Civil Engineering Infrastructures Journal, 48(1): 35-45, June 2015
ISSN: 2322-2093

Use of Numerical Simulation to Measure the Effect of Relief Wells for Decreasing Uplift in a Homogeneous Earth Dam

Salmasi, F.[1*]**, Mansuri, B.**[2] **and Raoufi, A.**[3]

[1] Water Engineering Department, Faculty of Agriculture, University of Tabriz, Tabriz, Iran.
[2] M.Sc. Student of Hydraulic Structures, University of Tabriz, Tabriz, Iran.
[3] M.Sc. Student of Hydraulic Structures, University of Azad Ahar, Ahar, Iran.

Received: 26 Jul. 2013 Revised: 29 Apr. 2014 Accepted: 15 Jun. 2014

ABSTRACT: Relief wells are used extensively to relieve excess hydrostatic pressure in pervious foundation strata overlain by impervious top strata, conditions which often exist landward of levees and downstream of dams and hydraulic structures. Placing well outlets in below-surface trenches or collector pipes helps dry up seepage areas downstream of levees and dams. Relief wells are often used in combination with seepage control measures, such as upstream blankets, downstream seepage berms, and grouting. Draining seepage water into relief wells decreases uplift and prevents piping. This study examined the effect of relief wells with different diameters at different distances downstream of a homogeneous earth dam using Seep/W software. Also the effect of upstream water level of reservoir on seepage flow to each well was carried out. Results show that by decreasing the distance between relief wells and increasing the diameter of the relief wells, total uplift pressure decreases. The optimum distance between relief wells to decrease uplift pressure was found to be 5 m. The proposed method is recommended in designing relief wells by providing optimum diameter and distance of wells for the sustained yield.

Keywords: Collector pipe, Earth dam, Relief well, Seepage, Uplift

INTRODUCTION

All water retention structures are subject to seepage through their foundations and abutments. The seepage may result in excess hydrostatic or uplift pressure beneath the elements of the structure or landward strata. Relief wells are often installed to relieve this pressure, which might otherwise endanger the safety of the structure (Gebhart, 1973). Relief wells, in essence, are controlled artificial springs that decrease pressure to a safe value and prevent the removal of soil in the piping or by internal erosion. The proper design, installation, and maintenance of relief wells are essential to assuring their effectiveness and the integrity of the protected structure.

A relief well system requires less square footage than seepage control measures such as berms. The wells require periodic maintenance and frequently lose efficiency over time for reasons such as clogging of well screens by muddy surface water, bacterial growth, or carbonate incrustation. Relief wells can be used to decrease groundwater pressure and the water level in discharge areas to manage salinity. Both relief wells and siphons can be used to decrease hydrostatic pressure and the water level, but their impact on water logging and soil salinity varies depending upon the quality of the groundwater, soil type, the magnitude and extent of the cone of depression and the quality and quantity of the leaching water (Salama et al., 2003).

Relief wells are often installed landward of levees and downstream of

---

[*] Corresponding author E-mail: Salmasi@Tabrizu.ac.ir

dams to provide factors of safety against piping and uplift or heave (USACE, 1992). A typical relief well includes a screen and a riser pipe and has an internal diameter of 6 to 18 in. They are sized to accommodate maximum design flow without excessive head loss. Well screens are usually wire-wrapped steel/plastic pipes or slotted or perforated steel/plastic pipes. Slotted wood-stave screens, which are no longer manufactured, continue to be found in existing installations.

The first use of relief wells to prevent excessive uplift pressure at a dam was by the US Army Corp of Engineers, Omaha District, who installed 21 wells between July 1942 and September 1943 as remedial seepage control for Fort Peck Dam in Montana (Middlebrooks and Jervis, 1997). The foundation was an impervious stratum of clay overlaying pervious sand and gravel. Although steel sheet piles were driven to provide complete cutoff, leakage occurred and high hydrostatic pressure developed at the downstream toe with a head of 45 ft above the surface of the ground. The high pressure was first observed in piezometers installed in the previous foundation. The first surface evidence of high hydrostatic pressure came in the form of discharge from an old well casing that had been left in place (USACE, 1992).

Alum Creek and Dillon Dams in Ohio are part of seepage control systems with relief wells to decrease excess hydrostatic pressure in pervious foundation materials. Eight relief wells were installed in 1977 at the toe of Alum Creek Dam. Each 8 in diameter well has sections of stainless steel screen embedded in the gravel pack (extending 8 in outward to the unbored formation) with a riser pipe extending to the ground surface, where it is covered by protective housing. Seven relief wells were installed in 1959 at the toe of Dillon Dam (USACE, 1992).

An empirical method developed by Warriner and Banks (1977) using the results of electric analogical studies by Duncan (1963) and Banks (1965) can be used to determine the head at any point in a random array of fully or partially penetrating wells (Van der Heijde et al., 1984). Mansur et al. (2000) examined the performance of relief well systems along Mississippi River levees. They described the design, construction, and maintenance of the relief well systems to prevent failure of levees resulting from sand boils and/or piping for different subsurface conditions along the levees in the alluvial valleys of major rivers. Related studies on prevention of piping in levees have been carried out by Davidson et al. (2013) and Ozkan et al. (2008). Geibel (2004) studied the rehabilitation of a bio-fouled pressure relief well network at Garrison Dam in North Dakota.

Parks (2012) studied Willow Creek Dam seepage. They used finite element analysis to show that the regional aquifer provided all flow into the relief well system and solely contributed to the exit gradients long the downstream toe. Flow rates in the dam’s 27 pressure relief wells were found to be lower than the flow rates when the reservoir was first filled, although piezometer levels were much higher. This fact points to the need to redevelop the pressure relief wells.

An exact solution for transient Forchheimer flow to a well does not currently exist. Mathias et al. (2008) presented a set of approximate solutions, which can be used as a framework for verifying future numerical models that incorporate Forchheimer flow to wells.

Based on Chen et al. (2009), neglecting the effect of well radius may lead to a significant error in the predicted drawdown distribution near the pumping well area. New analytical solutions describing aquifer responses to a constant pumping or a constant head maintained at a finite-diameter well in a wedge-shaped aquifer were derived based on the image-well method and applicable to an arbitrarily located well in the system.

Mishra and Majumdar (2010) presented a semi-analytical solution for well recharge under variable head boundary condition. These solutions were developed using the method of separation of variables and Duhamel's convolution theorem. The solution developed in their study was verified with the Jacob-Lohman solution and subsequently validated using field data pertinent to constant-head boundary conditions.

Patel et al. (2010) worked on simulation of radial collector well in shallow alluvial riverbed aquifer using analytic element method. They refer that to withdraw large quantities of groundwater from the alluvial aquifers for various uses near rivers bed, radial collector (RC) wells are often preferable to the installation of several small diameter tube wells. In regions where rivers are not perennial or have low flow conditions during most part of the year, the RC wells are placed in the riverbed to obtain uninterrupted supply of naturally filtered groundwater through highly permeable saturated riverbed aquifers.

Vashisht and Shakya (2013) developed a transient semi-analytical solution for evaluating the hydraulic head distribution in a leaky aquifer under constant surface-ponding conditions while draining through a fully penetrating multi-section screen of an injection well. Analyses showed that the hydraulic head distribution within the Radius of partial screening influence (Rps) in the aquifer is controlled by both the radial distance from the well and the monitoring depth but only by the radial distance beyond Rps.

Yang et al. (2014) derived a mathematical model describing the transient hydraulic head distribution induced by constant-head pumping/injection at a partially penetrating well in a radial two-zone confined aquifer.

The present study examined the effect of the distance between and diameter of relief wells on seepage discharge and uplift pressure. A homogenous earth dam resting on a pervious foundation was simulated using SEEP/W software. The design variables are relief well diameter, distance between wells and reservoir water level downstream of a homogenous earth dam.

MATERIALS AND METHODS

Governing Equations

Seepage discharge obeys Darcy's flow (Eq. 1):

$$q = -kA(\partial h / \partial l) \tag{1}$$

where q: is the seepage discharge (m^3/s), K: is the hydraulic conductivity coefficient (m/s), A: is the area of the cross-section (m^2), and $\partial h / \partial l$: is the flow hydraulic gradient (dimensionless). The governing equation (Eq. (2)) for water flow in porous media is Poisson's equation (Woyshner and Yanful, 1995):

$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} = q \tag{2}$$

where K_x and K_y: are hydraulic conductivity in the horizontal and vertical axes, respectively (m/s), h: is the total water head (m) and q: is the discharge flow rate (input/output) to the soil (m^3/s per unit area).

Eq. (1) assumes steady state flow and homogenous soil. Seep/W software uses the finite element method to solve Poisson's equation.

Numerical Simulation

The finite element method subdivides a continuum into small pieces, describes the behavior of the individual pieces and then reconnects all pieces to represent the behavior of the continuum. This process of subdividing the continuum into smaller pieces is known as discretization or meshing. The pieces are known as finite elements.

In SEEP/W, the geometry of a model is defined in its entirety prior to discretization or meshing. Automatic mesh generation algorithms have advanced sufficiently to enable well behaved, numerically robust default discretization with no additional effort required by the user. It is still better to examine the default-generated mesh, but any changes required can easily be made by changing a single global element size parameter or the number of mesh divisions along a geometry line object, or by resetting a mesh element edge size (Geo-Studio, 2007).

In most applications, an array of pressure relief wells is required to relieve substratum pressure or decrease the groundwater level. The number of and spacing between the wells must be analyzed to meet these requirements for both scenarios. The present study assumes a homogenous earth dam of the dimensions shown Figure 1. The boundary conditions are an upstream reservoir level of 12 m and downstream reservoir level of 7 m. To apply boundary conditions to the relief wells, the water head in the wells equals the downstream water head, which is 7 m in this case. The upstream and downstream slopes of the earth dam are assumed to be 1:2.5 (V:H), which is common for a base model. Seepage flow and uplift pressure calculation in all models employed the finite element method and Seep/W. The number of elements in the 2D model varied from 5883 to 23012. Saturation hydraulic conductivity was assumed to be 1 m/d.

In addition to numerical simulation of the base model without relief wells, nine other models for relief wells with different diameters (0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5 m) and distances apart (5, 10, 25, 50 m) were simulated. The upstream water head was assumed to be 12, 12.5 or 13 m. These numbers are hypothetical and represent commonly-applied ranges. The minimum distance between wells is assumed to be 5 m because a smaller distance usually will incur additional cost.

The sections selected for determining the amount of seepage were at 11.5 m downstream of the relief wells and 40.5 m upstream of the relief wells (dashed blue lines in Figure 2). Figure 2 shows the plan of Figure 1, with a relief well radius of 0.5 m and finite elements mesh sizes generated for numerical simulation. As can be seen in Figure 2, the fine element method was applied around the relief wells to attain greater accuracy.

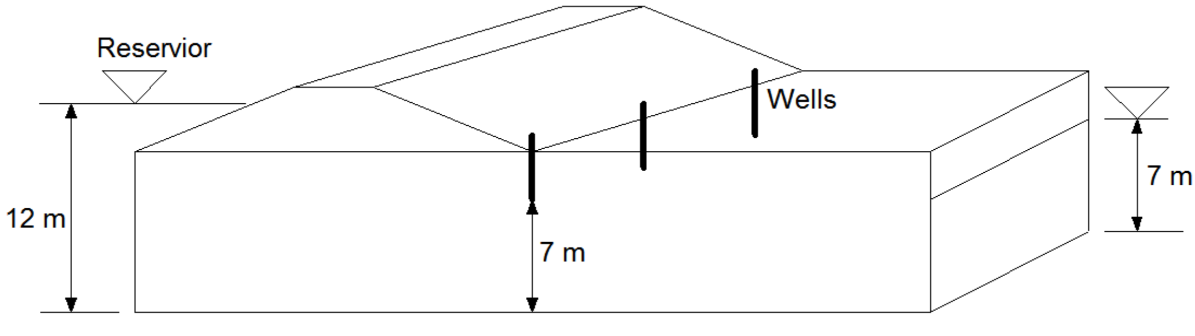

Fig. 1. Typical section of earth dam with relief wells at the toe of dam.

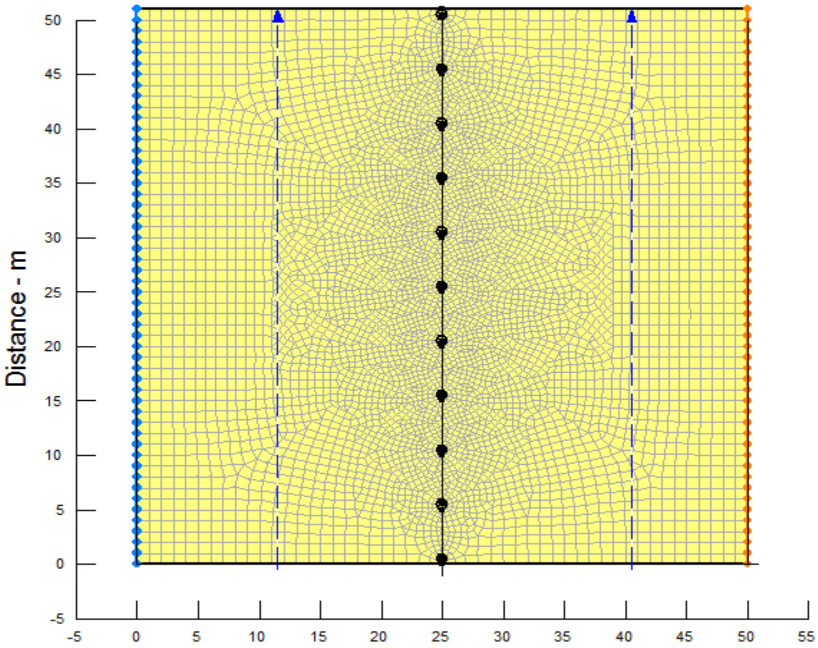

Fig. 2. Plan for relief wells by 0.5 m in radius at downstream side (toe) of earth dam.

RESULTS AND DISCUSSION

Figure 3 shows the results of numerical simulation to calculate seepage from the dam foundation by relief well diameter. The upstream reservoir level was assumed to be 12 m. The figure shows that as the distance between relief wells increased, the inlet seepage to each well increased in a parabolic manner. When the distance between relief wells was low (5-10 m), the seepage flow rate was the same for several of the wells. This indicates that, if the distance between relief wells is low, the effect of distance on inlet seepage flow to the wells is greater than the effect of well diameter. Maximum inlet flow to each well occurred when the distance between wells was at the maximum value of 50 m. Notice that, for upstream reservoir levels of 12 m, as the radius increased, the inlet seepage to each well increased.

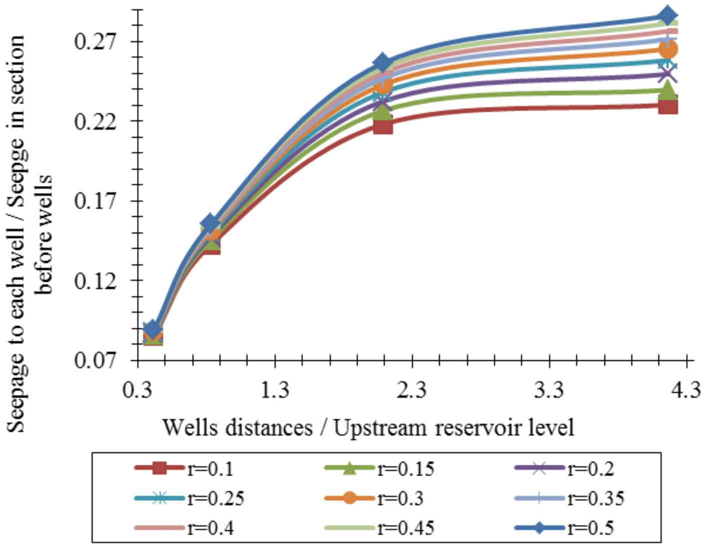

Fig. 3. Variation of relief wells distance against seepage value to each well (upstream reservoir level=12 m).

Figure 4 shows the results of numerical simulation to calculate seepage from the dam foundation by the distance between wells (upstream water level at 12 m). The figure indicates that, when the distance between relief wells (*S*) was low (5-10 m), inlet discharge to wells of different diameters was about the same. This indicates that relief well radius did not affect the discharge to each well when the distance was small. At distances of 25 and 50 m, the radius of the relief wells affected inlet discharge to the wells; as the radius increased, the inlet discharge increased. In addition, when the distance between these wells increased, the response increased in sensitivity.

Figure 5 shows uplift pressure in the earthen dam foundation for a series of relief wells 0.5 m in diameter and 12 m upstream of the reservoir. The figure shows that uplift pressure decreased as the distance between relief wells decreased. When there were no relief wells in the toe of the dam (*S* = 0), the decrease in uplift under the dam is linear. The presence of relief wells further decreased uplift, which decreased total uplift. In this example, the optimal distance between wells to decrease uplift was 5 m. This optimal distance was derived only for uplift pressure, regardless of economic factors. In reality, both hydraulic and total costs must be considered.

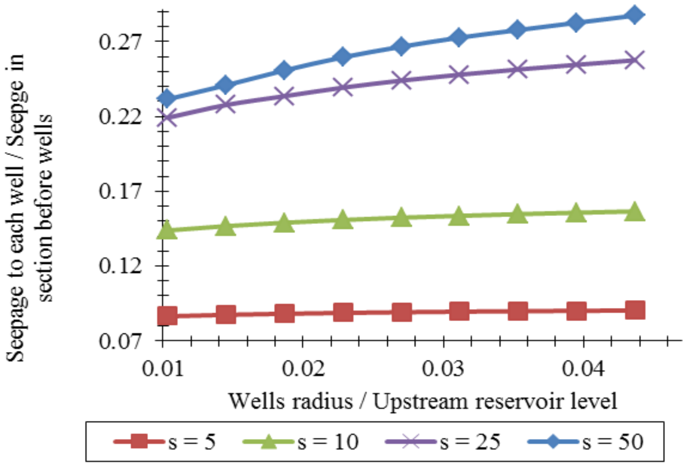

Fig. 4. Effect of wells radius on inlet seepage to each well (upstream reservoir level is 12 m).

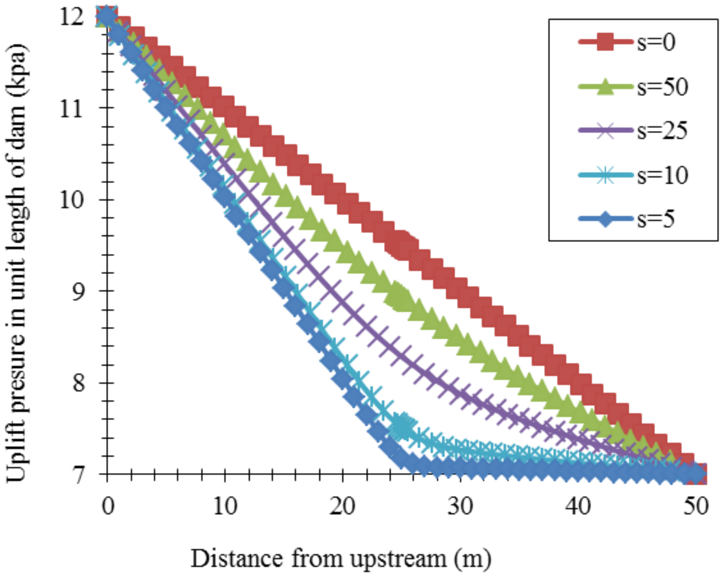

Fig. 5. Effect of wells distances (*S*) with 0.5 m in diameter, on uplift pressure.

Figure 6 shows uplift pressure in the foundation of the dam by distance between wells. As shown, uplift pressure decreased as well diameter (*r*) increased; however, when the distance between wells was small, uplift pressure decreased and dam stability to uplift pressure increased. The optimal distance between wells to decrease uplift pressure was 5 m. When seepage to the wells was high, the uplift pressure strongly decreased. Intensity in the vertical axis is defined as the ratio of calculated uplift pressure to uplift pressure in the base model (without relief wells).

Figures 7 and 8 show a row of relief wells in the toe of an earth dam that are 25 m apart with radii of 0.5 and 0.1 m, respectively (upstream water head is 12 m). Potential curves in the foundation of the dam, a phreatic line and seepage from the sections are also shown. The differences in the seepage rates between the figures indicate the entrance of discharge into the relief wells.

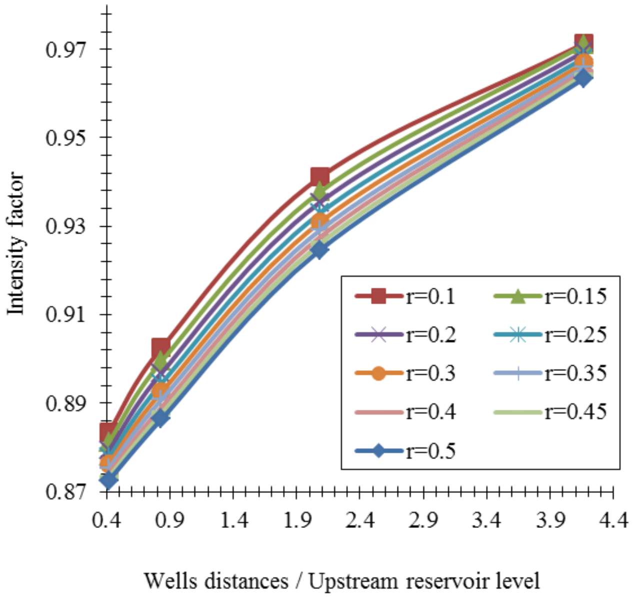

Fig. 6. Effect of various well diameters on uplift pressure when upstream reservoir level is 12 m.

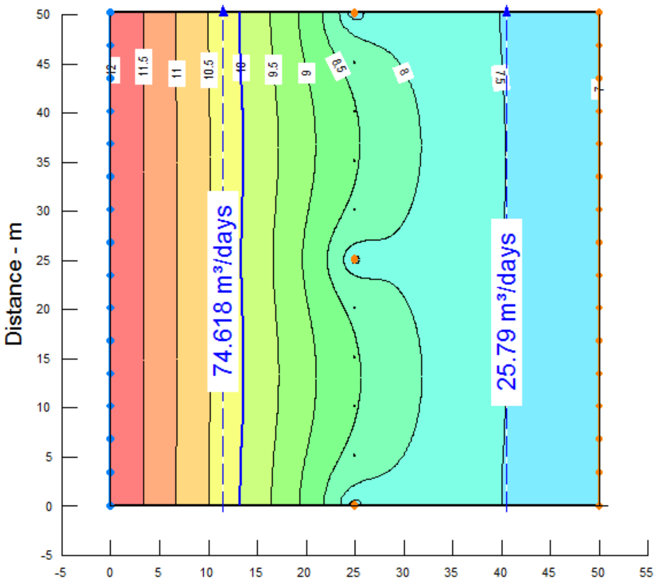

Fig. 7. Relief wells plan at toe of earth dam by 0.1 m radius and 25 m distance from each other.

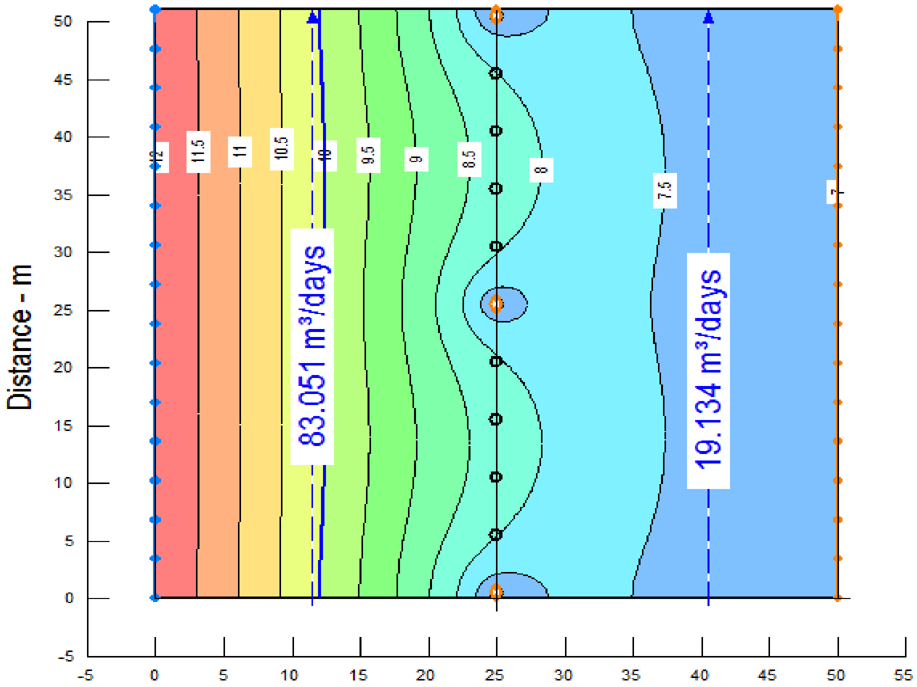

Fig. 8. Relief wells plan at toe of earth dam by 0.5 m radius and 25 m distance from each other.

Figure 9 indicates that, when the upstream reservoir level increased, inlet seepage to each well increased. When the distance between wells was small (5-10 m), upstream reservoir levels showed similar results for inlet seepage flow to each well. This indicates that the upstream reservoir level had no effect on inlet seepage to each well. At 25 and 50 m between wells, the upstream reservoir level affected seepage into the wells; increasing the reservoir water level, increased inlet seepage to each well. Seepage rate increased as the distance to the wells increased.

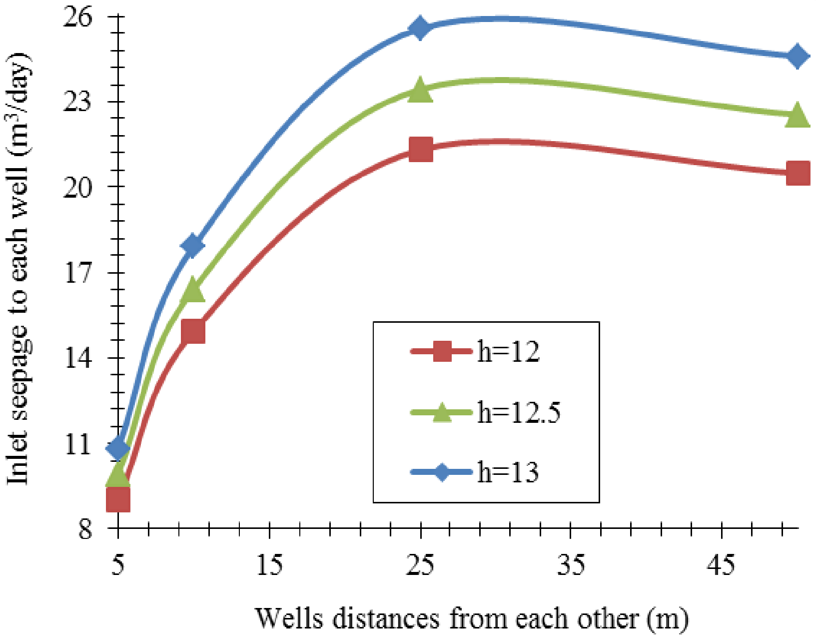

Fig. 9. Effect of upstream reservoir level on seepage flow to each well (well radius is 0.5 m).

Figure 10 shows that when the upstream reservoir level increased (25 m between wells), seepage into each well increased. For different upstream reservoir levels, inlet seepage to each well increased linearly. When the radius of the wells increased, inlet discharge to each well increased.

Total uplift pressure in the dam foundation at different upstream reservoir levels for 0.1 and 0.5 m diameter wells are shown in Figures 11 and 12, respectively. The figures show that, as upstream reservoir level increased, uplift pressure in the dam foundation decreased. As the distance between wells increased, uplift pressure increased in a parabolic manner. Increasing the distance between relief wells with small diameters at different upstream reservoir levels produced similar uplift pressures. In relief wells with large diameters (0.5 m), uplift pressure varied.

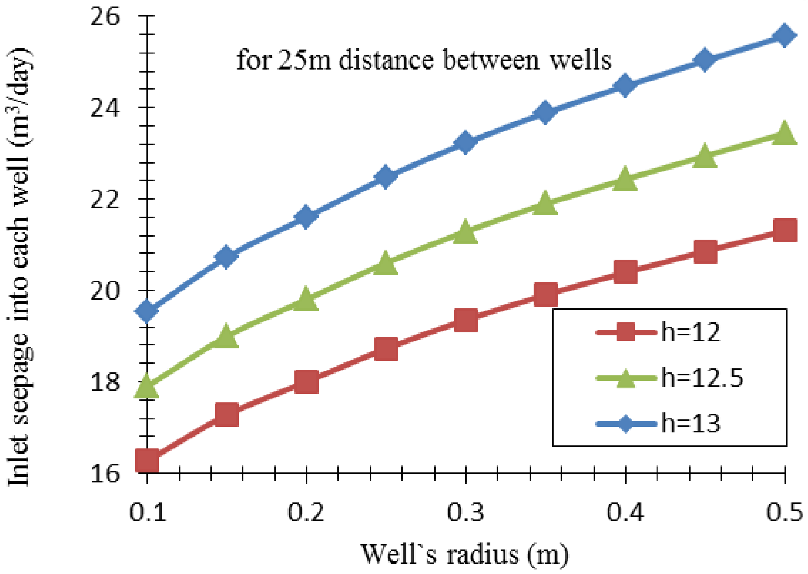

Fig. 10. Effect of upstream reservoir level on inlet seepage flow to each well (25 m distance between each other).

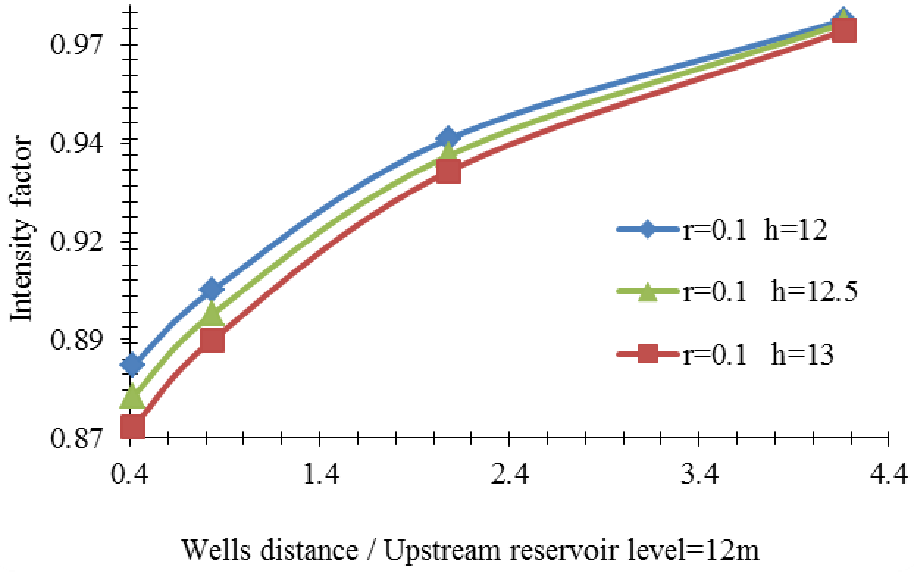

Fig. 11. Effect of upstream reservoir level on uplift pressure for a well with 0.1 m in diameter.

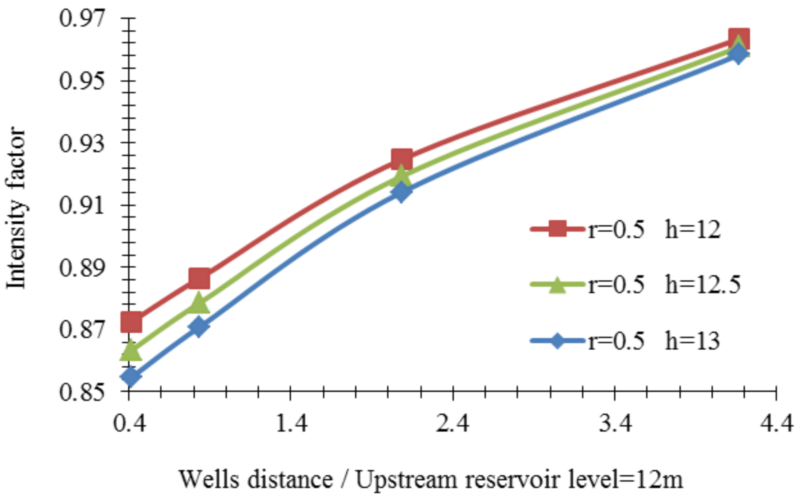

Fig. 12. Effect of upstream reservoir level on uplift pressure for a well with 0.5 m diameter.

CONCLUSIONS

Relief wells, in essence, are controlled artificial springs that decrease pressure to a safe value and prevent the removal of soil in the piping or by internal erosion. The proper design, installation, and maintenance of relief wells are essential to assuring their effectiveness and the integrity of the protected structure. The present study examined the effect of the distance and diameter of relief wells on seepage rate and uplift pressure using Seep/W software. Results showed that:

- When the distance between wells was large, the effect of well diameter on inlet discharge into each well was greater than the effect of the distance between wells.
- Maximum inlet seepage to each well occurred when the distance between wells was at a maximum.
- Increasing the well diameter or decreasing the distance between wells decreased uplift pressure. The benefit for placing wells 5 m apart to decrease uplift pressure is hydraulic and not economic.
- In zones where seepage to wells was high; the decrease in uplift was appreciable. When the upstream water head increased, inlet seepage to each well increased and uplift pressure decreased.

REFERENCES

Chen, Y., Yeh, H. and Yang, S. (2009). ”Analytical solutions for constant-flux and constant-head tests at a finite-diameter well in a wedge-shaped aquifer”, *J. Hydraululic Engineering*, 135(4), 333–337.

Davidson, G., Rigby, J., Pennington, D. and Cizdziel, J. (2013). “Elemental chemistry of sand-boil discharge used to trace variable pathways of seepage beneath levees during the 2011 Mississippi river flood”, *Applied Geochemistry*, 28(1), 62-68.

Gebhart, L.R. (1973). “Foundation seepage control option for existing dams”, American Society of Civil Engineers, *Inspections, Maintenance and Rehabilitation of Old Dams, Proceedings of Engineering Foundation Conference in Washington*, 660-674.

Geibel, N.M. (2004). “Rehabilitation of a bio-fouled pressure-relief well network, Garrison dam, North Dakota”, *Environmental and Engineering Geoscience*, 10(1), 175-183.

Geo-Studio. (2007). *User guide, Seepage modeling with SEEP/W, An engineering methodology*, Third Edition, GEO-SLOPE International Ltd.

Mansur, C., Postol, G. and Salley, J. (2000). “Performance of relief well systems along Mississippi river levees”, *Journal of Geotechnical and Geo-Environmental Engineering*, 126(8), 727–738.

Mathias, S., Butler, A. and Zhan, H. (2008). ”Approximate solutions for Forchheimer flow to a well”, *Journal of Hydraulic Engineering*, 134(9), 1318–1325.

Middlebrooks, T.A. and Jervis, W.H., (1997). “Relief wells for dams and levees”, *Journal of Hydraulic Engineering*, ASCE, 112(2), 1323-1336.

Mishra, G. and Majumdar, P. (2010). ”Unsteady solution for well recharge in a low diffusive aquifer”, *Journal of Irrigation and Drainage Engineering*, 136(12), 870–875.

Ozkan, S., Adrian, D., Sills, G. and Singh, V. (2008). Transient head development due to flood induced seepage under levees”, *Journal of Geotechnical and Geo-Environmental Engineering*, 134(6), 781-789.

Parks, S.A., (2012). *Seepage and stability of a dam in an artesian setting*, M.Sc. Thesis, Graduate College at the University of Nebraska.

Patel, H., Eldho, T. and Rastogi, A., (2010). ”Simulation of radial collector well in shallow alluvial riverbed aquifer using analytic element method”, *Journal of Irrigation and Drainage Engineering*, 136(2), 107–119.

Salama, R., Ali, R., Pollock, D., Rutherford, J. and Baker, V. (2003). *Management and structure review*, Department of Environmental Protection, A Report to Water and Rivers Commission, Minister for Environment, Western Australia.

USACE, US Army Corps of Engineers. (1992). *Design, construction, and maintenance of relief wells*, Washington, D.C., 20314-1000, EM11102-1914. 29.

Van Der Heijde, P.K., Huyakorn, P.S. and Merecer, J.W., (1984). “Testing and validation of groundwater models”, *Proceedings of Practical Application of Groundwater Modeling,* NWWA/IGWMC Conference, Columbus, OH, USA.

Vashisht, A. and Shakya, S., (2013). ”Hydraulics of a drainage well fully penetrating a leaky aquifer through a multisection screen”, *Journal of Hydraulic Engineering*, 139(12), 1258–1264.

Woyshner, M.R. and Yanful, E.K., (1995). “Modeling and field measurements of water percolation through an experimental soil cover on mine tailings”, *Canadian Geotechnical Journal*, 32(1), 601-609.

Yang, S., Huang, C., Liu, C. and Yeh, H. (2014). ”Approximate solution for a transient hydraulic head distribution induced by a constant-head test at a partially penetrating well in a two-zone confined aquifer”, *Journal of Hydraulic Engineering*, 140(7), 401-403.