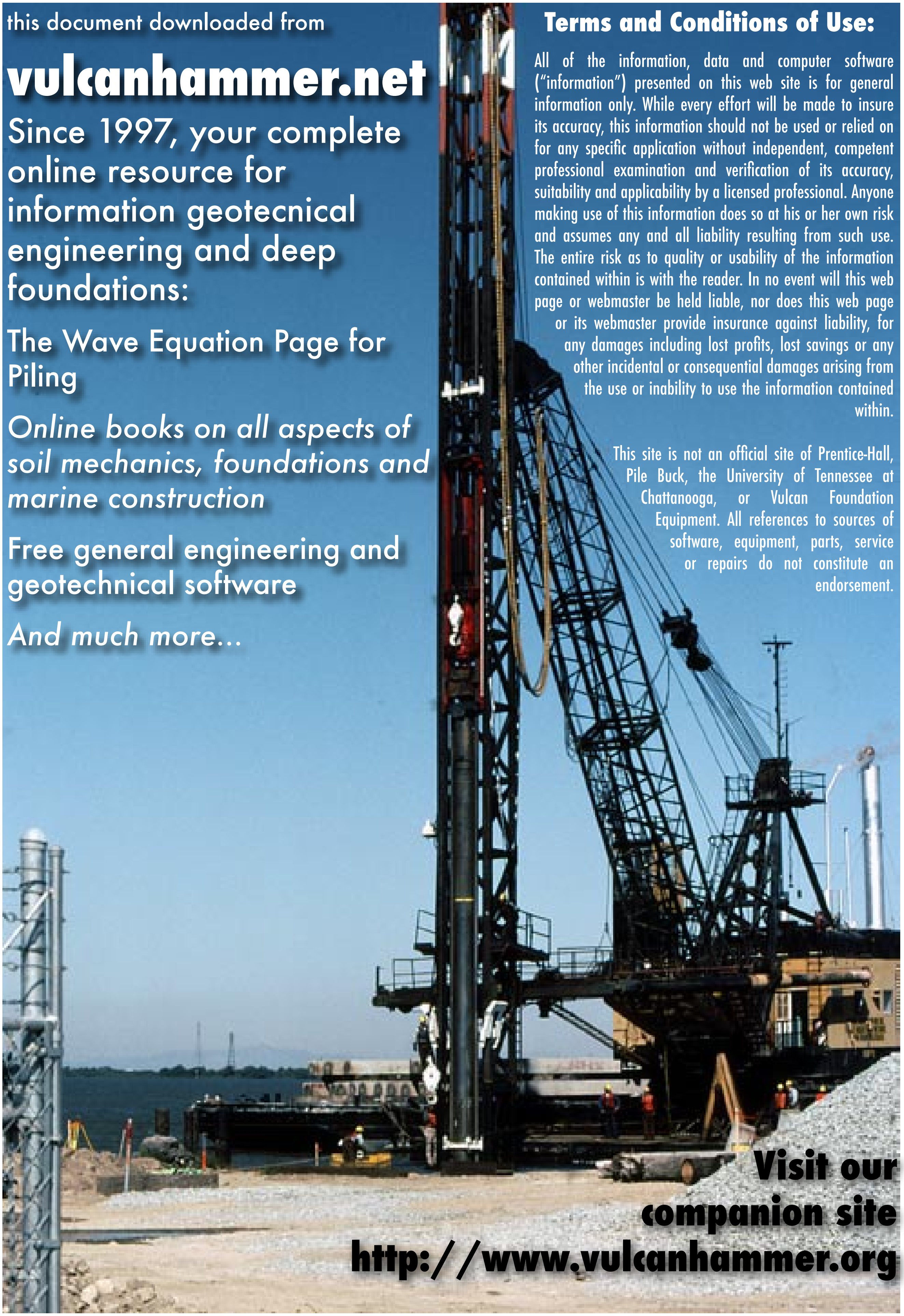

REMR Technical Note CS-ES-4.6

Flow-Net-Computed Uplift Pressures Along Concrete Monolith/Rock Foundation Interface

Introduction

One of the key stages in a stability evaluation of navigation and flood-control structures is the calculation (or assignment) of uplift pressures along the base of the hydraulic structure and/or along a critical rock joint or joints within the foundation. Using accurate piezometric instrumentation data at a site along with knowledge of the site geology is the preferred method for establishing uplift pressures. However, when instrumentation data are not available or when the reservoir levels to be analyzed exceed those for which the piezometric measurements were made, other procedures must be used to establish the distribution of flow and the corresponding uplift pressures. Three procedures are widely used by engineers to establish the uplift pressures along an imaginary section or sections through the structure-foundation interface and/or along a section or sections within the rock foundation. These three procedure are (1) a prescribed uplift distribution as given, for example, in an engineering manual specific to the particular hydraulic structure; (2) uplift pressures computed from flow within rock joints; or (3) flow-net-computed uplift pressures.

Purpose

This technical note presents the results of a study involving two-dimensional (2-D), steady-state flow through a permeable rock foundation. The results show the impact of homogeneous, anisotropic permeabilities (i.e., $K_x \neq K_y$) and the impact of base separation on the uplift pressures along the base of a rock-founded retaining monolith.

Steady-State Seepage Analysis

Today, analytical tools such as the finite-element method (FEM) are available to compute the distribution of heads and flow within permeable foundations. Most problems involve the analysis of steady-state seepage given problem-specific geometry and boundary conditions. An FEM model of two- or three-dimensional steady-state seepage can consider homogeneous or heterogeneous regions comprising the flow regime as well as isotropic or anisotropic permeability within each of these regions. The Windows version of the Corps' FE seepage program (X8202 in the CORPS Library) (Tracy 1983), called FASTSEEP (Engineering Computer Graphics Laboratory 1993), was used in this analytical investigation of 2-D steady-state seepage.

Seepage Problem Analyzed

The case of a concrete gravity lock retaining wall founded on permeable rock was used in this study. Figure 1 shows the concrete monolith to be 82.7 ft high and 45 ft wide. This monolith has a base-to-height ratio of 0.54, which is within the range (0.33 to 0.7) that is typical for gravity earth-retaining monoliths (Ebeling et al. 1992). This particular monolith was chosen for further study because its geometry (e.g., base-to-height ratio) is typical of gravity retaining monoliths and because this monolith has been extensively analyzed in the REMR Research Program for separation along the base of the monolith under extreme loading. The monolith was analyzed by means of (1) the conventional equilibrium method of analysis as well as the FEM with three different crack/crack propagation models; (2) a base separation analysis with the use of interface elements; (3) a base separation analysis with the smeared crack approach; and (4) a linear elastic fracture mechanics discrete crack analysis. In the case of the extreme loading (e.g., no lock pool) and a conservative assignment of material properties, all four analytical procedures showed that as much as 50 percent of the base of the monolith may separate from its rock foundation along their interface.

All nine seepage analyses assumed that the monolith was impermeable and that the permeable foundation was homogeneous. No drainage was included within the foundation in these problems. A typical set of dimensions is shown in Figure 1, along with a summary of the parameters that were varied in the nine seepage analyses. Three cases of monolith-to-foundation contacts were considered: (1) full contact along the interface (B_e/B = 100 percent), (2) an intermediate case of three-quarters contact along the interface (B_e/B = 75 percent), and (3) the extreme case of only half of the monolith in contact with the foundation (B_e/B = 50 percent). For each case, three sets of foundation permeabilities ($K_x = K_y$, $K_x = 10K_y$, and $K_x = K_y/10$) were considered.

Flow Nets for Anisotropic Permeabilities with Full Contact Along the Interface

Figures 2 through 4 show the steady-state flow nets for the permeable foundation with $K_x = K_y$, $K_x = 10K_y$, and $K_x = K_y/10$, respectively, for a monolith in full contact with the rock foundation (B_e/B = 100 percent). The water table in the backfill is assumed to be at elevation (el) 396 ft, and the head in front of the monolith is assumed to be at el 340 ft.

A comparison of the flow net in Figure 3 for $K_x = 10K_y$ with that shown in Figure 2 for $K_x = K_y$ shows that along any given flow line below the monolith, there is less of a change in elevation between flow channels than that for the isotropic case (Figure 2). That is to say, the more permeable horizontal direction orients the flow channels in a more horizontal direction. The converse is true when the flow net in Figure 4 for $K_x = K_y/10$ is compared with that shown in Figure 2. In this case, the more permeable vertical direction orients the flow channels in a more vertical direction.

Flow Nets for Isotropic Permeabilities with Partial Contact Along the Interface

Figures 2, 5, and 6 show the steady-state flow nets for the case of isotropic permeability ($K_x = K_y$) and 100, 75, and 50 percent, respectively, of monolith-to-rock base contact. In all analyses of monoliths with partial contact (i.e., a crack extending from the heel), full hydrostatic water pressures within the backfill (corresponding to a water table at el 396 ft) were assigned along the cracked portion of the interface. Comparison of the three figures shows that the symmetry of the flow channels is preserved about a vertical line located midway between the toe and the crack tip (which is the heel in Figure 2).

Uplift Pressures Along the Interface

The distributions of uplift pressures along the monolith-to-rock interface are shown in Figures 7, 8, and 9 for B_e/B = 100 percent (i.e., full contact), 75 percent, and 50 percent, respectively. Each figure shows the resulting uplift distribution for the cases of $K_x = K_y$, $K_x = 10K_y$, and $K_x = K_y/10$. The linear uplift distributions corresponding to flow confined along the interface (i.e., one-dimensional (1-D) flow) are also included in these figures. The three figures show four important results. First, 2-D seepage within the isotropic foundation alters the resulting distribution of uplift pressures when compared to uplift pressures resulting from 1-D flow. Second, the distributions of uplift pressures for the three ratios of permeabilities are nearly the same. Third, the distributions of uplift pressures from the 2-D analyses are antisymmetric to the distribution of uplift pressures for 1-D flow about a point midway between the tip of the crack and the toe of the wall. Finally, the point of antisymmetry is maintained midway between the crack tip and the toe for all crack lengths.

The resultant uplift force, equal to the area under each of the uplift pressure distributions, is the same value for each of the four analyses shown in Figure 7. This is also the case for the results shown in Figures 8 and 9.

The resulting force for the linear uplift pressure distribution in Figure 7 (1-D flow) acts at a point along the interface that is two-thirds the distance from the toe to the heel, acting at a point 30 ft from the toe ($B_e = B =$ 45 ft). The resultant uplift forces computed from the results of the other three

2-D analyses shown in Figure 7 act at points that are between 4 and 5 percent closer to the toe of the wall than the points for the linear uplift distribution. This difference is even less for the results shown in Figures 8 and 9.

Conclusions

The principal results of this study are as follows:

a. Anisotropic permeabilities (i.e., $K_x \neq K_y$) orient the flow channel in the direction of larger permeabilities. This effect is observed in the resulting 2-D steady-state seepage flow net.

b. Given a prescribed crack length, the magnitude of the resulting uplift force is equivalent for the 1-D analysis to the uplift forces computed from the three 2-D analyses ($K_x = K_y$, $K_x = 10K_y$, and $K_x = K_y/10$).

c. The distributions of uplift pressure along the monolith-to-rock interface calculated using 2-D FE seepage analyses are similar but not exactly equivalent to the distribution from 1-D seepage analyses. Even though the resultant uplift forces are equal in magnitude differences in the distributions of uplift pressures between the two analyses result in the uplift forces acting at different points along the interface.

The authors caution against making generalities based on the results of this study to more complicated seepage problems. They attribute many of the similarities in the previously stated 1- and 2-D study results to the following features of the nine idealized problems:

- The distance from the toe of the monolith to the left extent of the finite-element mesh (i.e., a location of a flow or head boundary condition) was large and equal to the distance from the heel to the right extent of the mesh (another flow or head boundary condition).

- The base of the monolith was parallel to the primary flow channels in all four seepage analyses

- The permeable foundation was modeled as homogeneous

- The primary flow channel immediately below the monolith was nearly horizontal as was the rock-to-monolith interface.

- No drainage features were included in the foundation.

Any one of these factors will impact the conclusions stated previously and will contribute to larger differences in the results between the different types of seepage analyses when compared to the results of this study.

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Acknowledgments

The following WES Research Team Members are acknowledged for their contributions to this project: Dr. Robert M. Ebeling and Mr. Michael E. Pace.

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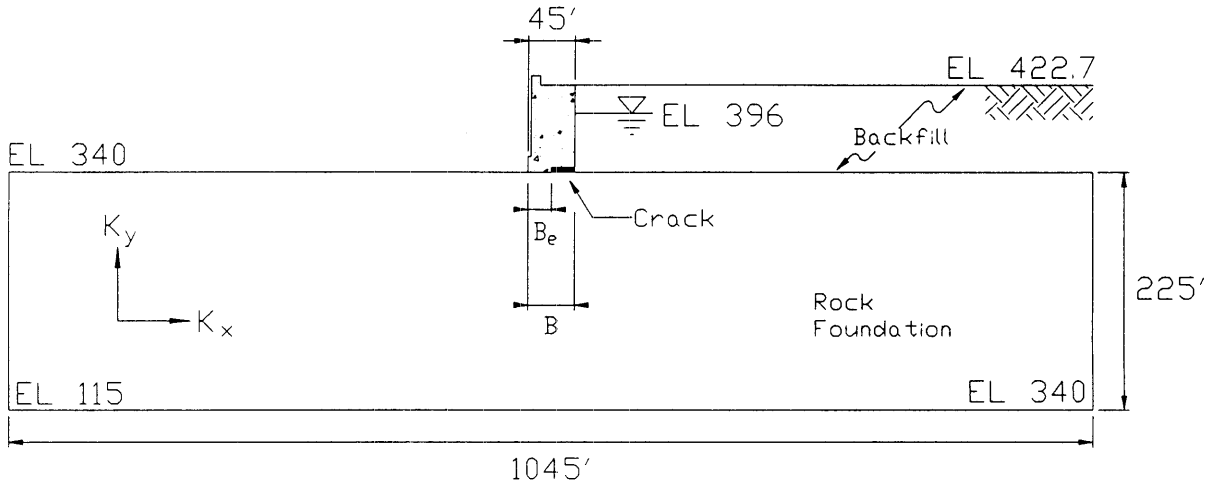

$\frac{B_e}{B} = 100\%$	$\frac{B_e}{B} = 75\%$	$\frac{B_e}{B} = 50\%$
$K_x = K_y$	$K_x = K_y$	$K_x = K_y$
$= 10K_y$	$= 10K_y$	$= 10K_y$
$= \frac{1}{10}K_y$	$= \frac{1}{10}K_y$	$= \frac{1}{10}K_y$

Figure 1. Problem geometry and cases considered

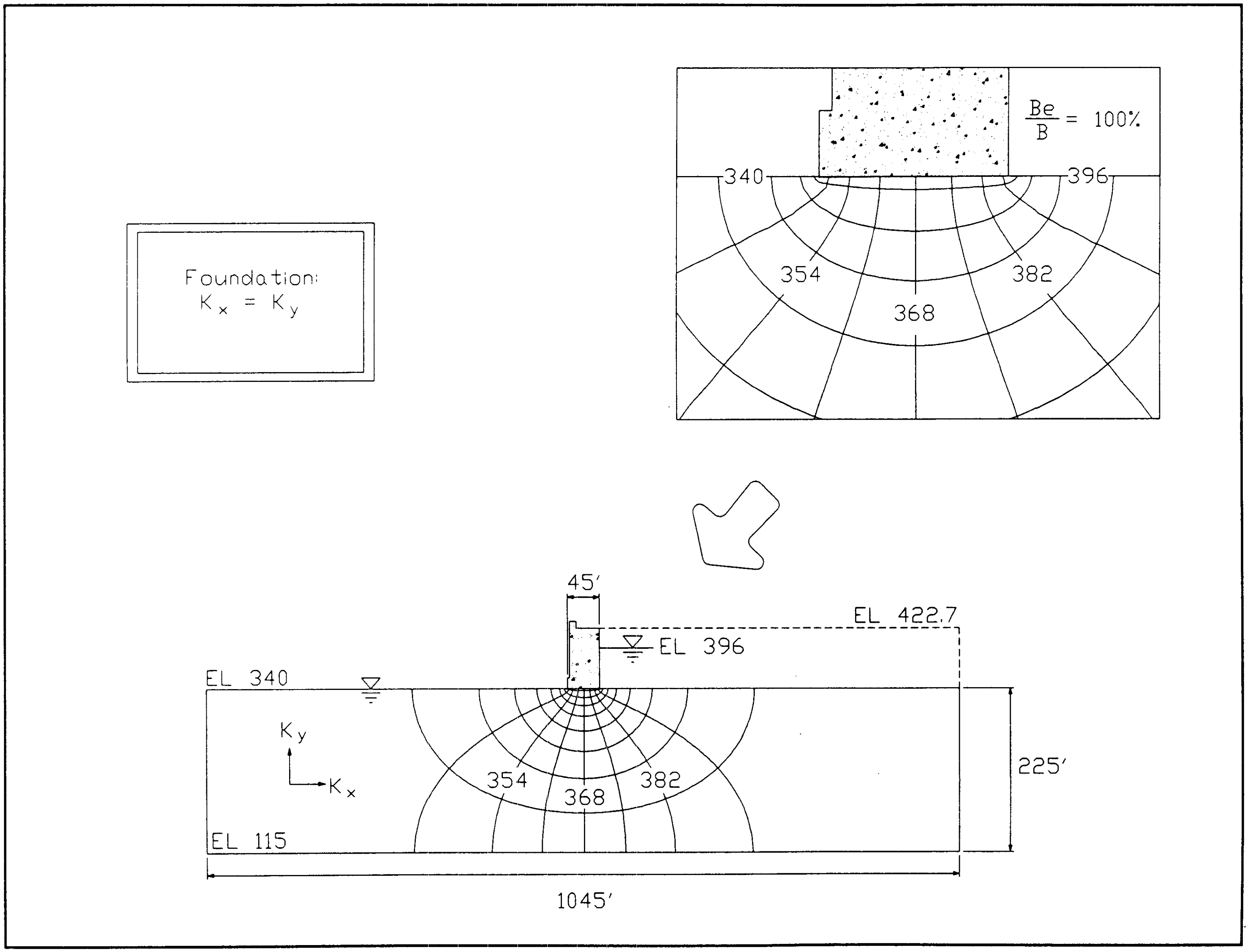

Figure 2. Results for B_e/B = 100 percent, $K_x = K_y$

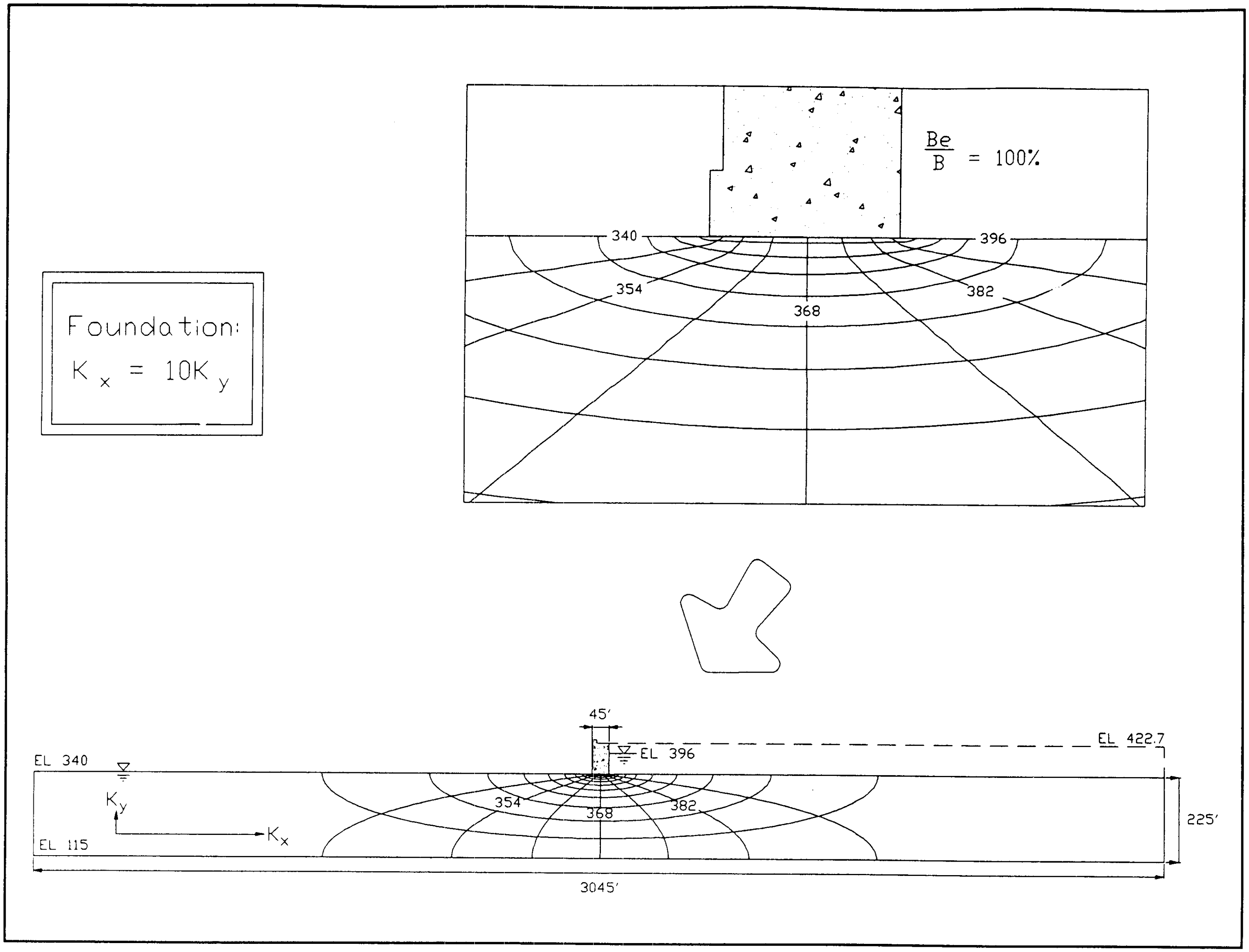

Figure 3. Results for B_e/B = 100 percent, $K_x = 10K_y$

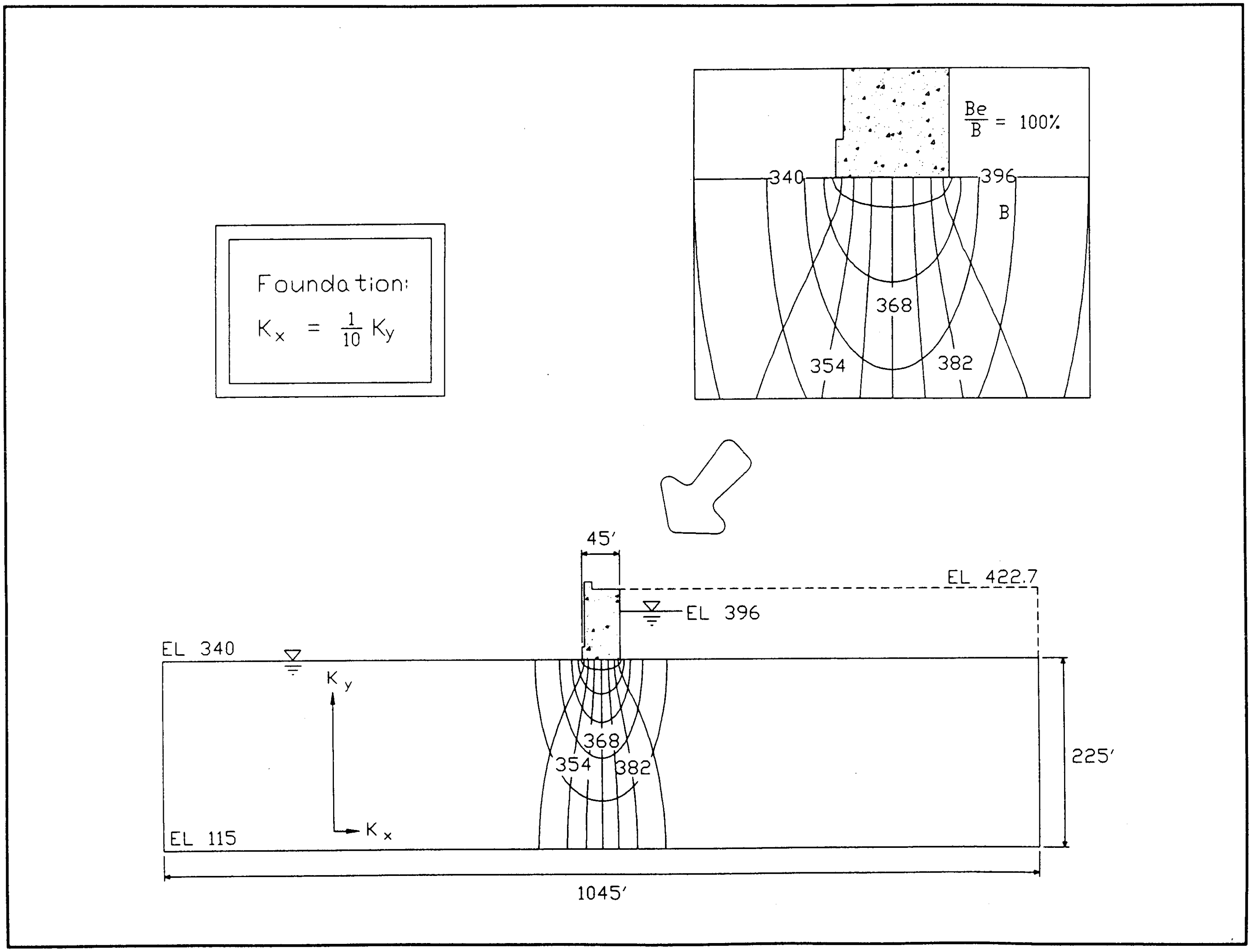

Figure 4. Results of B_e/B = 100 percent, $K_x = \frac{1}{10} K_y$

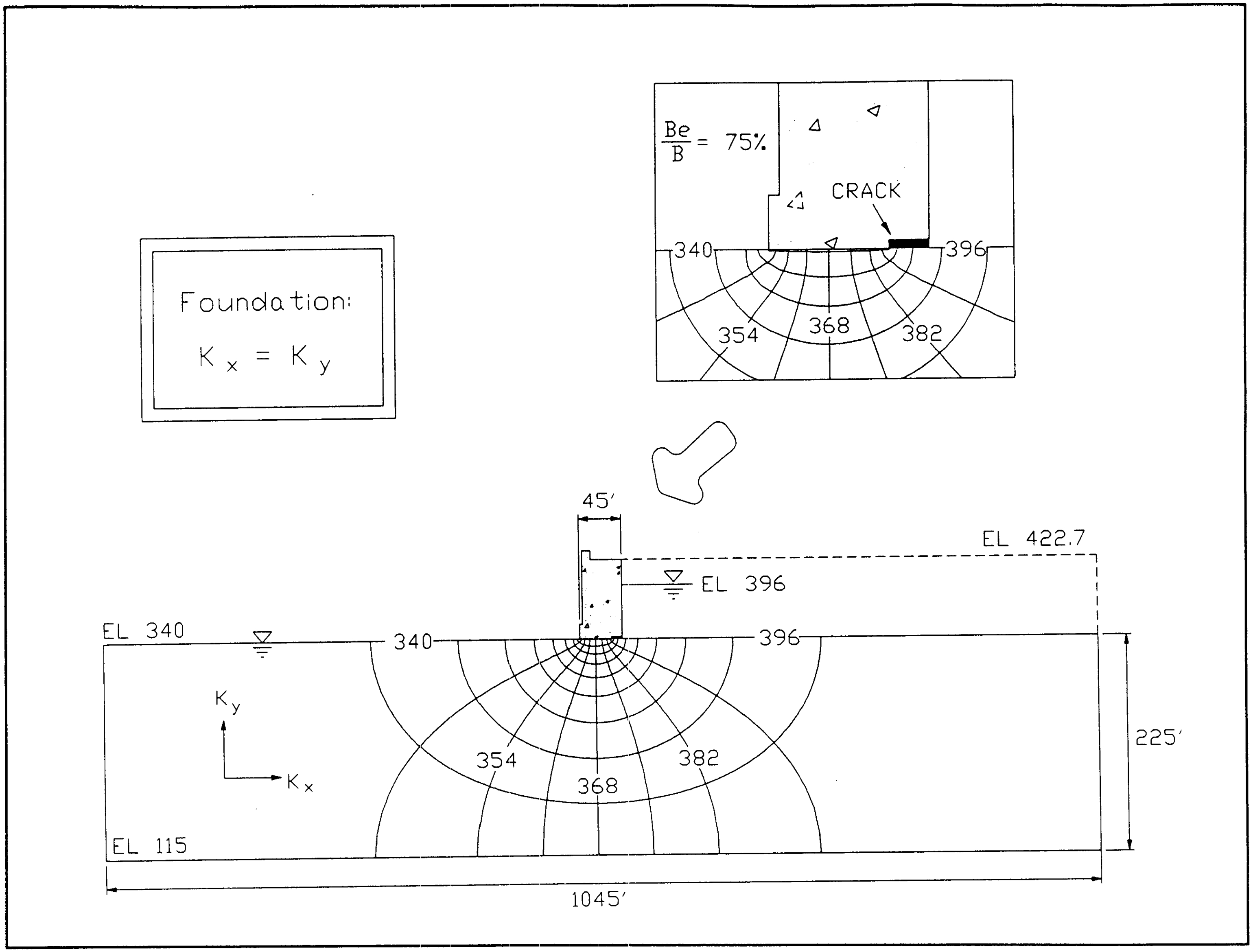

Figure 5. Results for B_e/B = 75 percent, $K_x = K_y$

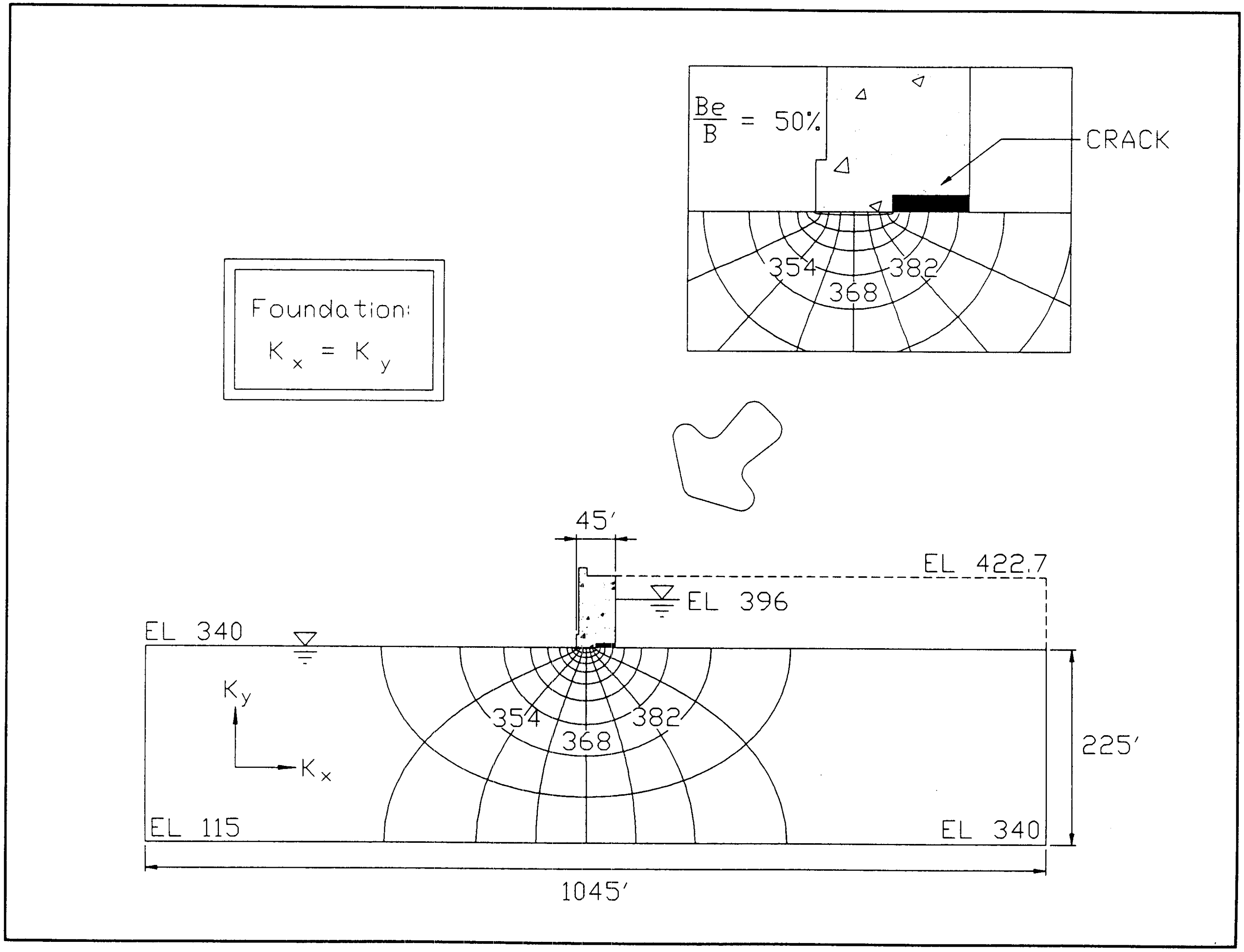

Figure 6. Results for B_e/B = 50 percent, $K_x = K_y$

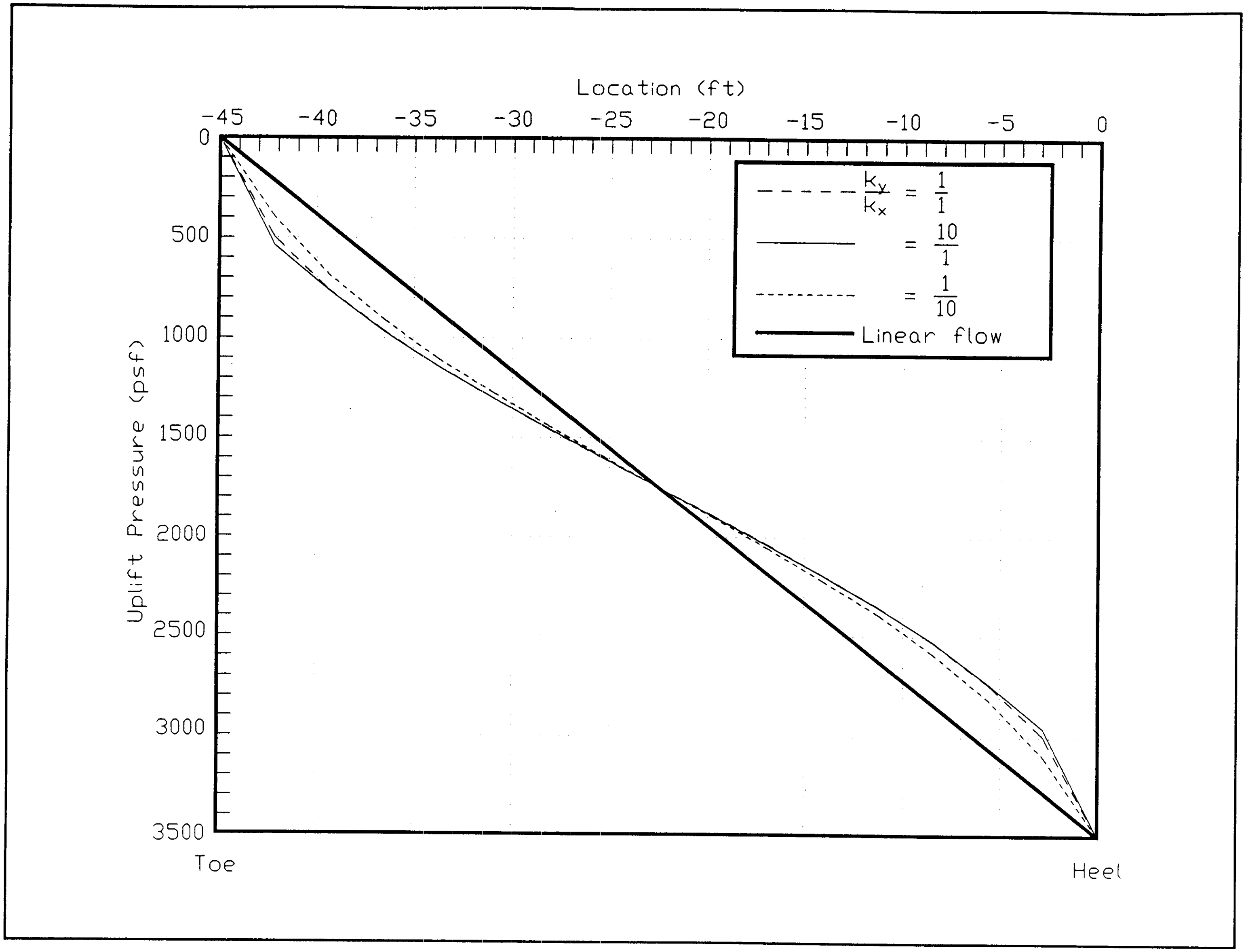

Figure 7. Uplift values for $\frac{B_e}{B}$ = 100 percent

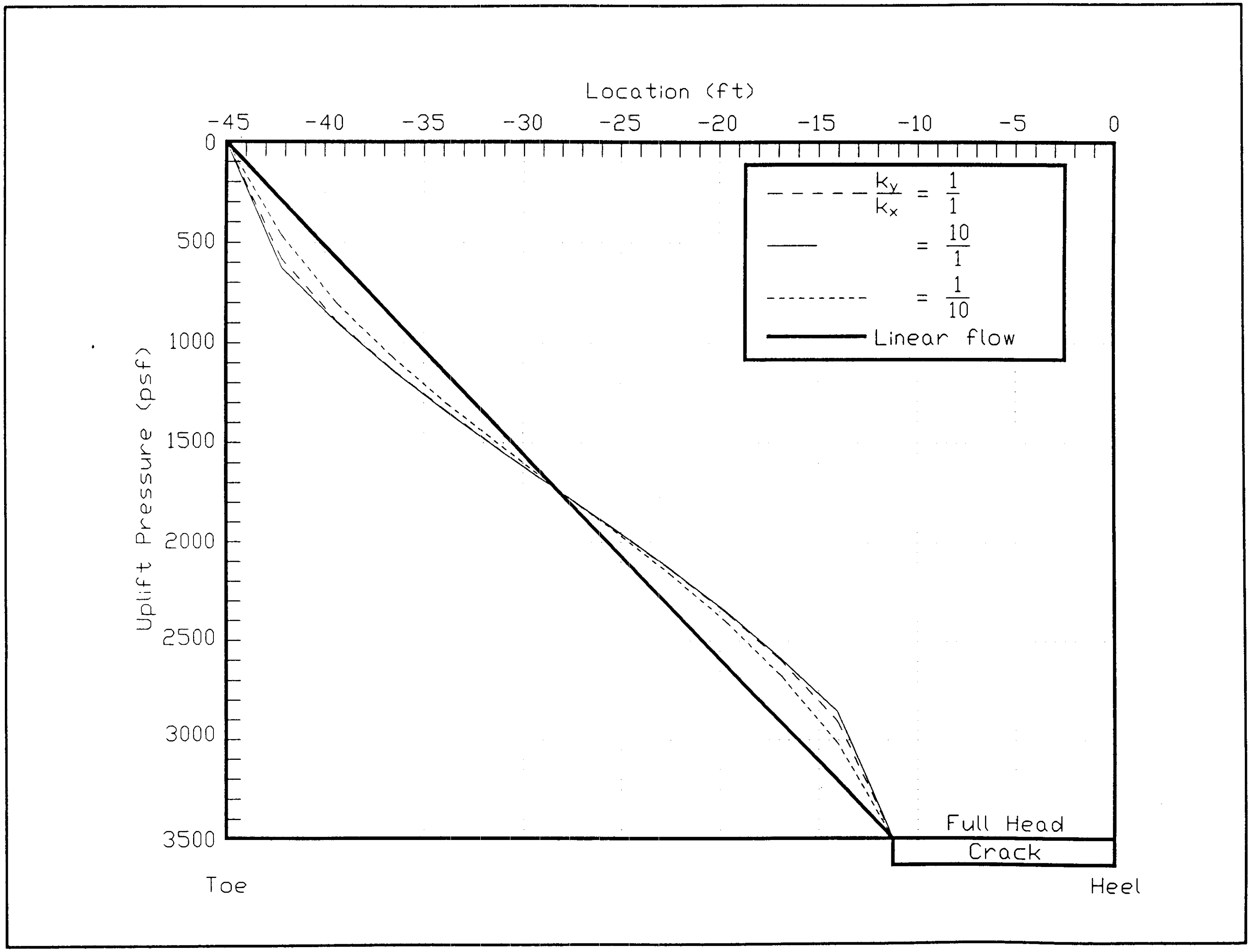

Figure 8. Uplift values for $\frac{B_e}{B}$ = 75 percent

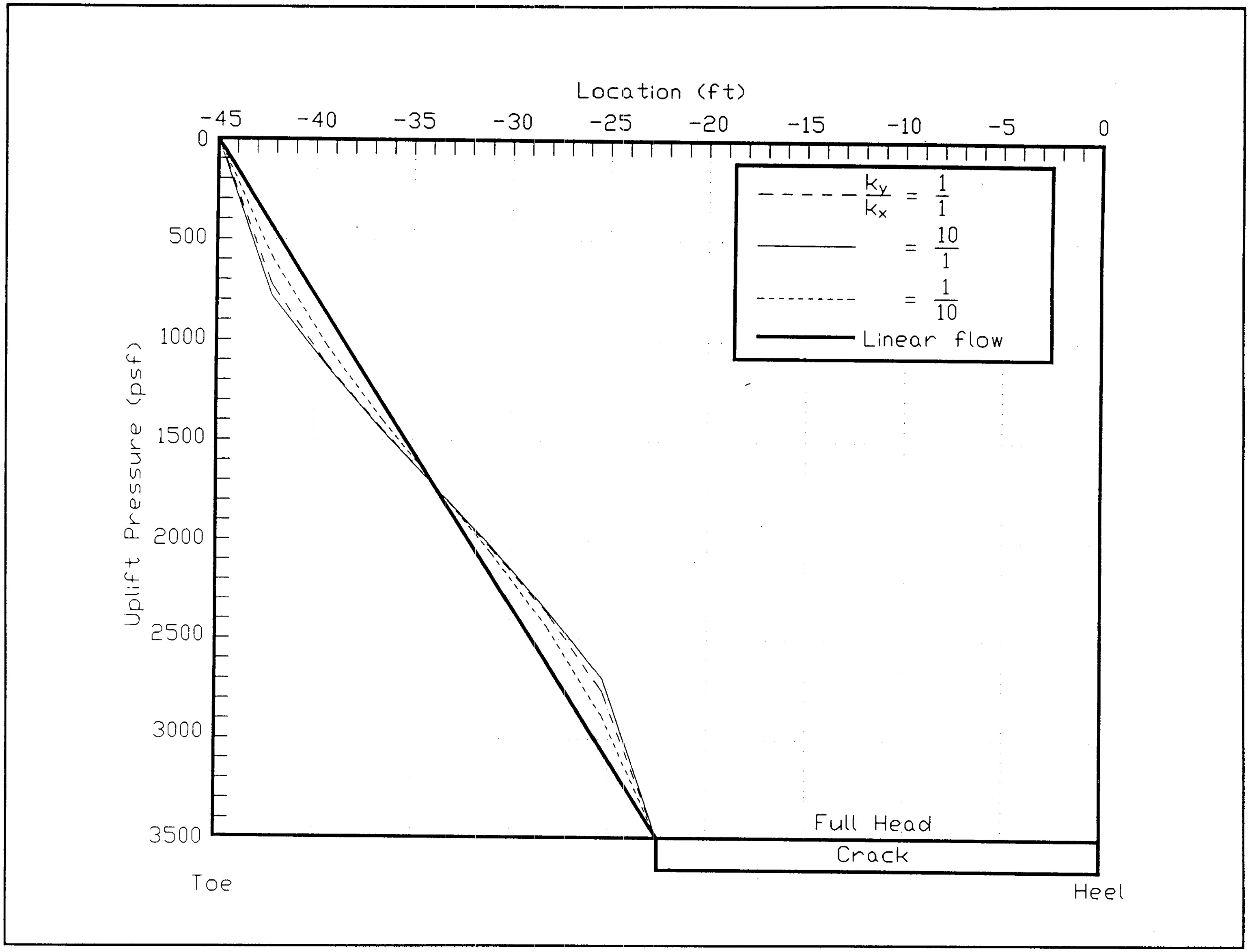

Figure 9. Uplift values for $\frac{B_e}{B}$ = 50 percent