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Design Method for a Finite Line of Fully Penetrating Relief Wells

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ABSTRACT

A line of relief wells having finite length may be installed to provide underseepage control at isolated features along a flood control structure. If infinite line solutions are applied to design a finite system, then seepage flow around the end of a finite well line can result in significant design errors due to increased and variable mid-well uplift pressures and discharges associated with the finite system. Finite well line effects are complicated relative to the infinite case by additional variables for system length and boundary distances. This paper presents a graphical method, developed through finite element modeling, for the design of a finite line of fully penetrating relief wells. The method can improve understanding of finite line performance and allows accounting of discrepancies between finite and infinite designs. The new design charts can be used to compare finite versus infinite well line uplift pressures and to select a proper finite well line design length.

INTRODUCTION

Relief well systems have been studied and used by the U.S. Army Corps of Engineers (USACE) since the 1930s to reduce uplift pressures and the risk of subsurface internal erosion in pervious foundations along flood control structures. When a line of wells terminates with impervious end boundaries (e.g. at bedrock valley walls that abut a dam) or it is so long that there are no end effects at a location of interest it can be considered as having infinite length. This assumes the pervious foundation depth and hydraulic conductivity are uniform, and the effective seepage entrance and exit are parallel to the line of wells. In this case, flow is overall perpendicular to the well line, pressure distribution is identical for all the wells, and the system can be mathematically analyzed as an infinite line of wells. In practice, a limited line of wells may be used to provide seepage control at pumping stations, outlet structures, or other isolated features or reaches of dam or levee. In such cases, the seepage source and pervious foundation can extend far beyond the end of the well line, and this must be accounted for to avoid serious design errors (Bennett and Barron 1957; Guy et al. 2014). For a finite line of relief wells, flow non-perpendicular to the line occurs, head along the line and discharge are non-uniform, and both can exceed expectations of an infinite case. This can also occur if well penetration or spacing changes significantly along the line. This complexity of non-uniformity has limited the development of design curves for finite relief well lines to date, whereas this has been accomplished for infinite lines.

Infinite well lines. USACE (1992) summarizes an analytical design method for infinite well lines, based on the Blanket Theory system of closed-form solutions for computing underseepage flows and pressure (USACE 1956, 2000; Brandon et al. 2018). The approach solves for the well spacing, penetration, and discharge required to achieve the allowable uplift (measured as excess head) landward of the structure. The USACE (1992) equations require

inputs of average and mid-well uplift factors (θ_{av} and θ_m), which adjusts heads and flows along a well line relative to a slot or trench. The origin, historical evolution, and accuracy of these uplift factors were studied in Keffer et al. (2019). Several methods for estimating the uplift factors exist and yield practically similar results, but the nomogram design chart found in USACE (1955, 1956) has commonly been used. The nomogram in USACE (1992) is missing the required pole point (a critical component for its use), and in Keffer and Guy (2021) another design nomogram is presented. Figure 1 includes the full penetration portion of this nomogram. The uplift factors which the nomograms yield are calculated by and allow for an infinite line to be characterized based on three dimensionless ratios: a/r_w , D/a , and W/D . These ratios are defined as well spacing (a) to effective well radius (r_w), pervious foundation (i.e. aquifer) depth (D) to well spacing, and well depth (W) to foundation depth (i.e. penetration). This method assumes the effective penetration into a homogeneous, isotropic foundation. In a stratified aquifer, the effective foundation depth should be determined by transforming each of the strata into a single isotropic stratum. Then the well penetration should be calculated as a percentage of the total transmissivity of the transformed foundation, as described in USACE (1992). The nomogram provides uplift factors independently of entrance and exit distances, and these distances are considered by equations which use the uplift factors to compute infinite line (illustrated in Figure 2A) heads and discharge.

Finite well lines. While the importance of finite well line effects, as illustrated in Figure 2B, has been recognized, historical research and literature have been limited. USACE (1956, 1992) includes a chart to compare infinite line mid-well excess head (h_m) to the excess head at the center of a finite line (h_{m-mid}), measured along the well line. This chart was not intended to be comprehensive for system design as it includes only a limited range of relevant parameters and insufficient information for practical application. Bennett and Barron (1957) briefly described the study of electric analog models, which were supplemented by analytical computations. Limited past test results have included well discharge measured along infinite and finite lines, but insufficient information exists to verify the results or use them for design. USACE (1963) was intended as design guidance for computing well discharge and mid-well pressures along a finite line. Decreasing well spacing at the end of the well line to obtain heads similar to the center of line is also discussed. There is no design guidance for estimation of heads landward of a finite line, which will often govern the design, and its use in practice has been limited due to the fact that it contains hundreds of data tables that require extensive plotting and interpolation. Sharma (1974) developed analytical expressions for various arrays of relief wells and boundary conditions. This included a finite number of wells in a linear array and parallel to an infinite line source (i.e. finite well line). There were no example results for verification of these finite line formulas. These formulas compute pressure at the well, but not landward of a finite line.

For finite well lines, the problem cannot be simplified to the extent that the infinite case can. To define the system characteristics and compute heads and discharge, the individual entrance and exit distances (S and x_3 , respectively) and length of the well line (L_w) must be considered in addition to the nomogram parameters (USACE 1963). These problems can be evaluated in different ways using image well theory or numerical modeling such as finite element (FE) method, but a design curves-based approach does not currently exist.

Purpose. The purpose of this paper is to present an initial practical method for the design of full penetration finite-length relief well systems that was developed through research into the

history of well system design and numerical modeling. Design of finite well lines is complicated by the need to consider variables that are not included or have different effects than in infinite line design. The FE method was used to perform simulations to find the variables which need to be included in finite well systems analysis. Design data and a method for determining the length of a finite line of fully penetrating, uniformly spaced relief wells to achieve acceptable head are presented. A series of practical design charts was developed to modify an infinite well line design for system length. This provides a means to estimate excess head along and landward of a finite well line and evaluate it with respect to allowable values. The scope of this paper is limited to full penetration wells. However, many systems contain partial penetration wells due to economic or geologic constraints, so they should be considered in a future paper.

MODELING APPROACH FOR FINITE WELL LINES

Analysis of a finite well line is more complex than an infinite line due to the non-uniform flows and heads, as described above. To develop a practical graphical design method, the effects of several parameters on head and discharge were considered. FE models were used to determine the sensitivity of the model to these factors, and many simulations were performed to cover a range of values useful to practitioners, in terms of the average uplift factor and distance to boundary conditions. The resulting data were analyzed so that behavior and trends among L_w , θ_{av} , S , x_3 , and head ratios (finite versus infinite line) could be identified. The data were formatted into relatively simple charts that can be utilized by practitioners for a range of design scenarios.

Parameter selection. Blanket Theory equations for computing excess head and discharge for an infinite system (Equations 7-6, 7-7, 7-9, and 7-10 in USACE (1992)), include net hydraulic gradient towards the well system (ΔM), θ_{av} , and θ_m . Note that USACE (1992) Equations 7-2, 7-4, and 7-8 are in error, and corrected forms are in Keffer and Guy (2021). ΔM is defined by the net hydraulic loading on the levee (H), S , x_3 , and average net head in the plane of the wells (h_{av}). As h_{av} is a concept that only applies to infinite well lines, this study considered the effect of distances from finite well lines to the boundaries in terms of both S and x_3 rather than ΔM . The USACE (1955, 1956) nomogram for determining θ_{av} and θ_m accounts for the effects of well system geometry independently of the exterior boundary conditions that cause flow through the system (Keffer and Guy 2021), and requires inputs of a , r_w , W , and D . Since this study focused on fully penetrating relief wells ($W/D = 100\%$), the nomogram returns a unique value of θ_m for each value of θ_{av} . This is not true for partially penetrating wells because variations in W/D or D/a can result in different uplift factors for the same value of a/r_w . This allowed for infinite and finite well system performance to be evaluated in terms of θ_{av} . For each combination of these parameters and resulting infinite line h_m , the effect of L_w was studied.

Modeling methodology. To evaluate the effects of finite line length on excess head and discharge for fully penetrating ($W/D = 100\%$) relief wells, the authors constructed experiments with a series of numerical models. The FE method was used in the software GeoStudio Seep/W 2020 version 10.2.1.19666 ("GeoStudio" 2020). For verification of the more time-efficient plan view Seep/W models, Rocscience RS3 version 4.004 ("Rocscience Inc." 2021) was used to build a limited number of three-dimensional FE models.

Key input variables in the models included a , r_w , W , D , S , and x_3 . A practical chart-based design approach is not feasible with six input variables. Bennett and Barron (1957) suggest that

the average uplift factor may apply to both infinite and finite systems. Therefore, θ_{av} (defined by a/r_w , W/D and D/a in Figure 1) was used as an intervening variable. This reduces the problem to four inputs: θ_{av} , S , x_3 , and L_w . $\theta_{av} = 0.18, 0.44,$ and 0.81 were used for this study to cover the practical range of a/r_w (20, 100, and 1,000 respectively) for well systems where $W/D = 100\%$. Results for fully penetrating wells were not sensitive to changes in nomogram parameter D/a , which can be inferred from Figure 1, so $D/a = 1$ was used. S and x_3 were varied from 100 ft to 2,500 ft as representative of a typical and wide range of practical situations. L_w was increased from a to as much as 10,000 ft, but trends could be sufficiently defined more typically at 1,500 ft where changes in excess head ratios tended to lessen.

Total head hydraulic boundary conditions for the source (pool), exit (tailwater), and relief well (assuming no losses/inefficiency) were set at 100 ft, 80 ft, and 80 ft, respectively for a net hydraulic loading on the levee and well system of $H = 20$ ft. The top face of the model (i.e. ground surface) represented an impervious soil blanket with a no-flow boundary. This study is focused on the ratio of finite to infinite system results, so results can be applied to sites with different hydraulic boundary conditions and soil properties. This is logical when one considers a flow net: If boundary conditions change, equipotential lines change in value but not appearance/location. When hydraulic conductivity of the soil changes, system discharge changes proportionally, but equipotential lines are not affected. Therefore, since this paper is concerned with ratios of the equipotential line values for finite to infinite systems, the design curves contained herein can be used for any infinite line solution and head conditions. Irrespective of head values computed for an infinite solution, ratios are used to increase them for a finite case.

Infinite well lines were modeled by placing impervious boundaries on both sides of the well, perpendicular to the well line and source/exit boundaries (parallel to overall flow direction) at a distance equal to $a/2$ (Figure 2A). This represents a well line that is mirrored infinitely about the impervious boundaries (a “mirrored solution”). Infinite line models were calibrated to Blanket Theory results which were computed using a computer program first published in Guy et al. (2010). The infinite line model was used to create each initial finite line model by extending one of the impervious boundaries (an orange boundary in Figure 2B) far enough away to capture full three-dimensional effects of the semi-infinite aquifer (i.e. an infinite boundary that doesn’t affect model results). The opposite impervious boundary is at $a/2$ from the well to represent the center of a finite line that is mirrored once about that boundary. Only half of the finite well line length ($L_w/2$) is modeled (Figure 2B). Mirrored solutions reduce file size and computing time while yielding identical results as a full-length model. L_w is increased by adding wells parallel to the line source at spacing a .

Figure 2 shows a plan view model of an example levee case in infinite (Figure 2A) and finite (Figure 2B) well line scenarios. Relief wells are located along the landside levee toe. The pervious aquifer soil in this study has isotropic hydraulic conductivity $k_f = 100$ ft/day. S and x_3 are determined with piezometer measurements or calculated with Appendix B of USACE (1992). As mentioned above for total head boundary conditions, this paper can be applied to cases with different foundation hydraulic conductivity and depth.

A graded mesh was used, which adjusts element size based on geometric complexity. Essentially, most of the model contained simple aquifer geometry where relatively large elements could be used to reduce file size and computing time. An area of a finer, uniform mesh was applied to an area surrounding the well line to provide adequate resolution for the curvilinear head contours near the wells and enhance calibration to Blanket Theory.

Measurement of results. Excess head results were extracted from the models with total head measurement lines along the top of the model (i.e. top of the aquifer). Ground surface/tailwater elevation (equal in these models to the line exit) was subtracted from the total head measurement to calculate excess heads midway between wells in an infinite line (h_m), at the center of the finite line (h_{m-mid}), and midway between the end wells in the finite line (h_{m-end}). Blanket Theory considers head landward of an infinite well line with the concept of average head in the well line (h_{av}), as defined in USACE (1992). As h_{av} only applies to infinite lines, new terms are presented to consider landward heads. Maximum excess head landward of the wells was also measured perpendicular to the well line from the locations of h_{m-mid} and h_{m-end} along Figure 2B, Sections Y-Y' and Z-Z' (annotated as h_{d-mid} and h_{d-end} , respectively). The distances of h_{d-mid} and h_{d-end} landward of the well line varied. Comparing total head contours between Figures 2A and 2B illustrates how excess head increases as the system changes from infinite to finite, and landward head can exceed in-line head. Figure 3 shows example excess head profiles from measurements along (Figure 3A) and normal to (Figure 3B) well lines.

Notation with lower-case “ h ” used for excess head have been corrected for well losses, H_w (well efficiency and elevation losses). Since H_w is assumed to equal zero in this study, these symbols are interchangeable with upper-case “ H ” notation found in literature (e.g. H_w is added to h_m to get H_m in USACE (1992)). H_w is partially based on well discharge, so it would be different for each well in a finite line because excess heads, and therefore well discharges, are non-uniform. For a finite well system, an initial estimate of this hydraulic head loss component of H_w can be made utilizing the average well discharge of the system (Q_{w-avg}). A method for estimating Q_{w-avg} is presented and discussed below.

Models were calibrated to Blanket Theory results for h_m and single well discharge (Q_w) before use in finite line cases. Calibration was generally within 5% for h_m and 3% for Q_w . FEM was calibrated to Blanket Theory Q_w to further ensure model accuracy and representation of the same conditions. Although h_m of full penetration well systems is not sensitive to k_f and D , Q_w is affected by these model parameters. Q_w was measured in FEM with two methods for verification: the difference in model flow was taken adjacent to source and exit model boundaries, and flow directly into the well geometry.

RESULTS AND DISCUSSION

Model results for $\theta_{av} = 0.44$ (determined with Figure 1 or the referenced full nomogram) are plotted on Figures 4 and 5 to illustrate the relationship between the various excess head values and ratios. Design charts (Figures 6 through 8) also include $\theta_{av} = 0.18$ and 0.81 to describe finite system behavior at the lower and upper limits of the nomogram as described above. For each series of models, the four excess head measurements referenced above (h_{m-mid} , h_{m-end} , h_{d-mid} , and h_{d-end}) were recorded. h_m and Q_w were computed for an otherwise identical infinite well line with Equations 1 and 2 (USACE 1992; Keffer et al. 2019). Then, these measurements were used to calculate four ratios ($h_{m-mid-ratio}$, $h_{m-end-ratio}$, $h_{d-mid-ratio}$, $h_{d-end-ratio}$) with Equations 3 through 6. Net seepage gradient toward an infinite well line (ΔM) is defined by Equation 7-6 of USACE (1992).

$$h_m = a(\Delta M)(\theta_m) \quad \text{Eqn. 1}$$

$$Q_w = a(\Delta M)(k_f)(D) \quad \text{Eqn. 2}$$

$$h_{m-mid-ratio} = \frac{h_{m-mid}}{h_m} \quad \text{Eqn. 3}$$

$$h_{m-end-ratio} = \frac{h_{m-end}}{h_m} \quad \text{Eqn. 4}$$

$$h_{d-mid-ratio} = \frac{h_{d-mid}}{h_m} \quad \text{Eqn. 5}$$

$$h_{d-end-ratio} = \frac{h_{d-end}}{h_m} \quad \text{Eqn. 6}$$

Uplift factor as intervening variable. The six primary input variables were reduced to four by use of the USACE (1955, 1956) nomogram design chart to calculate θ_{av} , which accounts for effects of several key parameters with a/r_w , W/D , and D/a . This was possible through testing which indicated Equations 3 through 6 were sensitive to θ_{av} instead of nomogram inputs. Figures 6 through 8 show that θ_{av} has an overall negative relationship with the uplift ratios. Further investigation showed there is limited sensitivity to well spacing. As a and r_w were changed while maintaining constant a/r_w , the excess head ratios (Equations 3 through 6) increased as a decreased. This can be explained by the Blanket Theory equations for h_m (Equation 1, or Equations 4 and 8 of Keffer et al. (2019), which are corrected forms of equations from USACE (1992)) where a is included as a standalone input variable (i.e. outside of θ_{av}), and h_m increases as a increases. To capture maximum excess head ratios, a practical minimum a for each value of θ_{av} (and therefore a/r_w) was used based on diminishing effect on the ratios and realistic r_w values.

Effect of boundary distances. Distances from the well line to the source and exit boundaries (S and x_3 , respectively) were studied to determine trends in how variation of these parameters affected finite line head ratios. Model results (Figures 4 and 5) show that h_{m-mid} , h_{m-end} , h_{d-mid} , and h_{d-end} responds to S and x_3 as expected according to Equations 7-6 and 7-9 of USACE (1992), which includes ΔM . As S and x_3 increases (i.e. source and exit move away from well line), $h_{m-mid-ratio}$, $h_{m-end-ratio}$, $h_{d-mid-ratio}$, and $h_{d-end-ratio}$ increase. If S and x_3 are changed such that ΔM is constant, head ratios still change (this would not cause change in h_m), so they must be considered individually. Figures 4, 6, and 7 show that $h_{m-mid-ratio}$ and $h_{m-end-ratio}$ are equally sensitive to S and x_3 . In-line head ratios are similar for scenarios with opposing values of S and x_3 (e.g. $S = 2,500$ ft, $x_3 = 1,200$ ft and $S = 1,200$ ft, $x_3 = 2,500$ ft).

Design charts. Behavior of model results allowed for the creation of design charts (Figures 6 through 8) by fitting trendlines to the data. The relationship between L_w and excess head ratios was defined by either a logarithmic or power trendline for each model series of θ_{av} , S , and x_3 . Landward maximum ratios ($h_{d-mid-ratio}$ and $h_{d-end-ratio}$) yielded practically similar values, so Figure 8 includes the maximum of these ratios ($h_{d-ratio}$) for use in design. Practical maximum values for the vertical axes were selected for Figures 7 and 8. While this truncates some of the data for $h_{m-end-ratio}$ and $h_{d-ratio}$ (outside of the range needed for a feasible well system design), legibility of the design curves is enhanced. Only the maximum and minimum set of curves are

shown for $\theta_{av} = 0.81$ in Figure 8. This is to improve clarity and preserve the vertical axes for all the plots, while providing adequate resolution for a designer to use and be able to infer that the omitted curves would return lower h_d -ratios than the displayed maximum values.

Relief well discharge. Well discharge needs to be considered as it contributes to actual system performance (e.g. through H_w described above), and well systems sometimes discharge into a collector pipe (as opposed to the ground surface). This collector must be sized appropriately to ensure water in the well housing doesn't backup and flood above the well riser. This would increase elevation head loss (i.e. effective well riser elevation in calculations), decrease well discharge, and thereby increase excess head. Since discharge among wells is non-uniform in a finite system, there is not a single discharge value that can be calculated, as with infinite systems (Q_w). As expected, due to an increase in head towards the end of a finite line, well discharge also increases.

Model results were used to study finite line effects on flows, after being normalized to H . The ratio of discharge from a well in an infinite line (Q_w/H) to average well discharge for finite well lines (Q_{w-avg}/H) was measured. Since both Q_w and Q_{w-avg} were proportional to excess head along a well line, the head ratios were found to be useful for estimating Q_{w-avg} . The average of $h_{m-mid-ratio}$ and $h_{m-end-ratio}$ (Figures 6 and 7) is approximate to the ratio of Q_{w-avg}/H to Q_w/H for a given finite well system. Therefore, Q_{w-avg} can be estimated by multiplying infinite line Q_w by the average of $h_{m-mid-ratio}$ and $h_{m-end-ratio}$. This relationship is only an approximation because it estimates the average flow from all the wells in a finite line (where flow is non-uniform). This is a quick, practical flow estimation method. It slightly overestimates Q_{w-avg} because Q_w is based on h_{av} for infinite lines (USACE 1992). However, this method is based on h_m which exceeds h_{av} for full penetration systems. For example, Q_{w-avg} may be overestimated by as much as 20% for $\theta_{av} = 0.18$ and 10% for $\theta_{av} = 0.44$ when $L_w < 1,000$ ft, but a more typical overestimation is from 5% to 10%. This estimation should be limited to cases when $L_w < 1,000$ ft due to a divergence (i.e. more significant overestimation) between the estimated and measured values for longer systems.

Example design of finite well line. A levee example will be used for a brief demonstration of design chart usage. Key input variables are summarized here: $H = 20$ ft, $a = 50$ ft, $a/r_w = 100$, $D/a = 1$, $W/D = 100\%$, $k_f = 100$ ft/day, $S = 1,200$ ft, $x_3 = 1,200$ ft, and $L_w = 250$ ft. $\theta_{av} = 0.44$ and $\theta_m = 0.55$ can then be calculated with Figure 1 or the full nomogram referenced above. First, the well line is analyzed as an infinite system (Figure 2A) with the Blanket Theory approach (USACE 1992; Guy et al. 2010). Calculations result in $h_m = 0.44$ ft (Equation 1), $h_{av} = 0.35$ ft (Equation 2 or 7 of Keffer et al. (2019)), $\Delta M = 0.016$, and $Q_w = 21$ gallons per minute (gpm; Equation 2). Head values can be adjusted for L_w with design plots in Figures 6 through 8, where the following ratios to h_m are obtained: $h_{m-mid-ratio} = 3.0$, $h_{m-end-ratio} = 3.8$, and $h_d-ratio = 7.3$. Multiplying these ratios by h_m yields excess uplift heads of: $h_{m-mid} = 1.3$ ft, $h_{m-end} = 1.7$ ft, and $h_d = 3.2$ ft. Excess head profiles for this example scenario are illustrated in Figures 3, 4, and 5 (with stars on Figures 1, 4, and 5). In practice, excess head is evaluated against an allowable value based on depth and unit weight of the landside confining top strata at the location of interest. Input parameters for further design iterations could then be adjusted to obtain allowable results. Average well discharge in the finite system is estimated by multiplying the average of $h_{m-mid-ratio}$ and $h_{m-end-ratio}$ by Q_w . $Q_w = 21$ gpm and the average of the in-line ratios is 3.4, so multiplying them yields $Q_{w-avg} = 71$ gpm. This can be used for initial estimates of well losses and collector system size. A final design could use FE models to measure exact flows and losses.

A plan view head contour plot such as in Figure 2B could be utilized by the practitioner to aid in understanding the excess head values estimated by Figures 6 through 8. Total head contours for several wells in an infinite line would be sketched based on boundary conditions and the Blanket Theory-derived h_m . Next, wells would be deleted until system length is equal to the L_w under consideration. Figures 6 through 8 can then yield factors that are multiplied by h_m to generate new head values of h_{m-mid} , h_{m-end} , and h_d . These are new point values of excess head that can be used to modify the total head contours. Similarly, head profiles such as those in Figure 3 could be labeled with these head values for the designer to better visualize these new values.

To analyze a problem with S or x_3 values different from those plotted herein, the nearest conservative curve or linear forecasting could be used. Figure 1 shows the range of potential uplift factors for full penetration relief well systems. Currently, Figures 6 through 8 could be used to estimate head ratios for full penetration uplift factors other than those shown by using the nearest curve that would yield conservative ratios or linear forecasting between the three provided values. The choice of ratio(s) (Equations 3 through 6 or Figures 6 through 8) to be considered should be based on project-specific goals such as the performance of an isolated location of low ground elevation at a levee pumping station (Guy et al. 2017) or outlet structure (USACE 1992). Whereas, if the ground surface landward of a pumping station doesn't rise to provide increased uplift resistance, hd -ratio may be a concern.

CONCLUSIONS

Finite well line design is complicated by four variables that affect performance differently compared to infinite line design. The authors used the FE method to conduct simulations which determined that infinite system design could be modified for finite well lines of length L_w with these four variables: θ_{av} , S , x_3 , and L_w . An extensive series of models was used to define a practical range of values for uplift factors and boundary distances for full penetration well systems. The array of model data was used to identify behavior of finite well systems and their performance relative to an infinite system. A series of practical design charts was developed that can modify an infinite well line design to account for system length. This paper also extends the practice to cover head landward of the well line, which can govern design.

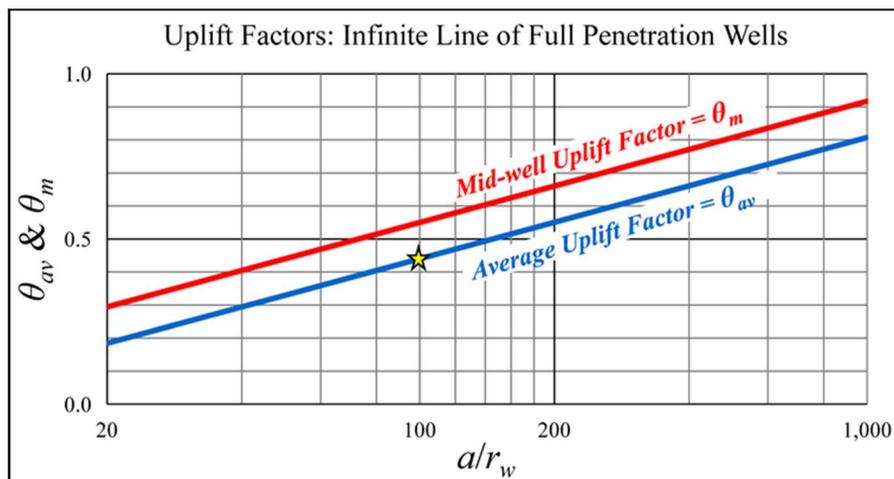


Figure 1. Nomogram results extracted for $W/D = 100\%$ (Muskat 1937; USACE 1955, 1956; Keffer and Guy 2021) and any D/a . Yellow star indicates the value used in the example.

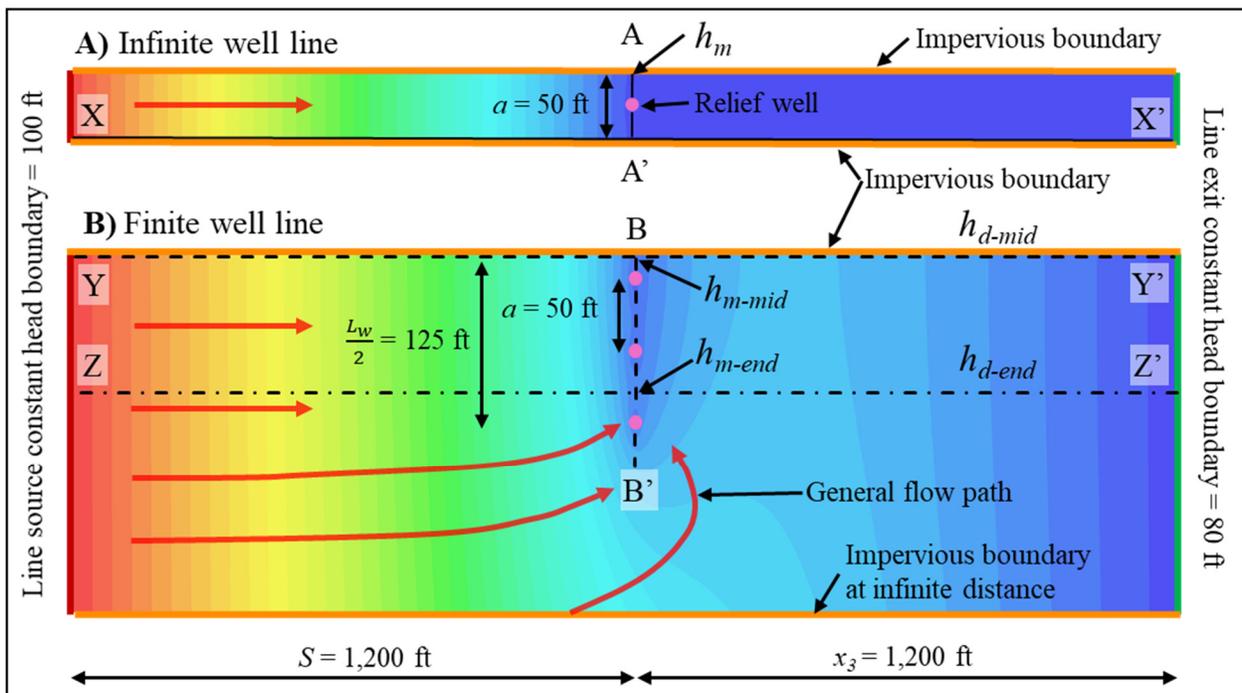


Figure 2. Plan view of FE model with head contours in the levee foundation. Key variables and example problem values for a fully penetrating relief well system are shown. Head measurements for finite lines were taken along the dashed lines. Scenarios include: A) infinite line of wells (infinitely-mirrored solution); B) finite line of wells (once-mirrored solution) of length L_w .

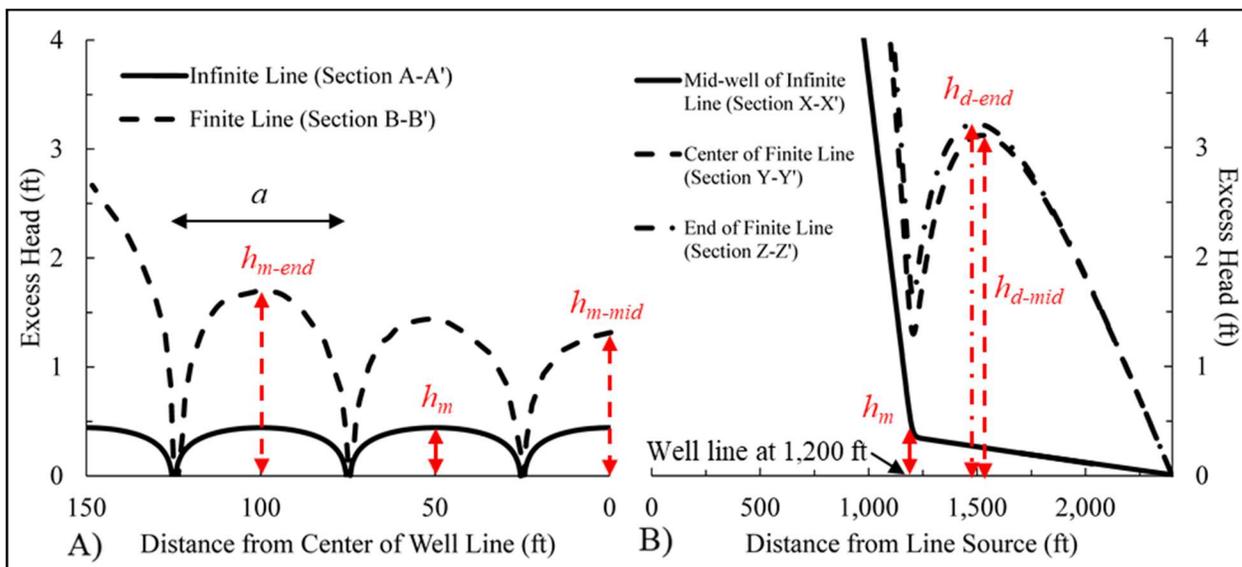


Figure 3. A) Profiles of excess head along infinite (solid) and finite (dashed) well lines. B) Profiles of excess head midway between wells at the center and end of lines. Charts were made with data from Figure 1.

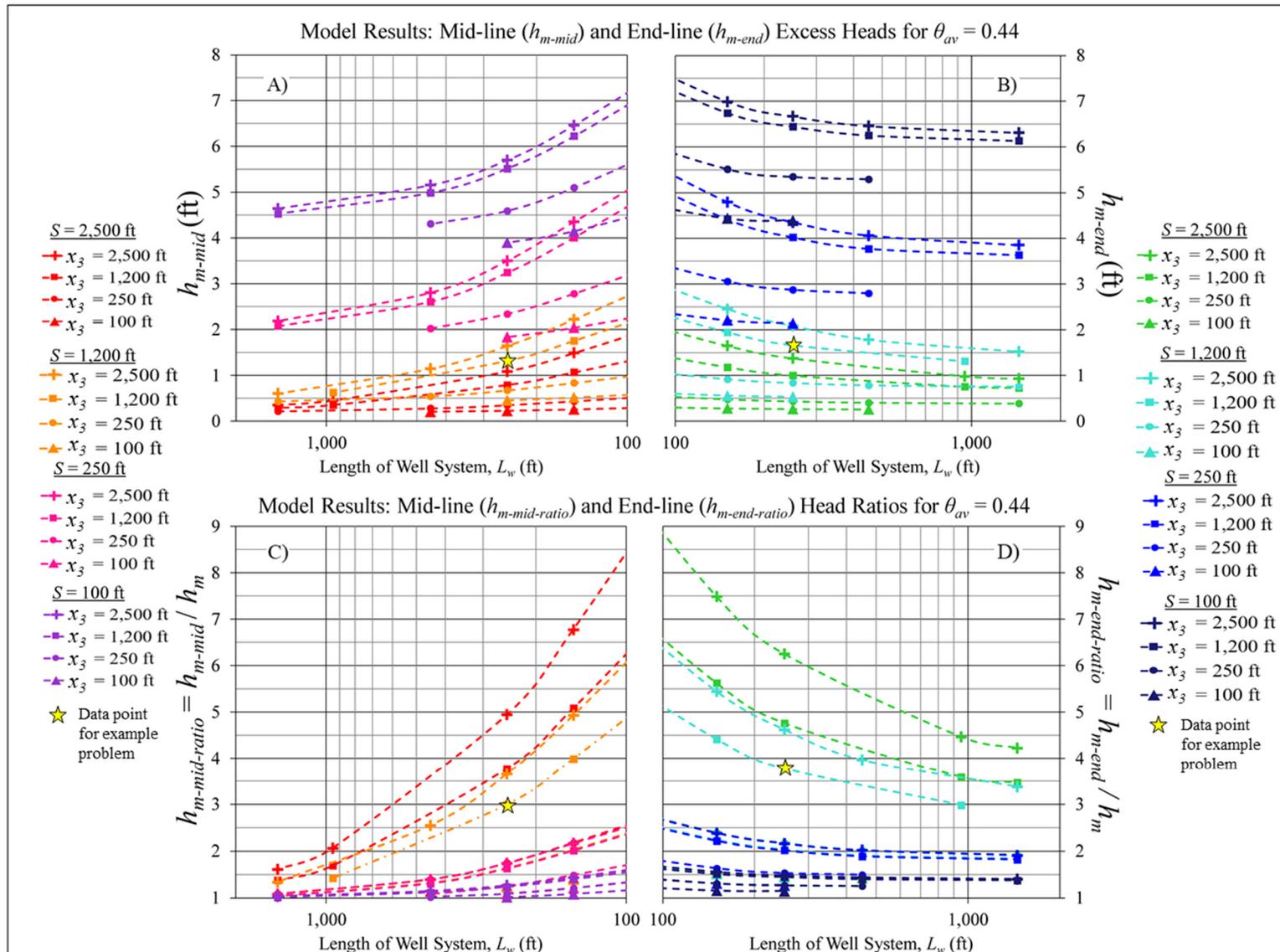


Figure 4. Finite well line model results for: A) h_{m-mid} , B) h_{m-end} , C) $h_{m-mid-ratio}$, and D) $h_{m-end-ratio}$ when $\theta_{av} = 0.44$. A) and B) are specific to the example scenario (where $h_m = 0.44$ ft), but C) and D) apply to any choice of model inputs for $\theta_{av} = 0.44$ and L_w .

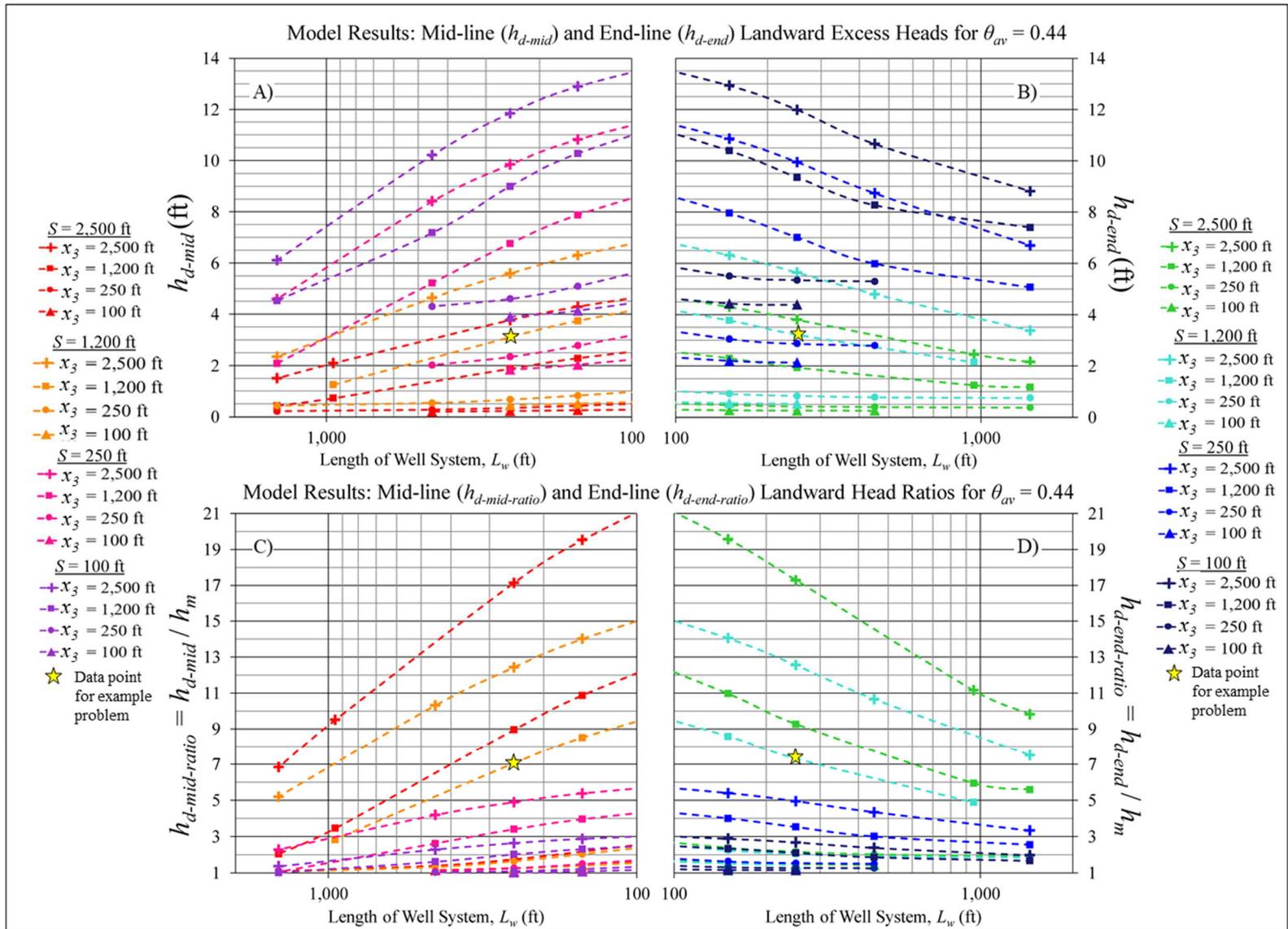


Figure 5. Finite well line model results for: A) h_{d-mid} , B) h_{d-end} , C) $h_{d-mid-ratio}$, and D) $h_{d-end-ratio}$ when $\theta_{av} = 0.44$. A) and B) are specific to the example scenario (where $h_m = 0.44$ ft), but C) and D) apply to any choice of model inputs for $\theta_{av} = 0.44$ and L_w .

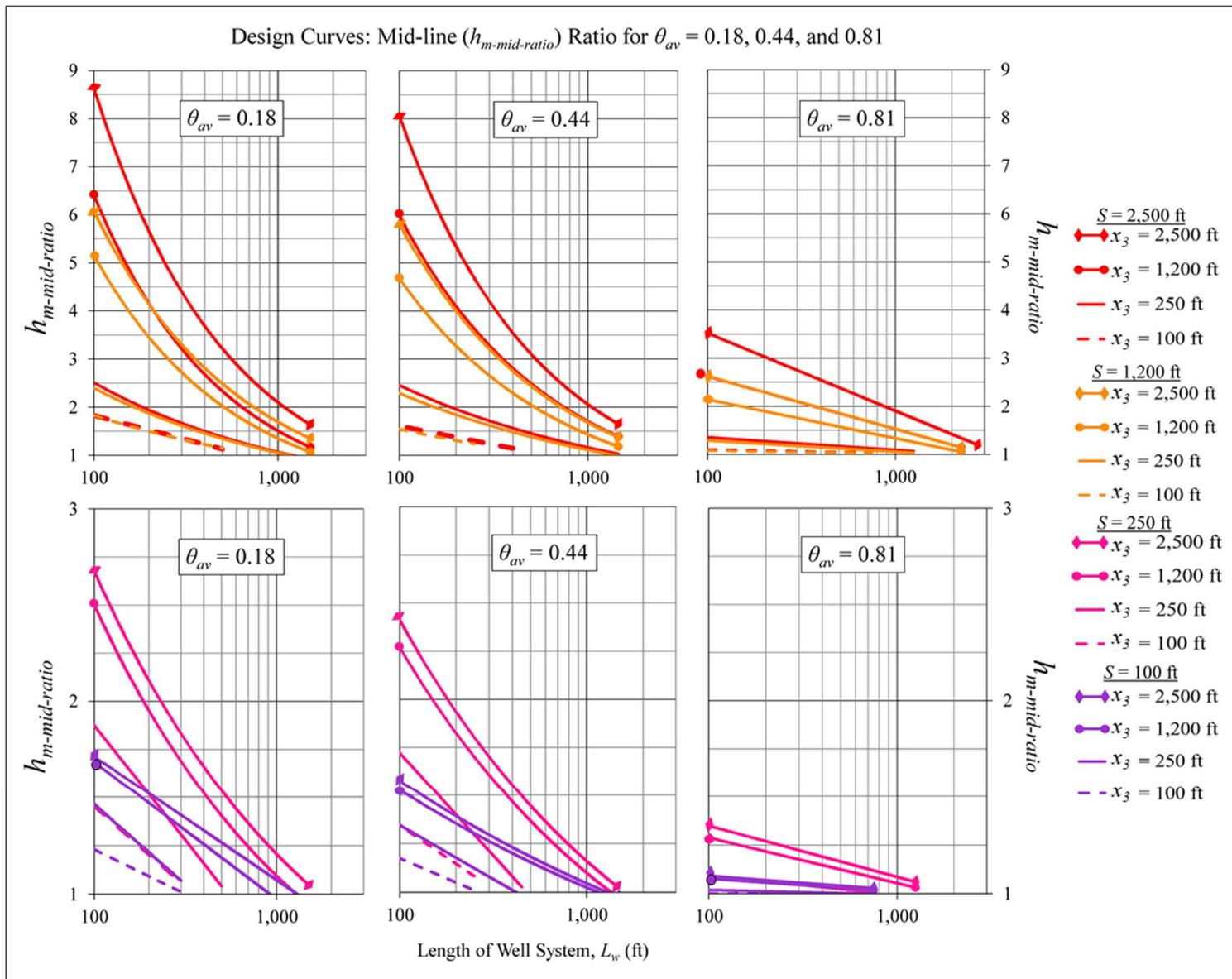


Figure 6. Design curves for $h_{m-mid-ratio} = h_{m-mid}/h_m$.

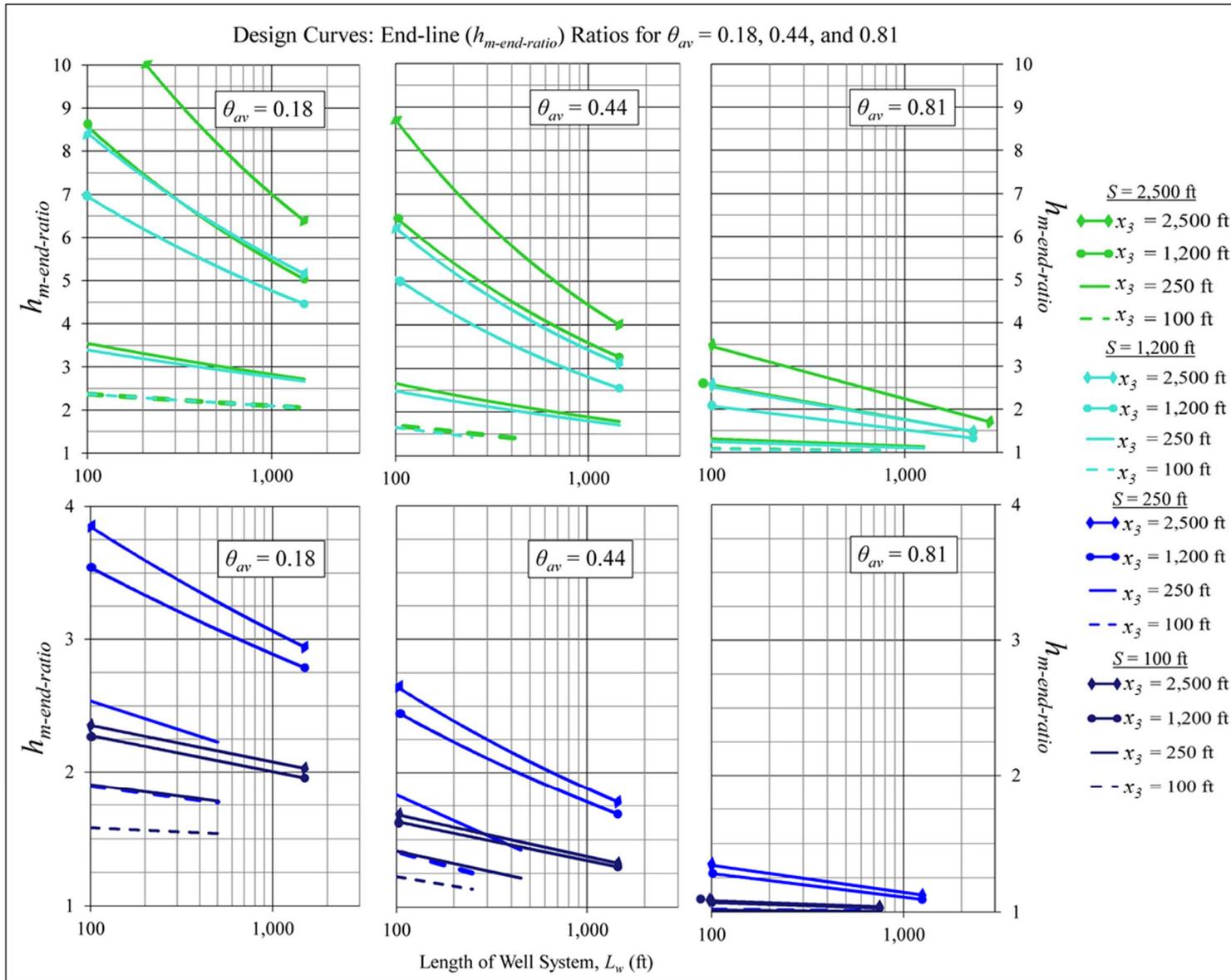


Figure 7. Design curves for $h_{m-end-ratio} = h_{m-end} / h_m$.

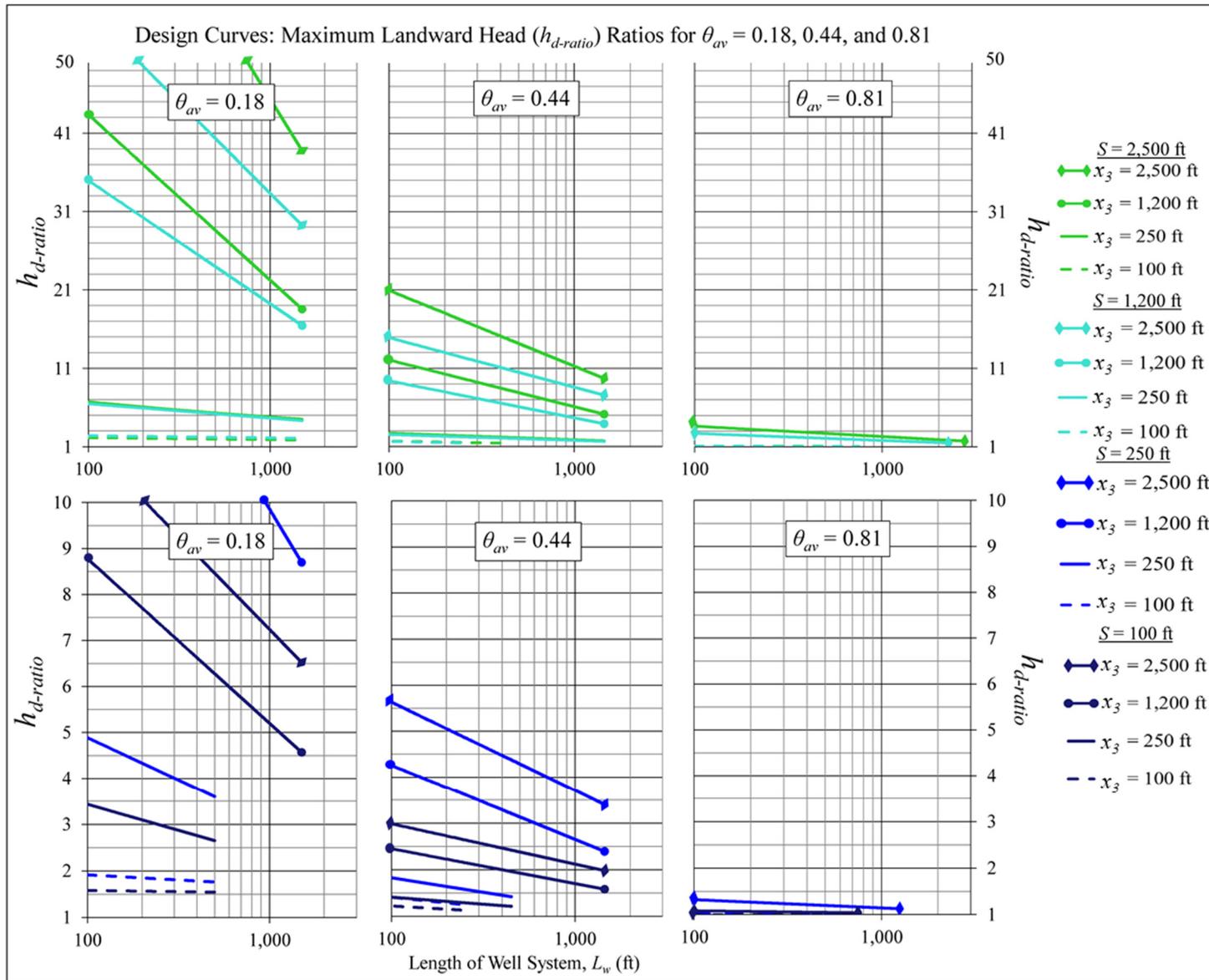


Figure 8. Design curves for $h_{d-ratio}$ (greater of h_{d-mid} and h_{d-end} divided by h_m).

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