# Chapter 7
# Design Of Well Systems

## 7-1. General Approach

The design of relief well systems consists essentially of determining the location and penetration of wells that will reduce the piezometric surface of the substratum pressure, $h_o$, in landside or downstream areas to an allowable head, $h_a$. Analyses are made using formulas presented in Chapter 4 and 5. Where wells are required along the toe of a levee or dam, the wells will generally be located along a line so that their locations are defined by a well spacing. The well spacing is first determined assuming an infinitely long line of wells, and then the spacing is reduced where necessary to allow for the reduced efficiency of a finite number of wells compared to the infinite number. For given boundary conditions and the same allowable head, there are any number of combinations of well spacing and penetration that will suffice. The final selected spacing and penetration should be based to a great extent on the most economical design. The presence of natural topographic features may require adjustment in the design well spacing to ensure that well outlets are located at the lowest practical elevation.

## 7-2. Design Heads

The design of relief well systems for dams are based on steady state conditions which would prevail with the reservoir pool at the maximum design level. This reservoir pool normally is taken as the top of the surcharge pool. The design net head is the difference between the latter elevation and downstream tailwater elevation, usually taken as downstream ground surface or lower, if appropriate. In the case of relief well design for levees, the design net head is usually taken as the difference in elevation between net grade of the levee and tailwater.

## 7-3. Boundary Conditions

Boundary conditions which must be determined include the distance to the effective source of seepage entry, $S$; the distance from the line of relief wells to the effective seepage exit, $x_3$; and the distance to a blocked exit, $L_B$, if such exists. Procedures for the determination of these values are given in Appendix B.

## 7-4. Design Procedures

Direct application of the formulas in Chapter 4 and 5 is not possible as they are based on the assumption that the hydraulic head losses in the well are zero. As shown in Figure 5-4, the head losses must be determined on the basis of the computed well flow and added to the maximum landside head with wells, which in turn would result in a lower factor of safety with respect to uplift. If the tops of the well risers extend above tailwater, the difference in elevation should be added to the well losses in determining the maximum landside head with wells. The maximum landside head will always occur midway between wells for fully penetrating wells. For partially penetrating wells, there may be a difference as the average head may exceed the head midway between wells. To maintain the required factor of safety, a reduction in well spacing is required so as to lower the maximum landside head with wells. Thus, an iterative procedure must be utilized to find the well spacing which satisfies the condition that when well losses are considered, the head midway between wells or the average head, whichever is greater, equals the design values. Procedures involving this concept are presented below.

## 7-5. Infinite Line of Wells, Impervious Top Stratum

The general procedure for designing a system of relief wells along an infinite line with an impervious top stratum extending to a great distance landward follows. The procedure is valid for both fully and partially penetrating well systems.

*a.* Compute the allowable head, $h_a$, under the top stratum at the downstream toe of the dam or levee from Equation 3-2. Assume tailwater elevation coincides with ground surface (or as appropriate).

*b.* Assume that $H_m$, the net head midway between wells, is equal to $h_a$ and that well losses, $H_w$, are equal to zero (see Figure 5-4a).

*c.* For a given well penetration, $W$, compute $H_m$, for various trial values of well spacing, $a$, based on Equation 5-14. Interpolate to determine the required well spacing for $H_m = h_a$.

*d.* Calculate the well flow, $Q_w$, for the above well spacing and penetration using Equation 5-17.

*e.* Assume the well dimensions, and calculate the well losses, $H_w$, corresponding to $Q_w$.

*f.* Repeat step c using $h_m = H_m - H_w$ in place of $H_m$ in Equation 5-14, and determine a new value of *a*.

*g.* Repeat steps (d) through (f) until relatively consistent values of *a* are obtained on two successive trials. The value of a derived in this manner satisfies the design requirement for fully penetrating wells.

*h.* If the wells are not fully penetrating, repeat step (b) assuming that $H_{av}$, the average net head, is equal to $h_a$.

*i.* For a given well penetration, *W*, compute $H_{av}$ for various trial values of well spacing, *a*, based on Equation 5-15. Interpolate to determine required well spacing for $H_{av} = h_a$.

*j.* Calculate the well flow, $Q_w$, for the above well spacing and penetration using Equation 5-17.

*k.* Assume the well dimensions and calculate the well losses, $H_w$, corresponding to $Q_w$.

*l.* Repeat step (i) using $h_{av} = H_{av} - H_w$ in place of $H_{av}$ in Equation 5-15 and determine a new value of *a*.

*m.* Repeat steps (*j*) through (*l*) until relatively consistent values of *a* are obtained on two successive trials. For design, select the lesser value of well spacing determined from steps (*g*) and (*l*) for a given well penetration.

*n.* Repeat for various well penetrations to develop a relation between well penetration and spacing that satisfies design requirements.

## 7-6. Infinite Line of Wells, Wells in Ditch

The design of an infinite line of wells with the well outlets located in a collector ditch to lower landside ground-water levels below ground surface should be based on the assumption that the top stratum is impervious regardless of its permeability. The design procedure is essentially similar to that described in the preceding paragraph with the following exceptions:

*a.* Assume an elevation for the well outlets, $h_w$, and compute the allowable head, $h_a$, under the top stratum beneath the collector ditch from Equation 3-3. Proceed with steps (*b*) through (*g*) to obtain a design well spacing that satisfies Equation 3-3.

*b.* Select a design ground-water level landward of the wells defined by $h_d = h_w + \Delta_D$. Assume $h_d = H_{av}$.

*c.* Proceed with step (*i*) using $h_d$ in place of $H_{av}$.

*d.* Continue steps (*j*) through (*n*) to obtain the design well spacing.

## 7-7. Infinite Line of Wells with Impervious Top Stratum of Finite Length

The procedure for design of an infinite line of wells with a landside impervious top stratum of finite length is presented below. The procedure is also applicable to the case of a semipervious landside top stratum after conversion to an equivalent length of impervious top stratum as discussed in Appendix B. The spacing for an infinite line of relief wells for a given penetration is determined using an iterative procedure. For small well spacings, the average uplift factor $\Theta_a$ will be equal to or larger than $\Theta_m$ and will control. For large well spacings, $\Theta_m$ will be equal to or larger than $\Theta_a$ and will therefore control. A summary of the equations used is shown on Figure 7-1. The procedure for computing the well spacing for both conditions is as follows:

*a.* Compute the allowable head beneath the top stratum at the downstream toe of the dam, $h_a$, from Equation 3-2.

*b.* Assume that the net head in the plane of the wells, $H_{av}$, is equal to $h_a$ and calculate the net seepage gradient toward the well line, ΔM, substituting in Equation 7-6 as follows:

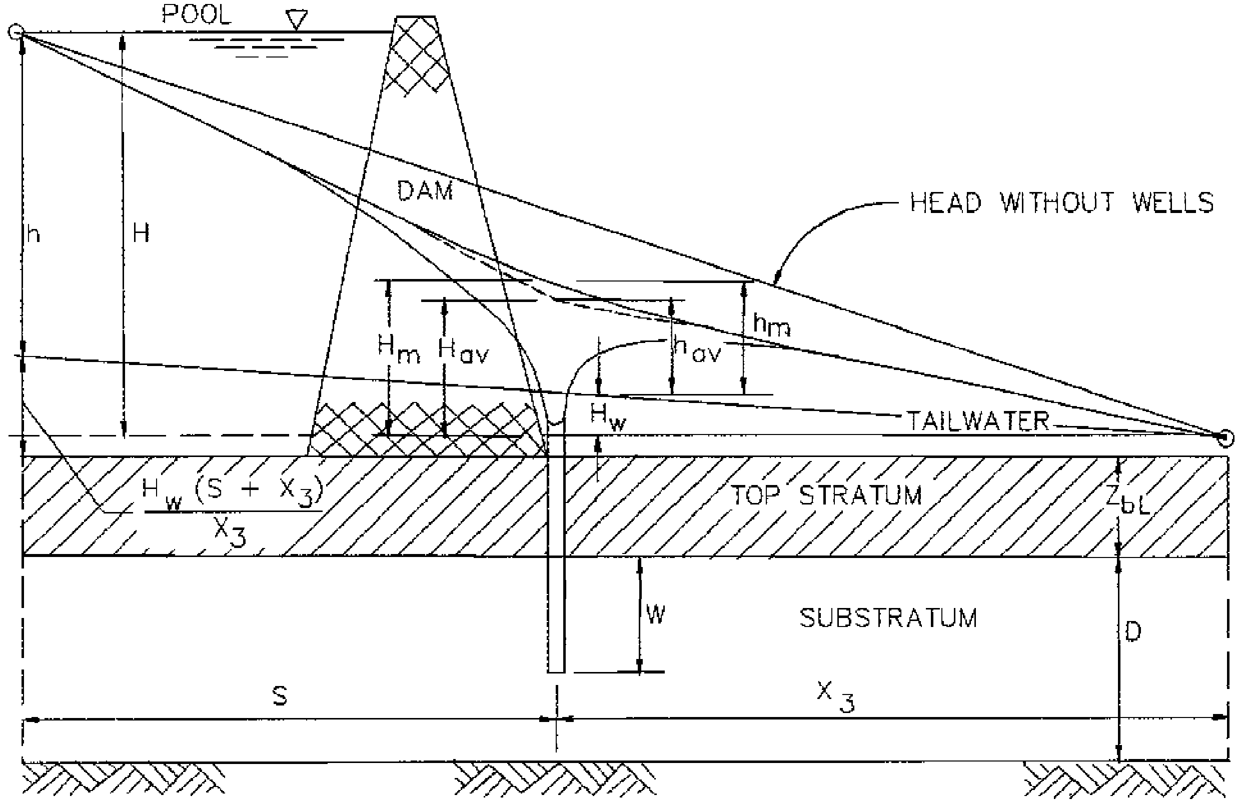
$$\Delta M = \frac{h - h_a}{S} - \frac{h_a}{x_3} \qquad (7\text{-}11)$$

where

S = distance from effective seepage entry to line of wells

$x_3$ = distance from line of wells at the landside toe to effective seepage exit (length of landside impervious top stratum)

*c.* Assume a well spacing and compute the flow from a single well using Equation 7-7.




$$h = H - H_w \left( \frac{S + X_3}{X_3} \right) \tag{7-1}$$

$$h_{av} = \frac{h\theta_a}{\frac{S}{a} + \left( \frac{s + X_3}{X_3} \right)^{\theta_a}} \tag{7-2}$$

$$H_{av} = H_w + h_{av} \tag{7-3}$$

$$h_m = h_{av} \frac{\theta_m}{\theta_a} = \frac{h\theta_m}{\frac{S}{a} + \left( \frac{s + X_3}{X_3} \right)^{\theta_a}} \tag{7-4}$$

$$H_m = H_w + h_m \tag{7-5}$$

$$\Delta M = \frac{H - H_{av}}{S} - \frac{H_{av}}{X_3} \tag{7-6}$$

$$Q_w = a\Delta M \; k_f \, D \tag{7-7}$$

$$\text{or } Q = \frac{hk_f D}{\frac{S}{a} + \left( \frac{s + X_3}{X_3} \right)^{\theta_a}} \tag{7-8}$$

$$h_m = a\Delta M\theta_m \tag{7-9}$$

$$h_{av} = a\Delta M\theta_a \tag{7-10}$$

**Figure 7-1. Nomenclature and formulas for design of relief wells at toe of dam**

*d.* Assume the well dimensions and calculate the well losses, $H_w$, corresponding to $Q_w$.

*e.* Compute the net average head in the plane of wells, $h_{av}$, using Equation 7-3.

*f.* Substitute values of ΔM and $h_{av}$ in steps (*b*) and (e) and solve for $\Theta_a$ using Equation 7-10.

*g.* Find $\Theta_a$ from Table 5-1 and Figure 5-6 or Figure 5-8 for the given well penetration using the values of *a* used in step (*f*) and the corresponding $a/r_w$ and $D/a$ values.

*h.* The first trial well spacing is that of value *a* for which $\Theta_a$ from step (*f*) equals $\Theta_a$ from step (*g*).

*i.* Find $\Theta_m$ from Table 5-1 and Figure 5-7 or Figure 5-8 for the given well penetration and first trial well spacing and the corresponding values of $a/r_w$ and $D/a$ values.

*j.* If $\Theta_a > \Theta_m$ repeat steps (*c*) to (*i*) using the first trial well spacing in lieu of the spacing originally used in step (*c*), and determine the second trail well spacing. This procedure should be repeated until relatively consistent values of *a* are obtained on two successive trials. Usually the second trial spacing is sufficiently accurate. If in step (*j*), $\Theta_a < \Theta_m$, a modified procedure is used for a second trial using steps (*k*) through (*t*).

*k.* Assume $H_m = h_a$ and compute $Q_w$ from Equation 7-7 using the value of ΔM obtained in step (*b*) and the first trial well spacing from (*h*).

*l.* Estimate $H_w$ from $Q_w$ of step (*k*).

*m.* Compute the net head midway between the wells as $h_m = H_m - H_w$.

*n.* Using $\Theta_a$ and $\Theta_m$ from steps (*h*) and (*i*), respectively, compute $h_{av}$ from Equation 7-4.

*o.* Using $H_w$ and $h_{av}$ from steps (*l*) and (*n*), respectively, compute $H_{av}$ from Equation 7-3.

*p.* Compute ΔM from Equation 7-6 using $H_{av}$ from step (*o*).

*q.* Using $h_m$ and ΔM from steps (*m*) and (*p*), respectively, compute $\Theta_m$ for various values of *a* from Equation 7-9.

*r.* Find $\Theta_m$ from Table 5-1 and Figure 5-7 or Figure 5-8 for the values of *a* used in step (*q*) and the corresponding $a/r_w$ and $D/a$ values.

*s.* The second trial well spacing is that value of *a* which $\Theta_m$ from step (*q*) equals $\Theta_m$ from step (*r*).

*t.* Find $\Theta_a$ from Figure 5-6 for the second trial well spacing and the corresponding values of $a/r_w$ and $D/a$.

*u.* Determine the third trial well spacing by repeating steps (*k*) to (*t*) using the second trial well spacing in lieu of the spacing originally assumed in step (*k*), and in step (*n*) using the values $\Theta_m$ and $\Theta_a$ from steps (*s*) and (*t*), respectively, instead of those from steps (*h*) and (*i*). This procedure should be repeated until relatively consistent values of *a* are obtained on two successive trials. Normally, the third trial is sufficiently accurate.

*v.* Repeat steps (*g*) through (*u*) for various well penetrations to develop a relation between well penetration and spacings that satisfies design requirements.

## 7-8. Computer Programs

A computer program for design of relief wells systems based on the above procedures was developed by Conroy (1984). Comparisons of the computer and hand solutions are presented by Cunny, Agostinelli, and Taylor (1989).

## 7-9. Head Distribution for Finite Line of Relief Wells

In a short, finite line of relief wells, the heads midway between wells exceed those for an infinite line of wells both at the center and near the ends of the well system as shown in Figure 7-2. With an infinite line of wells, the heads midway between wells are constant along the entire length of the well line. Many well systems may be fairly short; thus, it will be necessary to reduce the well spacing computed for an infinite line of wells so that heads midway between wells will not be more than the allowable head under the top stratum. The ratio of the head midway between wells at the center of finite systems to the head between wells in an infinite line of wells, for various well spacings and exit lengths, is given in Figure 7-3. The spacing of relief wells in a finite line should be the same as that required in an infinite line of wells to reduce the head midway between wells to $h_a$ divided by the ratio of $H_{m_n}/H_{m_\infty}$

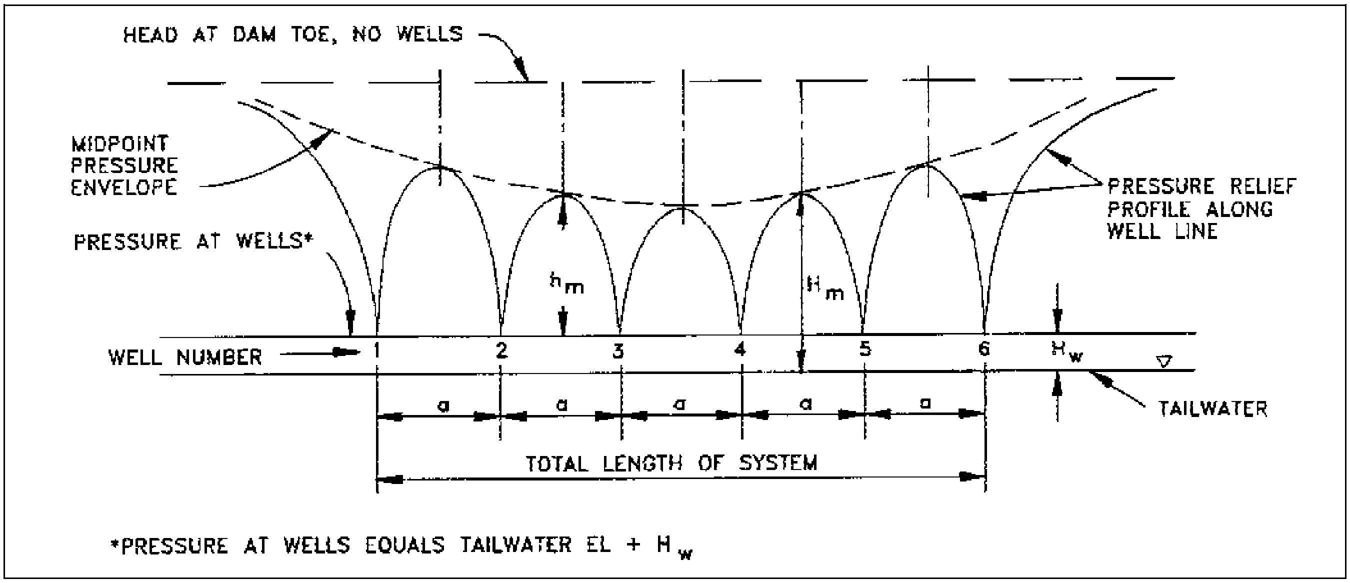



**Figure 7-2. Variation of pressure relief along a finite line of relief wells (after EM 1110-2-1905)**

from Figure 7-3. In any finite line of wells of constant penetration and spacing, the head midway between wells near the ends of the system exceeds that at the center of a system. Thus, at the end of both short and long well systems, the relief wells should generally be made deeper to provide additional penetration of the pervious substratum in order to obtain the same head reduction as in the central part of the well line. In the case of fully penetrating wells, the same head reduction can be obtained by additional wells using gradually decreasing well spacings near the ends of the line. The above-mentioned procedures for designing finite relief well systems, although approximate, are usually sufficient.

## 7-10. Well Systems at Outlet Works and Spillways

When well systems for outlet structures and spillway structures are being designed, the problem is to design a group with a finite number of wells with proper spacing and penetration which will reduce the head at the center of the well group to the allowable design head. In this type problem, usually the pressure at the well is known because such wells normally will be discharging into tailwater elevation, possibly through a collector system either under the stilling basin or along the channel-side slopes. Thus, the head at the well is equal to tailwater plus the hydraulic head loss in the well and collector system. This elevation when subtracted from the reservoir pool represents the net head acting on the system. For such a system of fully penetrating wells, the equations using the method of images for fully penetrating wells with a line source and impervious downstream top stratum are utilized, and the head at the center of the well group is calculated by superposition.

## 7-11. Well Costs

The design of relief well systems will normally produce various combinations of well spacing and penetration which satisfy the design criteria. The optimum design should be based on initial cost as well as overall costs including maintenance and possible replacement costs over the life of the structure. Costs should be calculated per 100-ft stationing as shown in Figure 7-4. Elements included in the estimate of initial costs are the cost of drilling or other installation technique, as well as the cost of well screen, riser pipe, and filter, all of which are on a foot basis. Additional fixed costs include back-filling, well development and testing, plus the costs of well guards, check valves, and horizontal outlet pipes if used. As shown in Figure 7-4, the well spacing and screen penetration should be selected that will result in the minimum well cost per station over the life of the structure.

## 7-12. Seepage Calculations

As previously noted, the presence of relief wells will tend to increase the total quantity of seepage beneath a levee or dam, $Q_s$. The seepage per foot of structure with no wells is computed by the equation

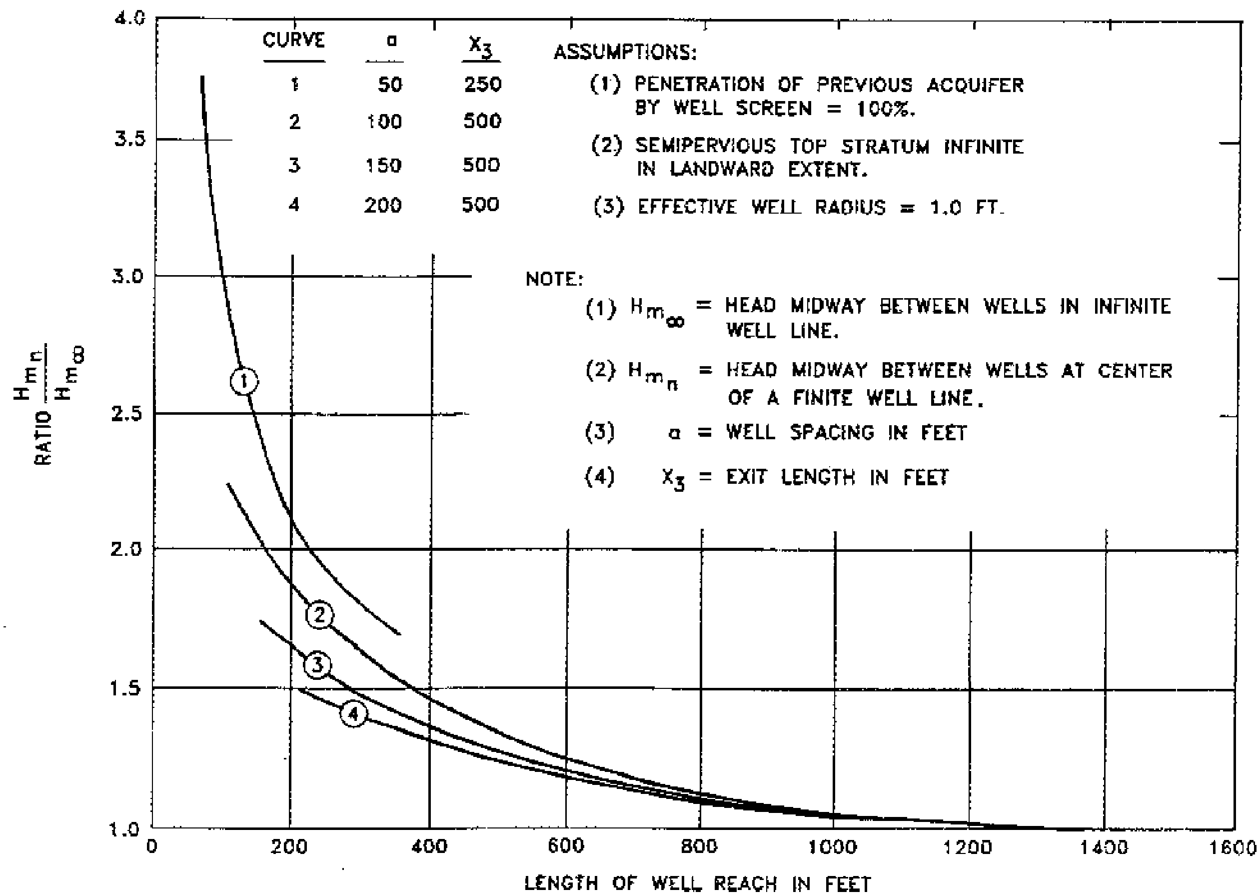



**Figure 7-3. Ratio of head midway between relief wells at center of a finite well system to head midway between wells in an infinite system (after EM 1110-2-1905)**

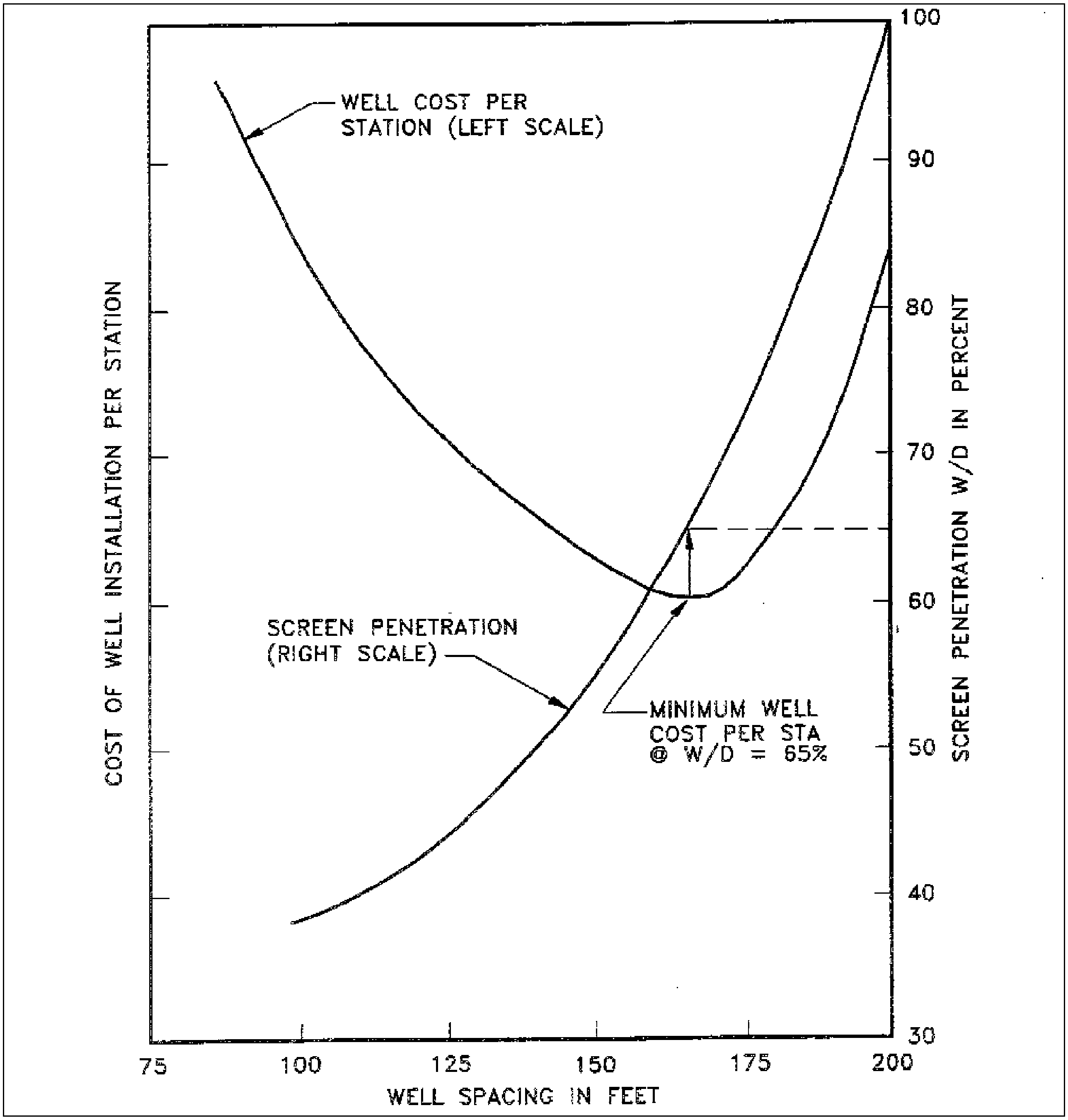



Figure 7-4. Determination of optimum well design

$$Q_s = \frac{kDH}{S + x_3} \qquad (7\text{-}12)$$

The seepage with wells is equal to the flow from the well system $\Sigma Q_w$, plus the seepage beyond the well system, $Q_{sw}$ , which is computed by the equation

$$Q_{sw} = \frac{kDH_{av}}{x_3} \qquad (7\text{-}13)$$

where $H_{av}$ is computed from equations in Figure 7-1. The estimation of the total quantity of seepage passing beneath a structure with or without wells can be of importance in selecting a well spacing which will intercept the desired amount of seepage.