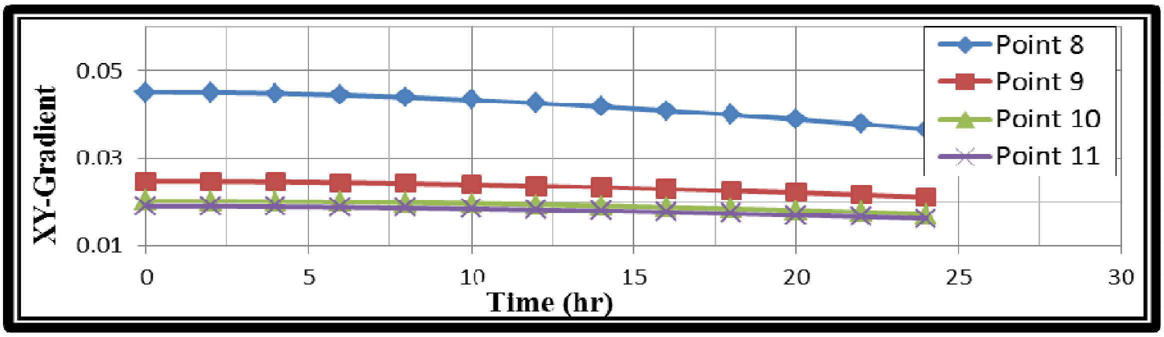

Fig. 18. XY-gradient during rapid drawdown for a period of reservoir emptying of 1 day in Al-Wand dam.

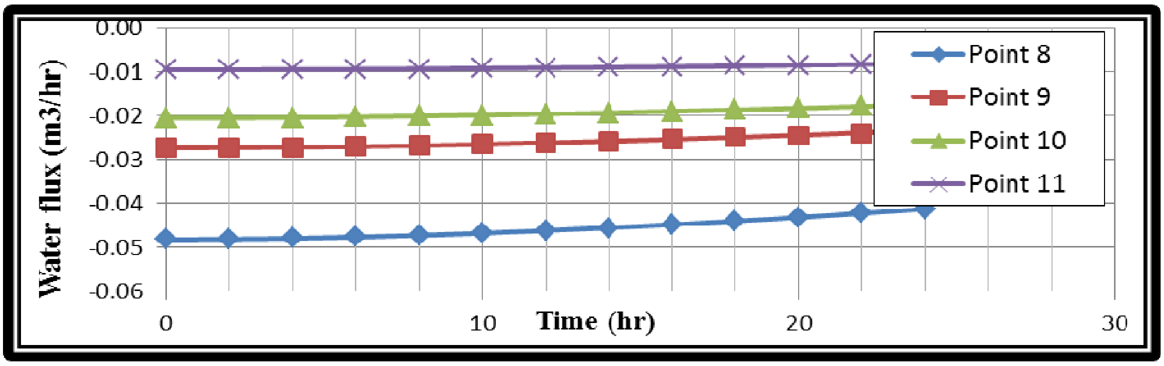

Fig. 19. Quantities of water flux during rapid drawdown for a period of reservoir emptying of 1 day in Al-Wand dam.

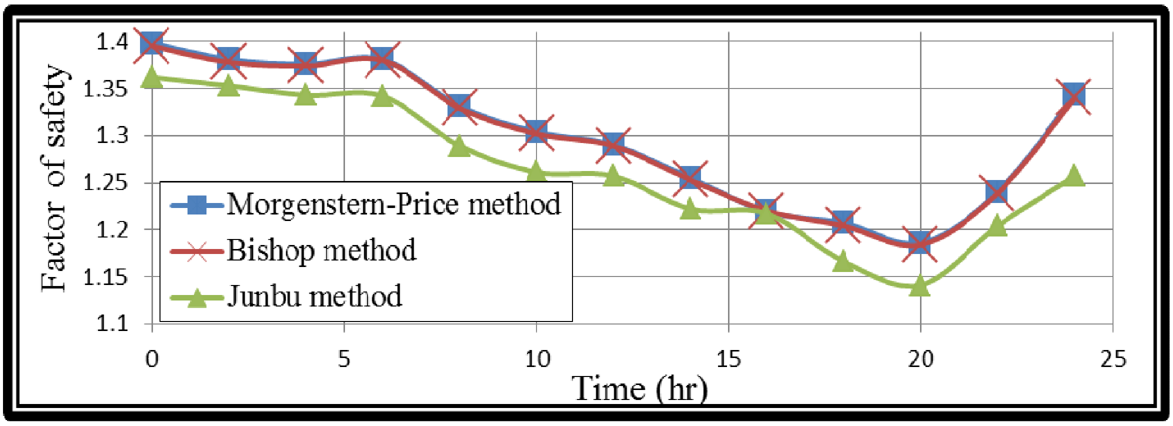

Fig. 20. Values of a factor of safety during rapid drawdown for a period of reservoir emptying of 1 day in Al-Wand dam.

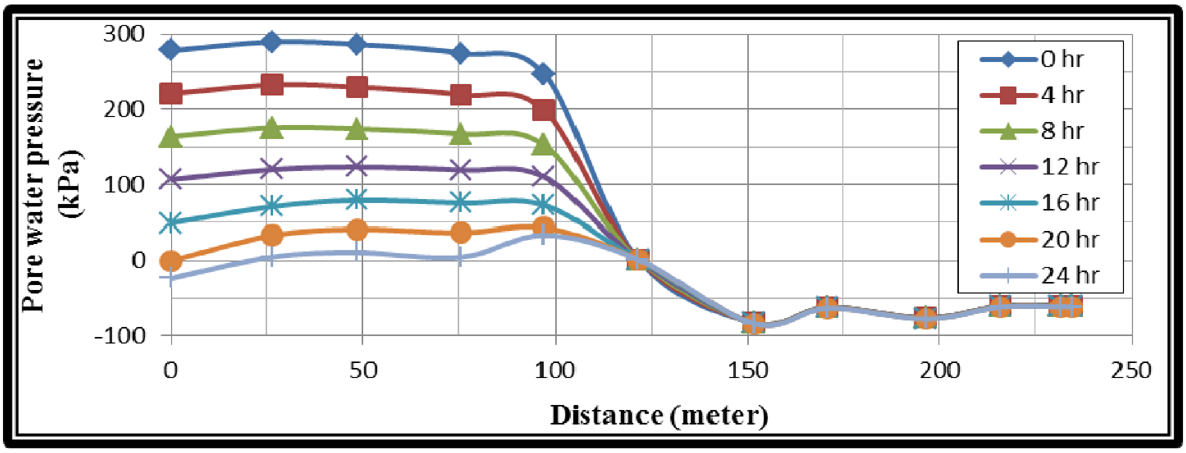

Fig. 21. Pore water pressure along the body of the dam for a period of reservoir emptying of 1 day in Al-Wand dam.

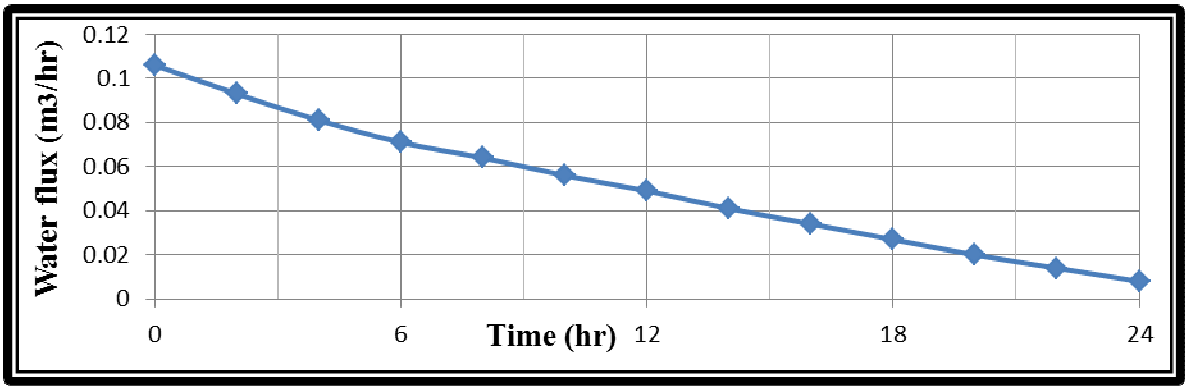

Fig. 22. Water flux for a period of reservoir emptying 1 day in Al-Wand dam.

When the reservoir is rapidly evacuated and drawn down, pore water pressures in the dam body are reduced in two ways: there is a slower dissipation of pore water pressure due to drainage, and there is an immediate elastic effect due to the removal of the total or partial water head.

Conclusions

1. During rapid draw down, the pore water pressure at all points within the dam body decreases linearly which indicates that steady state flow takes place. Some points in the dam downstream may be affected by negative pore water pressure during the period of water draw down which indicates that the water level becomes below these points.
2. The exit gradient at the dam downstream almost decreases during the period of water draw down which means that the factor of safety against boiling increases with time. When the period of reservoir emptying is long (≈ 10 days), the values of exit gradient are reduced to very low values (≈ 0.05) within this period while for short periods (1 to 3 days), the exit gradient values are greater.
3. The rate of flow at the dam downstream decreases with time; this decrease is caused by the rapid flow of water caused by emptying the reservoir in a short period. Generally, the water flux decreases linearly with time and with the water level in the reservoir which indicates that the rate of flow in the whole body of the dam shows almost uniform change.
4. The factor of safety against sliding of the dam slopes decreases slightly within the short period after the start of rapid draw down of water in the reservoir, then starts to increase.
5. When the period of reservoir emptying is long (≈ 11 days), the rate of flow is greater than that in the case of short periods (1 to 3 days). When the countervailing upstream water pressure has disappeared, it causes a danger to the upstream slope. Soils inside the dam body remain saturated, and seepage commences from it towards the upstream slope. Seepage and hydrodynamic pressures create downward forces acting on the upstream slope. Those are adverse to the stability and create a critical condition to the upstream slope.

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