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CHAPTER FOUR

FLOW-NET CONSTRUCTION

4.1 INTRODUCTION

Flow nets are a very practical and useful tool for solving many kinds of seepage and drainage problems, and those who possess skill in their construction have at their disposal an extremely powerful technique for designing safe and economical structures exposed to the damaging effects of water. This chapter contains helpful suggestions and step-by-step examples to enable the reader to draw suitable flow nets for a wide variety of conditions he may encounter. Also Section 3.3 contains detailed information about the properties and characteristics of flow nets and their many practical uses.

The thoughtful study of well-constructed flow nets can be of much benefit to the beginner because it can help him develop a general appreciation for the nature of seepage through porous media. In this text flow nets are presented for a wide variety of cross sections (nearly 100 examples are given). Also, a recent publication contains many examples of well constructed flow nets (U.S. Department of the Army, Corps of Engineers, 1986). If a flow net can be found for a cross section approximately similar to one being studied, much time can be saved because the general pattern is already known, and, as additional flow nets are constructed for approximately similar conditions, less and less time is required.

Study of the examples and the suggestions that are given in this book, together with a reasonable amount of practice, should enable engineers to learn to construct flow nets that are sufficiently accurate for many practical purposes. If the important checks described in this chapter are correctly made, flow nets will be fundamentally accurate; however, the beginner will be less likely to develop bad habits if his work is checked by someone who can distinguish errors.

The analysis of seepage by flow nets contributes to the proper design and construction of many kinds of engineering structure. It is generally recognized that the development of important works involving seepage should be executed in the following important steps:

1. Thorough field investigations establishing soil and geologic conditions at project sites.
2. Thorough experienced evaluation of field conditions.
3. Adequate studies and analyses.
4. Economical and sound designs.
5. Adequate specifications and construction.
6. Adequate instrumentation and observation of finished works.

Flow-net studies fit primarily into step 3; however, they are also useful in the study of seepage in completed projects (step 6).

All the flow net examples in this chapter are related to steady-state seepage. Use of flow nets to study moving saturation lines is described in Sec. 3.6. Several of the examples in this chapter are for cross sections simplified to facilitate the presentation of flow net construction techniques, and do not represent recommended designs (e.g., Figs. 4.4, 4.5, 4.6, 4.7, and 4.8). All dams should be designed with positive internal drainage systems as shown in Chapter 6 (Figs. 6.7, 6.12, 6.14, 6.21, and 6.23).

4.2 GENERAL SUGGESTIONS

This section contains a number of practical time-saving suggestions about the construction of flow nets. Much time and effort can be saved in obtaining accurate flow nets if the following procedures are observed:

1. Draw the cross section to be studied on good tracing paper; turn the sheet over and construct the flow net on the reverse side. After the flow net has been completed by freehand sketching trace it on the front side or on fresh paper. Use French curves if a smooth finished product is desired for illustrative purposes. *Freehand lines do not detract from the accuracy or usefulness of a flow net if the basic rules have been properly followed.*
2. Be practical in the number of lines drawn. Do not clutter up the drawing with too many lines, but do not use so few that essential features are lost. Remember that parts of a flow net can be subdivided to any degree that is required to emphasize detail (Fig. 3.5 and Fig. 4.2*d*).

3. Be practical in selecting a scale for the drawing. A scale that is too large wastes time and erasers. An 8½-by-11-in. sheet is a good size for many flow nets, although a sheet several feet wide may sometimes be needed for the analysis of a levee or dam with a wide berm or a wide upstream blanket and for groundwater studies of wide cross sections.
4. Before starting to sketch a flow net look for important boundary conditions and for prefixed flow net lines (Figs. 4.2*a* and 4.3*a*). In every flow net some flow lines and some equipotentials are established by the boundary conditions before the flow net is started. *Noting the prefixed lines helps one to get the general shape somewhat correct in the beginning.*
5. In drawing flow nets for composite sections (those having more than one permeability) look for dominating parts of a cross section. Highly pervious or highly impervious parts sometimes have a major influence on flow patterns (Figs. 4.7 and 4.8).
6. Do not overlook the overall shape while working on details and never refine a small portion of a flow net before other parts have been fairly well developed. Corrections made in one part have some influence on every other part.
7. Study the basic rules that must be carried out and follow them (Sec. 3.3).

When the basic rules are *not* followed serious errors can be made. Figure 4.1 shows two of the common errors made by beginners. Figure 4.1*a* shows extraneous equipotentials, both upstream and downstream from the structure, and Figure 4.1*b* shows flow lines disappearing into the boundary below the permeable formation. By studying a few correctly constructed flow nets such errors should be eliminated (i.e., Figs. 4.2*d* and 4.3*e*).

4.3 TYPES OF FLOW NET

Flow nets can be of several types, depending on the configuration and the number of zones of soil or rock through which seepage is taking place. A primary subdivision can be made that depends on the following conditions:

1. *Flow is confined* within known saturation boundaries and the phreatic line is therefore known.
2. *Flow is unconfined* and the upper level of saturation (the phreatic line) is *not* known.

A second subdivision can be made that depends on whether *(a)* the cross section can be drawn as one zone or unit of a single permeability or *(b)* the cross section contains two or more zones or units of different permeabilities. The latter is described in this book as a *composite section.*

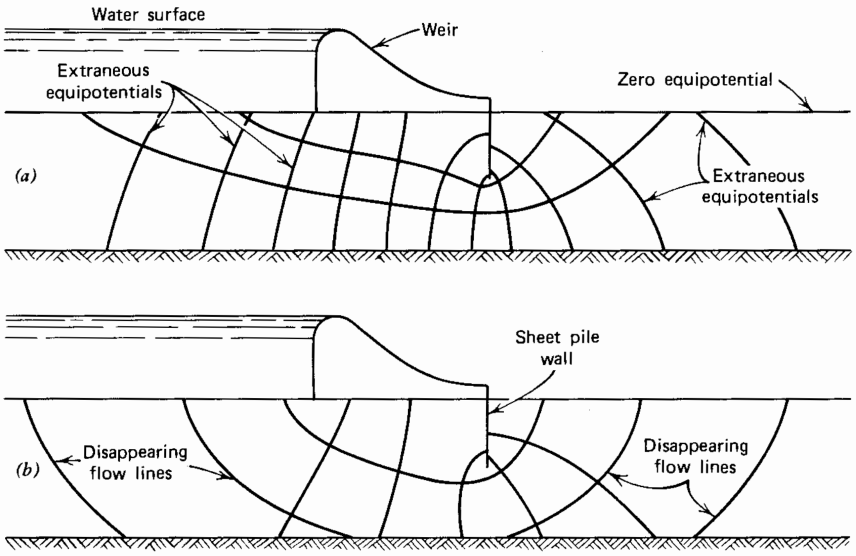


FIG. 4.1 Some common errors in flow nets by beginners.(*a*) Extraneous equipotentials. (*b*) Disappearing flow lines.

These criteria give four possible combinations of flow conditions:

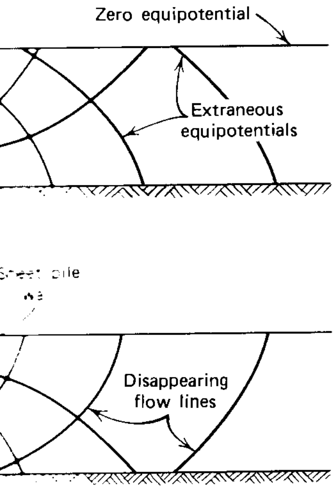
1a. *Confined flow in single permeability sections.*
1b. *Confined flow in composite sections (those having two or more permeabilities).*
2a. *Unconfined flow in single permeability sections.*
2b. *Unconfined flow in composite sections.*

Any of these types can be constructed for *isotropic* soil (horizontal and vertical permeabilities equal) or for *anisotropic* soil (horizontal and vertical permeabilities *not* equal). The rule for correcting for anisotropic conditions in which a single transformation factor is applied to an entire cross section is given in Chapter 3 (Sec. 3.3).

Step-by-step procedures for constructing flow nets are discussed in the remaining part of this chapter, starting with the simplest type and progressing to the more complex.

4.4 CONFINED FLOW SYSTEMS (Phreatic Line Known)

Example 1 Seepage Under Sheet Pile Cutoff Wall (single permeability section). Figure 4.2 shows a vertical sheet pile wall in a sandy foundation. This example represents type 1*a* flow because all seepage boundaries are defined in



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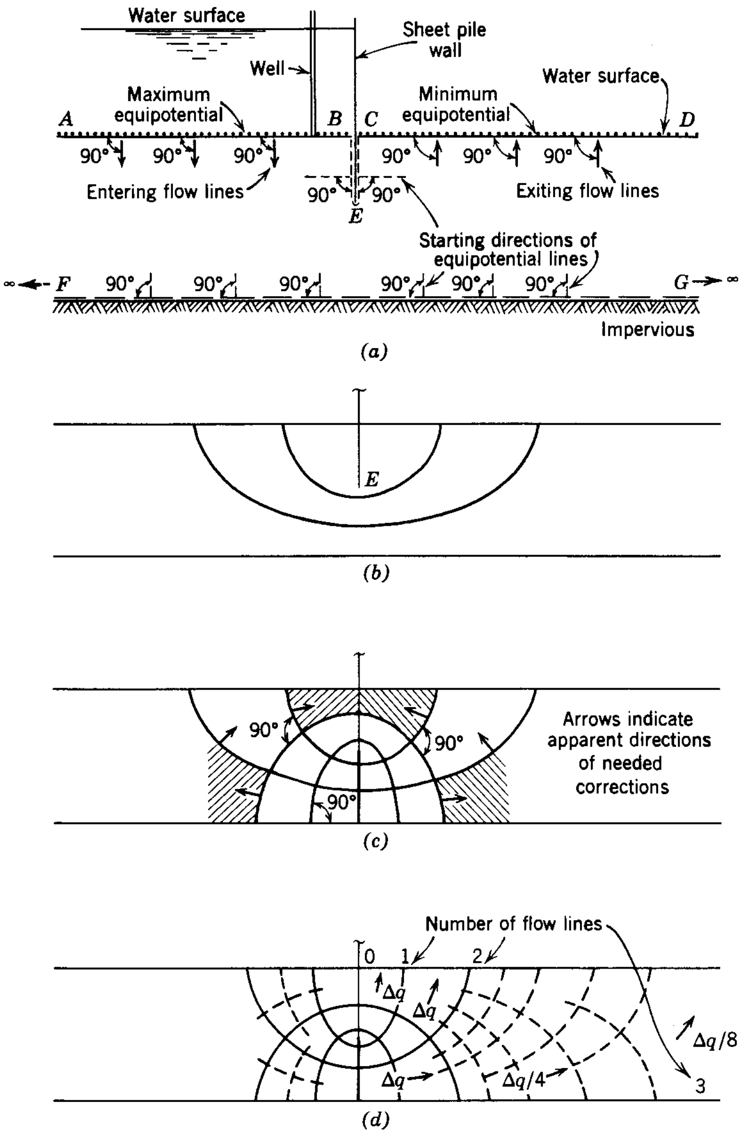


FIG. 4.2 Example of the construction of a flow net for confined flow in single permeability section (Example 1). (*a*) Identify prefixed conditions, noting starting directions of lines. (*b*) Draw trial family of flow lines (or equipotentials) consistent with prefixed conditions. (*c*) Keeping the lines drawn in (*b*), sketch first trial flow net. Make all lines intersect other set of lines at 90°. (*d*) Erase and redraw lines until all figures are square. Subdivided as desired for detail and accuracy.

advance of the flow net construction and seepage is restricted to the uniform sand layer.

By inspection of the cross section (Fig. 4.2*a*) the known flow net lines are the following:

Line *AB:* The maximum equipotential line.
Line *CD:* The minimum equipotential line.
Line *BEC:* The shortest flow line.
Line *FG:* The longest flow line.

With the knowledge that equipotential lines and flow lines must intersect one another at right angles, the directions of lines in the flow net are established at certain points. Thus all flow lines must enter the foundation at right angles to line *AB* and exit perpendicular to the line *CD;* also, equipotential lines must intersect lines *BE, EC,* and *FG* at right angles. The directions of these intersecting lines are shown at several random points in Figure 4.2*a*. Though the positions of the lines shown do not necessarily coincide with any that will be developed in the flow net, their directions give useful clues regarding the shape of the completed flow net. With the known restrictions in mind and knowing that all the lines will begin to curve soon after leaving fixed boundaries, the sketching can be started.

Flow nets can be developed in a number of different ways, including the following:

1. Immediately sketching both flow lines and equipotential lines, working from one part of a flow net into another.
2. Sketching a plausible family of flow lines before starting to sketch equipotentials.
3. Sketching a plausible family of equipotential lines before starting to sketch flow lines.
4. Combinations of the above or any other suitable procedures.

In Figure 4.2*b* the flow net is started by drawing two intermediate flow lines, making the entrance and exit angles 90° and keeping in the mind that seepage tends to concentrate at a focal point such as the bottom of the wall at point *E*. The next step (Fig. 4.2*c*) is to draw a family of equipotentials, *making all intersections with flow lines right angles and trying to make some of the figures squares.* This procedure, applied to this example, gives the first trial flow net (Fig. 4.2*c*). On cursory examination this flow net might appear to be fairly satisfactory, but a detailed examination shows that a number of the figures are not squares. If all intersections are 90° angles, the figures will be rectangular, as desired; however, if diamonds or other off-shaped figures are formed, lines should be deliberately shifted until all intersections are 90°

angles and all figures are basically rectangular in shape. The figures that are not squares and the apparent directions in which lines need to be shifted to convert the figures into squares should now be noted. The word "apparent" is used because we cannot always be sure at this stage just which of the initial adjustments will prove to be correct, since the shifting of any line alters the amount of the subsequent corrections required of intersecting lines. In Figure 4.2*c* some of the figures that definitely are not squares are crosshatched. The apparent directions of needed corrections of this flow net are indicated by the arrows.

By repeatedly erasing and redrawing portions of flow lines and equipotential lines and studying the overall pattern and individual parts a finished flow net can be developed (Fig. 4.2*d*). Portions of this flow net have been subdivided one or more times to give greater detail. (See also Fig. 3.5.)

Sometimes, when drawing flow nets, it is desirable to erase all lines, leaving only a trace of the most recent for redrawing and improving the entire flow net.

If a flow net has a whole number of flow channels (2.0, 3.0, 4.0, etc.), the corresponding number of equipotential spaces depends on the shape of the cross section and will not necessarily be a whole number. The finished flow net in Figure 4.2*d* has a whole number of flow channels and equipotential spaces; but if the shape had been slightly different, the number of equipotential spaces might have been 5.6, 6.5, or some other fractional number.

Likewise, if a whole number of equipotential spaces was selected for a flow net, the number of flow channels could be a fractional number. In this example (Fig 4.2) a slightly different shape could have produced 2.7, 3.5, or some other fractional number of flow channels. The flow net in Figure 4.4*c* with 1.2 flow channels is an example.

There is no objection to the construction of flow nets with fractional numbers of flow channels and equipotential spaces, but usually one or the other should be made a whole number.

Example 2 Flow Beneath Concrete Weir (single permeability section). Figure 4.3 is another example of confined flow in a section of one permeability (type 1*a*). Here, as in Example 1, all seepage boundaries are known before the flow net is started. The known flow net lines are the following (Fig. 4.3*a*).

Line *AB:*	The maximum equipotential line.
Line *CD:*	The minimum equipotential line.
Line *BEFGHC:*	The upmost flow line.
Line *IJ:*	The longest flow line.

Known directions of lines in the flow net that intersect these prefixed lines at right angles are shown at arbitrary points in Figure 4.3*b*.

In Figure 4.3*c* the flow net is started by drawing two intermediate flow lines,

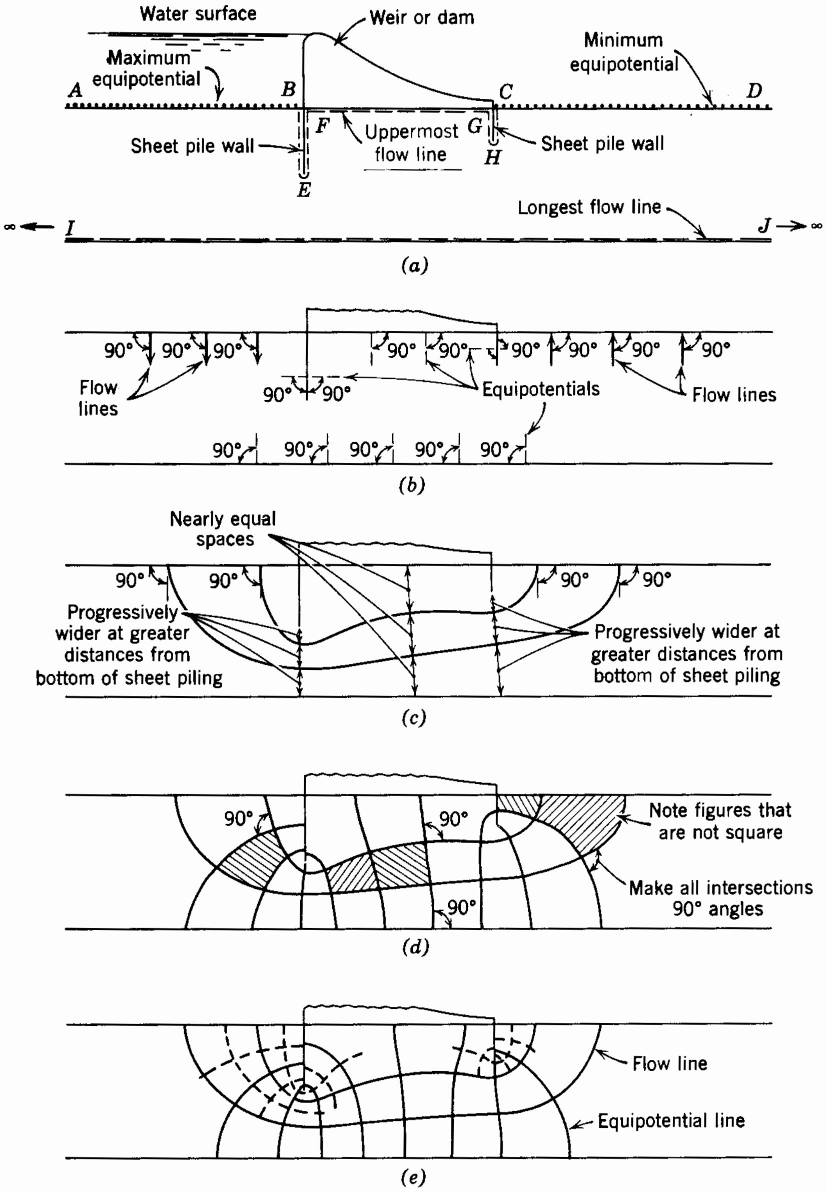
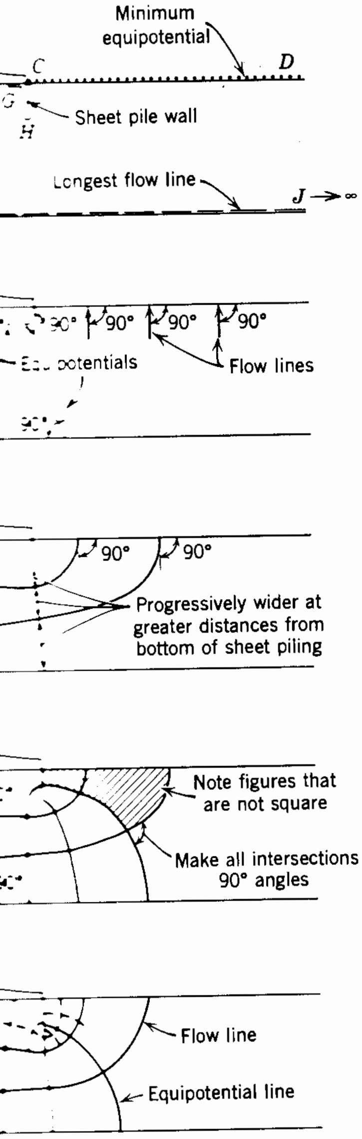


FIG. 4.3 Another example of a method of constructing flow nets with all boundaries known (Example 2). (*a*) Identify prefixed flow lines and equipotential lines. (*b*) Look for prefixed starting directions of lines.(*c*) Draw trial family of flow lines (or equipotentials) consistent with prefixed conditions. (*d*) Keeping the lines drawn in (*c*), sketch first trial flow net. Make all lines intersect other set of lines at 90° angles. (*e*) Erase and redraw lines until all figures are squares. Subdivide as desired for detail and accuracy.



...ing flow nets with all boundaries
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noting that flow radiates around the bottoms of the cutoff walls and that the lines tend to be somewhat equally spaced under the centers of wide structures.

In Figure 4.3*d* a trial family of equipotentials has been added to obtain a trial flow net, and several nonsquare figures have been crosshatched. The flow net obtained by progressive correction of errors is given in Figure 4.3*e*.

4.5 UNCONFINED FLOW SYSTEMS (Phreatic Line Unknown)

In the examples given in Sec. 4.4 the line of saturation, or *phreatic* line, is known in advance, which makes the procedure for obtaining the flow nets simpler than it is for cross sections in which the upper saturation line is not known. Cross sections with an unknown phreatic line are considered the most challenging because the phreatic line must be located simultaneously with the drawing of the flow net. The procedures described in this section permit flow nets of this kind to be constructed with minimum time and effort.

Example 3 Seepage Through Homogeneous Earth Dam. The cross section and known conditions for a type 2*a* flow net are given in Figure 4.4*a*. Line *AB*, the face of the dam, is the maximum equipotential line; line *AC*, the base of the dam, is a flow line. The exact position of the phreatic line is unknown, but it can reasonably be expected to lie somewhere within the shaded zone *BDE*. The general condition at the free surface is known (Fig. 3.6) and it is known that the net must be composed of squares.

Before starting to construct a flow net with an unknown phreatic line, the total head h should be divided into a convenient number of equal parts Δh, and light guidelines should be drawn across the region in which the phreatic line is expected to lie. In Figure 4.4*a* four intermediate guidelines (for convenience, called *head* lines in this section) are drawn at a vertical spacing $\Delta h = h/5$.

The conditions that establish the position of the phreatic line in Fig. 4.4 are the following:

1. Equal amounts of head must be consumed between adjacent pairs of equipotential lines.
2. Equipotential lines must intersect the phreatic line at the correct elevation.
3. To satisfy requirements 1 and 2, each *equipotential* line must intersect the phreatic line at the appropriate *head* line. this key requirement must be satisfied by all flow nets having an unknown phreatic line.

After drawing the horizontal guidelines or *head* lines across the region in which the phreatic line is expected to lie a *trial saturation line* (line *ab*, Fig. 4.4*b*) should be drawn; make a reasonable guess about its probable location