OPTIMAL RELIABILITY OF LIFELINE LEVEE SYSTEMS UNDER MULTIPLE NATURAL HAZARDS

by

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Table of Contents

1.0 INTRODUCTION

1.1 Problem Statement and Summary

This report is concerned with the development of probabilistic performance data on levees and levee systems subject to multiple natural hazards. These probabilistic data are designed to fit into reliability and consequence scenarios useful in the making of decisions under uncertainty for the design or rehabilitation of levees from landslide, erosion, overtopping, subsidence, earthquake ground motion, and other hazards.

The key issue in the present study proved to be the estimation of probabilities of failure for an extended system (i.e., the probabilities of different levels of performance must be prescribed in terms of the extent of the levee system). It was found that the probabilistic failure analysis of a conventional slip circle landslide failure by itself is insufficient. Such analyses do not define the three dimensional extent of the failure and do not consider end effects. Vanmarcke (Ref. 1-1) solved this problem by considering a cylindrical failure surface and the correlation of material properties. Central to the three dimensional approach is the spatial correlation of material properties. This report extends the concepts of Vanmarcke to include an ellipsoidal failure surface, multi-layered levee geometry and several types of hazards.

The research presented in this report was primarily concerned with developing reasonable procedures to estimate system component probabilistic forecasts and then using these forecasts in a decision under uncertainty type of analysis involving the use of scenarios. It was found in practical engineering studies of an actual levee system that essential techniques are lacking in the rational presentation of probabilistic information to decision makers who are concerned with the portion of the levee that might fail, the extent of failure, the interactions of hazards, the time to failure, and the consequences of each likely failure sequence. It was also found that scenarios are a natural and expedient way in which to present the information.

1.2 Levee Types

In general there are two basic types of levee designs to consider:

- dry levees - levees which are in use only when a river overbanks (e.g., Mississippi River levees);
- wet levees - levees which are almost continually holding back water, although the water level may vary considerably (e.g., Sacramento-San Joaquin Delta levees).

Although they both are designed to withstand an extreme flood condition, their response to such flood conditions may be very different.

1.3 Report Organization

This report is organized as follows: Chapter 2 discusses the types of hazards and causes of failure of levee systems; emphasis is placed on natural causes. Chapter 3 discusses development of the three dimensional probabilistic stability model and its uses to study the effects of different hazards. Two general levee profiles were considered in the study. Profile C (Figure 1-1) is based on the idealized recommendation of the Corps of Engineers (Ref. 1-2). Profile W (Figure 1-2) was taken from an extensive geotechnical study of the levees of Woodward Island in the Sacramento-San Joaquin Delta area of California. These two profiles represent what are referred to as controlled and casual construction, respectively. Chapter 4 places the levee reliability problem in the context of systems analysis and decision makers in the process of designing or rehabilitating levee systems.

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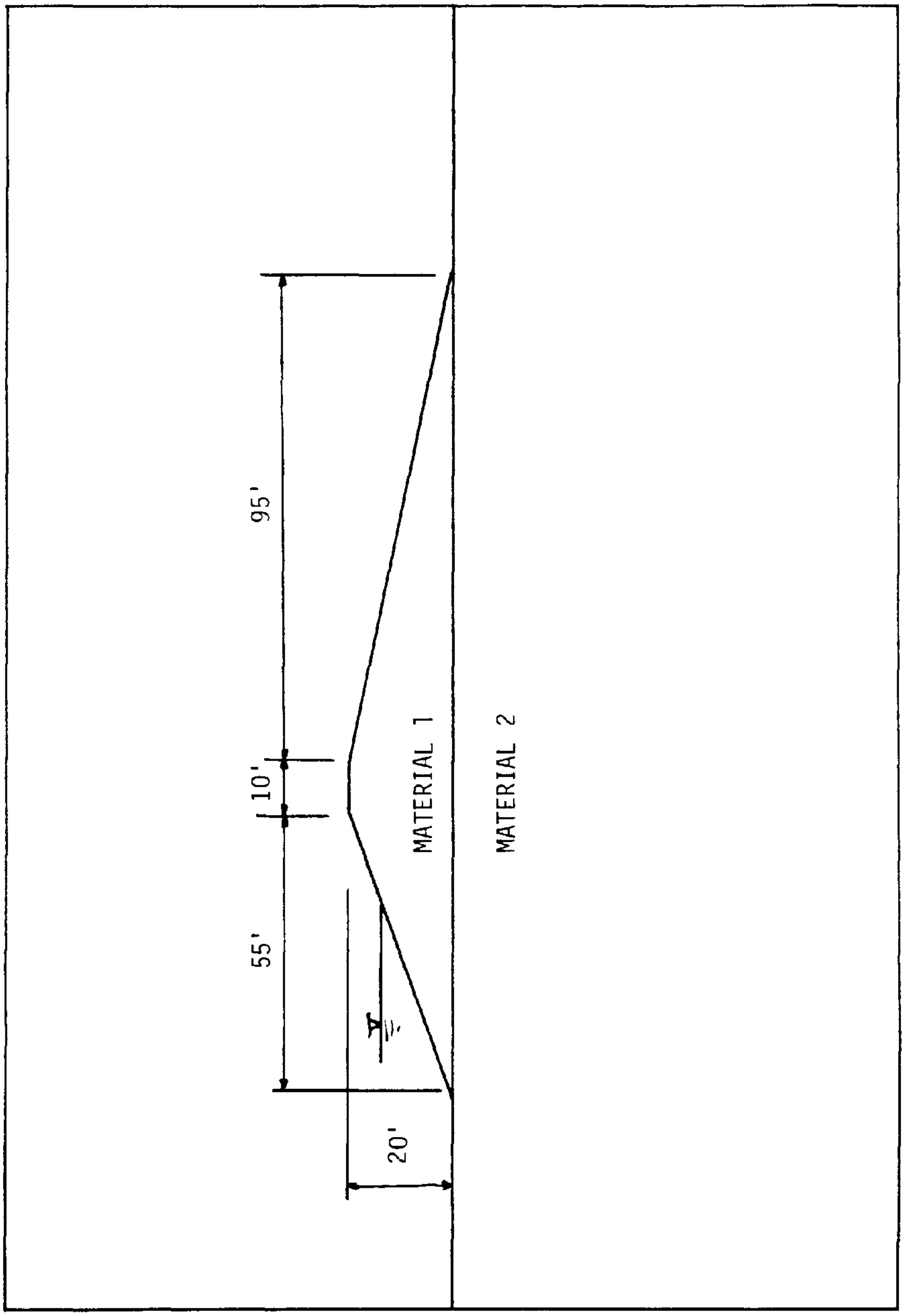

FIGURE 1-1 LEVEE PROFILE C

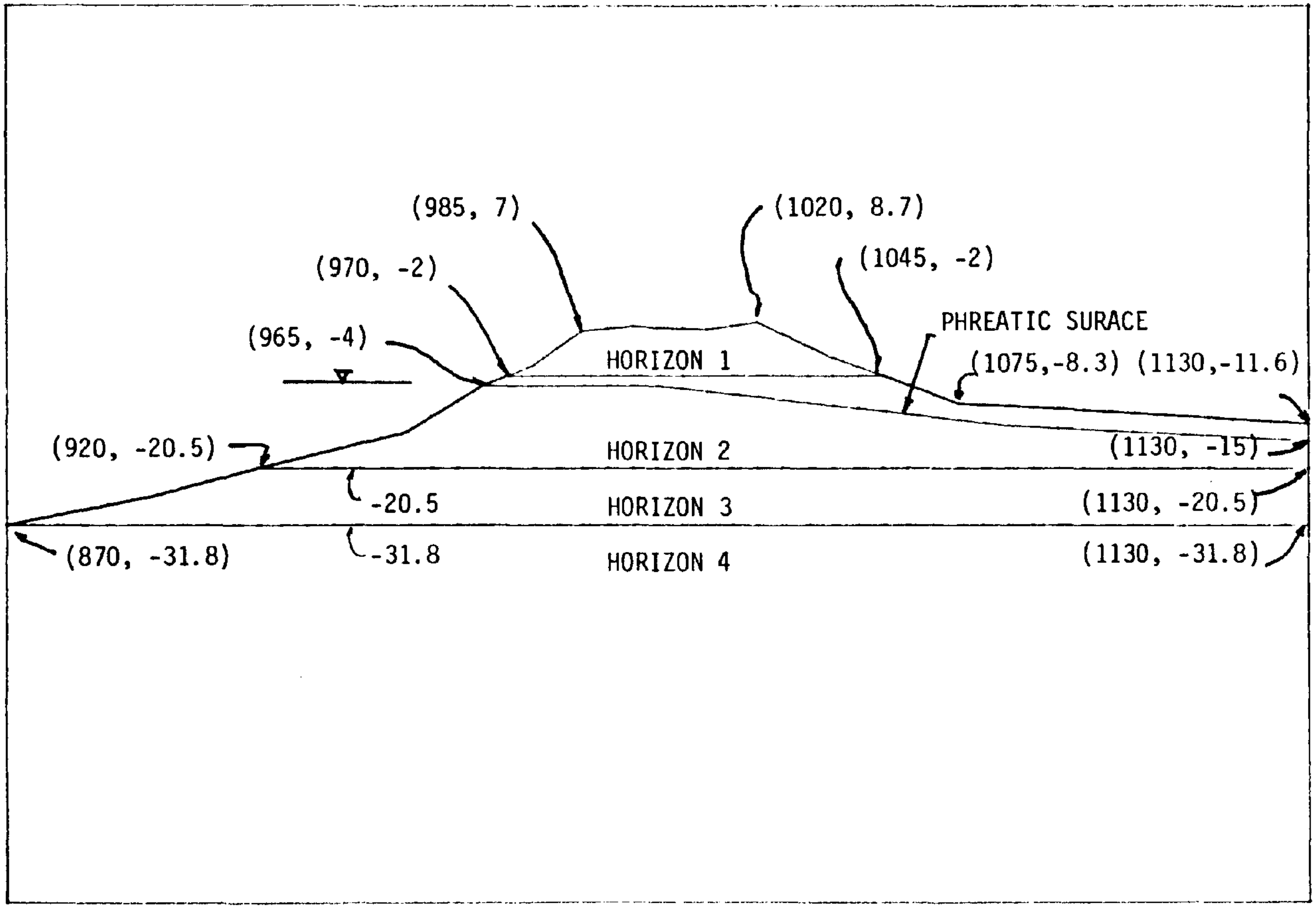

FIGURE 1-2 LEVEE PROFILE W WITH SOIL HORIZONS, COORDINATES (X, Y), AND ELEVATIONS

2. HAZARDS CAUSING FAILURE

2.1 Types of Failure

In general, a levee system is said to have failed when the protected area is flooded as a result either of water crossing the line of the levee from the riverside or water not being able to cross from the landside. The former failure can occur by overtopping from the riverside of the levee or by structural failure of the levee from hydrostatic pressure, piping, erosion, or earthquake. The latter failure can occur when accessorial facilities (i.e., pipes, pumps, ponds, and valves) fail to prevent flooding from interior drainage or through seepage.

2.1.1 Overtopping

Overtopping is caused by a flood stage which is higher than the levee crest height. Levee crest heights are usually designed to withstand specified peak flood stage plus a margin of safety which is based both on hydrologic and hydraulic considerations. However, what the designed crest height is and what the actual height is may differ considerably over time due to subsidence, erosion, compaction, etc. Levees which are poorly maintained will be more susceptible to overtopping over a period of time, because crest heights will decrease due to one or a combination of the above causes.

Flood stages for a given return period are uncertain. Hydrologic parameters used to predict discharge are based on limited historic records or on no historic data. Therefore, a level of uncertainty exists in these parameters. In addition, uncertainty exists in the hydrology of the flood. Although standard hydraulic techniques exist to predict flood profiles for given discharges, they are idealizations of a real world phenomenon which changes in time.

2.1.2 Stability

The stability failure of a levee at some location along the length is a problem in continuum mechanics, since the center of failure may occur anywhere along a reach, and the failure length can be almost any value within practical limits. In addition, the failure surface or zone of slippage may be any one of an infinite number of possibilities although failures may well be associated with a zone of weakness or a weak seam between two layers. Figure 2-1 illustrates the above three random variables, and indicates the continuum nature of each. To complicate the problem, the possible centers of failure, the lengths of failure, and the zones of slippage are all correlated to some degree with each other.

The conventional practice in evaluating existing levees is to look first at what are thought to be the weakest cross-sections, at least from the point of view of geometry. Soil samples are taken at these "weak" points and minimum factors of safety computed for a two-dimensional slice of the levee. In addition, a few "typical" cross-sections may also be evaluated. However, a systematic attempt is not made to find cross-sections with low soil strength and the three-dimensional aspects of the problem are not considered.

The failure problem of levees is analogous to the problem of a long rod subjected to an axial load F. The rod has a cross section, A, which varies randomly along the length, and has a unit strength, f_y, which also varies randomly along the length. The combination of geometry and strength is then the determining factor of whether the rod yields or not at any point, x. The probability of yield for the entire rod length, given the load F, is then:

$$P_F = \text{Prob}\left[F \geq \min_{\text{for all } x} (A(x)f_y(x))\right]$$

If the load F is also a random function of x (disregarding the issue of equilibrium) then the probability of yield becomes:

$$P_F = \text{Prob}\left[1 \geq \min_{\text{for all } x} \left(\frac{A(x)f(x)}{F(x)}\right)\right].$$

In the case of a levee slip failure, the random variables include the average shear strength, $\bar{S}$, over the slip surface, the area of the slip surface, A, the radius of rotation, R, and the driving moment (assuming a circular arc surface), M. These variables are not only a function of the location along the levee, but also the geometry of the cross section, the unit weights of the materials, and the angle of internal friction. Thus, the probability of slip failure is:

$$P_F = \text{Prob}\left[1 \geq \min_{\text{for all } x} \left(\frac{\bar{S}AR}{M}\right)\right].$$

2.1.3 Mechanical

Although they are not considered to be in the realm of failures due to natural causes, mechanical (and/or electrical) failure of drainage structures, closure structures, and pumping plant equipment have been identified (Ref. 2-1) as one of three major failure types. These devices are similar to other mechanical or electrical equipment and are subject to operation and maintenance requirements. The reliability and availability of these items during flood events must be included in the overall system reliability model.

2.2 Causes of Failure

Many failures have been associated with circumstances or mechanisms outside conventional theoretical analysis. Most of these failures occur not because of the inadequacies in the state of the art, but because of oversights that could have been avoided, or poorly understood phenomena. The probabilities of failure of levees could decrease if the causes not easily analyzed were dealt with rationally by acknowledging and quantifying the uncertainty involved.

2.2.1 Flood Depth

Although there is no consistent rational basis for doing so, most levee systems in the United States are designed to withstand the 100-year return period flood stage without overtopping. However, the 100-year return period flood cannot be predicted with certainty. This is due to a number of factors. The first is the definition of the 100-year flood. One hundred years is the return period or recurrence internal for this flood level and is defined as the average number of years within which this event will be equaled or exceeded. Since it is only the average number of years, there is approximately a 33 percent chance that the "true" number of years is less than 100.

Other factors which must be considered in predicting a given flood stage are hydrologic and hydraulic uncertainty. Hydrologic design is generally based on past events and any attempt to predict future events must be based on probability. Haan (Ref. 2-2) has pointed out the the hydrologic probability model may be rainfall input to a hydraulic model, to predict runoff, or a flood level frequency curve based on historical stream flows. In the former, not only is there hydrologic uncertainty, but hydraulic modeling uncertainty as well.

To calculate the exceedance probability requires that the engineer select a probability model for maximum floods. Very often this distribution is assumed to be either the extreme-value type I distribution or the log-Pearson distribution, fit to the available historic data.

Uncertainty exists in selecting the underlying distribution parameters, since the recorded data are only a sample of the population, and the sample statistics (average and standard deviation and coefficient of skewness) are only point estimates of the "true" population mean and standard deviation and coefficient of skewness.

The traditional engineering approach for considering uncertainties is to develop confidence limits on the "true" model parameters, and then assume an arbitrarily conservative value for each parameter based on a preselected confidence level. This approach has a serious drawback, however, in that it results in the use of design values associated with unknown levels of conservatism.

A more rational approach for considering uncertainties in predicting maximum floods is to treat the "true" parameters as random variables (more precisely, as functions of random variables, namely the maximum annual floods) with a distribution function f(θ) which may be updated by gathering data (i.e., flood stage data for n years) and using Bayes' theorem (Ref. 1-6 and 2-3). Knowing the distribution of the model parameters, the unconditional exceedance probability for maximum annual flood magnitude, x, is computed using the total probability theorem:

$$p_X = P[X \geq x] = \int_{\text{all } \theta} P[X \geq x | \theta] f(\theta) d\theta .$$

In words, the conditional probability, $P[X \geq x|\theta]$, which is computed using the assumed probability model, with parameters θ, is multiplied by the probability of those parameter values actually being the "true" values, and this product is summed over all possible values of the "true" parameters.

The joint distribution of the parameters may be based solely on subjective judgment, if there is no recorded data, or it may be the result of combining the sample likelihood function (likelihood of observing the recorded data) and a uniform or other prior distribution. In this latter case, the posterior distribution of the model parameters (the one which is used to compute the exceedance probability) is the product of three factors:

$$\left(\begin{array}{c}\text{Posterior distribution}\\ \text{of parameters, given}\\ \text{the recorded data}\end{array}\right) = \left(\begin{array}{c}\text{normalizing}\\ \text{constant}\end{array}\right)\left(\begin{array}{c}\text{Sample likeli-}\\ \text{hood, given}\\ \text{parameters}\end{array}\right)\left(\begin{array}{c}\text{Prior distri-}\\ \text{bution of}\\ \text{parameters,}\\ \text{without knowing}\\ \text{the recorded}\\ \text{data}\end{array}\right)$$

or $$f''(\theta) = NL(\theta|x_1, \ldots x_n)f'(\theta), \qquad \text{for all } \theta.$$

The normalizing constant, N, insures that $f''(\theta)$ is a proper probability density function. Thus,

$$N = \frac{1}{\int\limits_{\text{all } \theta} L(\theta|x_1, \ldots x_n)f'(\theta)d\theta} .$$

The sample likelihood function is a function of the model parameters, θ, and is written:

$$L(\theta|X_1 = x_1, \dots x_n = x_n) = \pi_{i=1}^{n} f(X_i = x_i|\theta),$$

where $f(X_I|\theta)$ is the assumed underlying distribution of maximum annual floods. For example, if the distribution were assumed to be extreme-value type I (Gumbel), then the likelihood function would be written:

$$L(m_X, \sigma_X|x_1, \dots x_n) = \pi_{i=1}^{n} \alpha\exp\{-\alpha(x_i-u) - \exp[-\alpha(x_i-u)]\},$$

where $\alpha = 1.282 / \sigma_X$, and $u = m_X - 0.450\sigma_X$ (Ref. 2-4). The model parameters, m_X and σ_X are uncertain.

Assuming a log-Pearson distribution, there would be three model parameters to consider, m_Y, σ_Y, and γ_Y (coefficient of skewness), where $Y = \ell n(X)$, and X is the maximum annual flood. The sample likelihood function for a log-Pearson probability distribution is written:

$$L(m_y, \sigma_Y, \gamma_Y|y_1, \dots y_n) = \pi_{i=1}^{n} \frac{1}{|\beta|\Gamma(\alpha)} [(y_i-c)/\beta^{\alpha-1}\exp(y-c)/\beta],$$

$$\text{for } c \leq y_i < \infty \quad (\beta > 0),$$
$$-\infty < y_i \leq c \quad (\beta < 0),$$

where

$$\alpha = (2/\gamma_y)^2,$$
$$\beta = \sigma_y\gamma_y/2,$$
$$c = m_y - \frac{2\sigma_y}{\gamma_y},$$

and $\Gamma(\cdot)$ is the gamma function.

If the probability of exceeding the maximum annual flood magnitude, x, in any one year is p_x, then the probability of nonexceedance in one year is $1 - p_x$, and the probability of nonexceedance in m years is written:

$$P_x[NE_m] = (1-p_x)^m$$

Solving for m, the number of years for which there is a probability $P_x[NE_m]$ of not exceeding flood level x,

$$m = \ln(P_x[NE_m])/\ln(1-p_x)$$

Conversely, the magnitude of the design maximum annual flood, x, corresponding to a specified probability of nonexceedance in a specified number of years, m, is found first by solving the above equation for p_x:

$$p_x = 1-(P_x[NE_m])^{1/m}$$

Once p_x is picked a trial and error procedure is used to determine x from the unconditional probability.

Tang and Yen (Ref. 2-5) account for model uncertainty by introducing a multiplicative factor which has a mean and variance. Unfortunately, no data is available regarding the variability of this factor, and therefore the level of uncertainty is subjective. Although, intuitively, we believe that the fewer simplifying assumptions used in the adopted formulation the less uncertainty in the model there will be.

Uncertainty in flood discharges can be translated into corresponding uncertainty in flood stage using standard hydraulic techniques. Stream reaches with a high degree of hydraulic sensitivity (i.e., relatively great changes in stage results from a relatively small change in discharge) will have a greater tendency for levee overtopping than less sensitive ones.

Other factors that must be assessed in the evaluation of the hydraulic uncertainty are the potential and magnitude of debris or sediment accumulation or ice jamming during the discharge event. Sources of debris, sediment, and ice in upstream areas should be considered, as well as any historical evidence of ice or debris blockage or sediment deposition. The behavior of such materials within the leveed reach, and particularly at bends or constrictions, must be considered.

Flood stages for a given flow can change over time due to a variety of factors, and any change will alter the hydrologic risk. Changes affecting flood stage include:

- increased land use change that results in increased runoff volumes, shorter times of concentration, and greater peak discharges for events having the same meteorological characteristics;

- removal of natural valley storage and conveyance due to excess encroachment in floodplains, including construction of levee systems, resulting in higher stages and discharges;

- construction of reservoirs that modify the flows so that historical records cannot be used for current risk assessment without hydrologic reanalysis;

- changes to river bed or bank geomorphology or vegetative cover that significantly alter stage-discharge relationships and flood elevations.

2.2.2 Flood Exposure

Even though levees are generally designed such that the probability of overtopping is small, levees exposed to flood stages lower than the crest for long durations are susceptible to damage and even failure due to loss of stability, underseepage, sand boils, and wave erosion. Bogardi (Ref. 2-6) introduced the concept of "flood exposure" to take account of the combined effects of flood stage and duration on levee systems. He defined flood exposure as the area under the hydrograph of high water stages exceeding a specified limit, usually the toe elevation (for dry levees). At times of high water stages the following adverse phenomena have been observed along flood levees:

- saturation, loss of stability;
- underseepage and leakage;
- boil formation;
- wave erosion.

Saturation occurs generally by seepage below and laterally through the levee body by increased hydraulic pressure. Responding on the relative permeabilities of the levee material and substrata, seepage will occur either more rapidly through the levee material, in which case stability is weakened and leakage is common, or through the substrata, in which case underseepage and boil formation with possible crevassing on the landside of the levee is likely.

Flood exposure is the function of two random variables, flood stage and duration. To determine the resistance to such a load, it is necessary to perform stability analyses in which slope stability is calculated for a time dependent zone of saturation. Determining the transient motion of the zone of saturation in an embankment can be time consuming and difficult. An example from Reference 2-7 of the movement of the zone of saturation is shown in Figure 2-2a, with a typical saturation line secant-versus-time plot shown in 2-2b. A simplified approach appears to be in order for use in determining levee stability. The two main assumptions made in this approximation are:

- the time required for full saturation can be estimated, if permeability and porosity data are available for the levee, material;
- the shape of a moving saturation line in a homogeneous section is independent of the soil permeability, provided the permeability remains constant along the moving saturation line.

The shape of the zone of saturation may be determined from transient flow nets, and depends on embankment geometry, initial and final water depth, and initial phreatic surface. For our purposes it is adequate to model the moving zone of saturation as a straight line, making an angle with the riverside slope of the levee, as shown in Figure 2-3. The equation of line AB is given in terms of $\theta(t)$, α and d:

$$h(x, t) = \frac{x}{\tan\left[\theta(t)-\pi/2-\alpha\right]} + d$$

This equation assumes that the moving surface is a straight line rotating about point A.

From Reference 2-7 the time required for the saturation line to move through each incremental distance Δl is written:

$$\Delta t = \Delta l / v_{sl},$$

where: $v_{si} = ki/n_e$,

k = permeability,

n_e = porosity,

i = average hydraulic gradient in the incremental distance, Δl.

The total time to complete the saturation is written:

$$T = \Sigma \Delta t = \frac{n_e}{k} \Sigma \frac{\Delta l}{i} .$$

Using this method, Cedergren (Ref. 2-7) developed a graph for approximating the time of saturation of earth structures in the general shape of a levee or dam (see Figure 2-4). The chart shown in Figure 2-4 is based on an effective porosity of 0.25 and h = 1 foot, and neglects capillarity. To estimate the time of saturation of a levee, the time determined from Figure 2-4 is multiplied by the height in feet of the final water stage above the initial water stage. Note that in order to apply this procedure to the levee problem in the manner described, it is necessary to make the following approximations:

- the initial phreatic surface acts as an impervious surface and motion of the saturation line is as shown in Figure 2-3;
- the length, L, is measured from the point where the initial water stage intercepts the riverside slope to the landside toe of the levee.

Stability of the levee at any time after the onset of a flood exposure event can then be determined.

Immediately following a flood event for which a rapid decrease in flood stage occurs, stability of a levee may be compromised due to the changing shape of the zone of saturation. During a rapid drawdown, the saturation line may be obtained by the transient flow-net method (Ref. 2-7), which considers a succession of transient flow nets. Browzin

(Ref. 2-8) proposed a mathematical model of the time dependent nature of the saturation line shown in Figure 2-5. The proposed relationship is written:

$$t_H = \frac{cn_e}{2k} L\ C_1\left(\frac{H_1}{H}\right) + C_2 \ln \frac{H}{H_1} + C_3 \left(1 - \frac{H}{H_1}\right),$$

where n_e = effective porosity,

k = coefficient of permeability,

and coefficients C_1, C_2, and C_3 are found from Figure 2-6. The factor c is introduced to correct possible biases resulting from assumptions made, and ranges from about 0.9 to 1.4. The shape of the saturation line is assumed to be elliptical, so that:

$$\frac{h^2}{H^2} + \frac{x^2}{a^2} = 1 .$$

Solving these equations at time, t_H, after the end of a flood exposure event will allow us to determine the stability of the levee as a function of time.

If the levee fails, flooding of the protected area would happen only if a second flood event occurs before the levee is repaired. Otherwise, this type of failure would not be the cause of flooding.

2.2.3 Erosion

2.2.3.1 External Erosion

External erosion of levees is generally caused by either wind-wave action, or flow velocity (scouring). In the case of wind-wave action Bogardi (Ref. 2-9) describes the hazard to the levee in terms of a critical degree of protection. The following development of the distribution function for this load is from Reference 2-9.

The flood stage, h_1, and the additional wave effect, h_m, result in the total height, h_T. The value, h_m, is composed of the wave height due to wind plus run-up on the slope. The task is to determine the distribution function of the random variable, h_T, where:

$$F(h_T) = F(h_1+h_m) \ .$$

The model assumes that the random variables, h_1 and h_m, are independent. The distribution function of the annual highest stages, h_1, is assumed to be known and available from characteristic stream gauges. For the calculation of wave effect, h_m, the basic relationship is the following:

$$h_{m_i} = f(D_i,\ v_i,\ \tan\alpha,\ \cos\beta), \qquad \text{(See Figure 2-7)}.$$

Therefore, referring to the notation given in Figure 2-7, the wave effect on the cross section due to the wind having direction S depends on the corresponding fetch length, D_i, wind velocity, v_i, angle of levee slope, and the angle between the tangent of the levee and the examined direction. For the sake of simplicity only the most important variables have been mentioned.

In practice, the inundation area along the flat-slope reaches of large rivers is several kilometers wide. For these conditions the flood wave peak may last several days and during this period the water level changes very little. This justifies approximating the stochastic flood wave hydrograph by a constant peak value of random duration. Obviously, the highest waves occuring during this period may create the critical erosion situation.

From past records covering several years of wind measurements of the meteorological stations situated in the vicinity of the investigated levee section, maximum wind velocities for different directions (for instance for the eight main directions) and for different durations could be used. According to the above relationship, the maximum wave effect for different directions can be calculated for the critical period. The highest of these gives one sample element of h_m. Naturally, the probability of the yearly highest waterlevels occurring in different months of the year should be considered and the distribution of the wave effect, corresponding to the monthly critical period should be weighted with the appropriate probabilities.

Other types of external erosion are caused by excessive stream velocity, unstable streambed, and channel configurations which contribute to water flows impinging on levees and causing scour. When bank protection is subjected to stable currents, then surface erosion will occur when the tractive force produced by flow velocity exceeds the critical tractive force for levee surface protection. In addition, waves caused by unstable streambed formations near the levee, or flow impingement on the levee produce uplift pressures in combination with stream velocity and can cause surface erosion when tractive forces are smaller than critical. Consequently, when bank protection is designed for flow velocity alone and significant waves occur along the bank, surface erosion may occur for flows substantially less than the design flow.

Scour may be the result of unforeseen circumstances. An example is given in Reference 2-10, which describes a levee failure caused by scour. Naturally carried sediments were deposited upstream of a channel inlet, and, subsequently, sediment-free water was delivered to a rather steeply sloped reach. This was responsible for general streambed degradation downstream of the channel. In addition, channel meandering resulted in flow impingement on the levee causing deep scour at the riverside toe. The angle of impingment was estimated to be approximately 25 degrees.

Wide streams which are free to meander will have points and angles of impingement which are uncertain and should be addressed in design using probabilities.

2.2.3.2 Internal Erosion

Turnbull and Mansur (Ref. 2-11) made the following observations regarding underseepage and sand boils:

- sand boils are the result of excessive hydrostatic pressure and seepage through deep pervious strata underlying levees - severity is dependent upon the water head, source of seepage, perviousness of substratum, and characteristics of the landside top stratum;

- there is a positive correlation between surface geology and location and occurrence of sand boils;

- seepage flow and hydrostatic heads landward of a levee can be estimated theoretically, from piezometric data, and a knowledge of the foundation conditions.

Failure due to seepage is progressive. Seepage under or through a levee applies pressure to the soil particles, and if the pressure is great enough to carry or lift the particles, a sand boil or piping of materials from below or within the levee occurs. Piping, or sand boiling, does not in itself constitute failure of the levee, however. Either slope instability or the phenomenon of crevassing must occur as a result of piping in order that a levee fail from seepage. Turnbull and Mansur (Ref. 2-11) made the statement that "although a number of levee crevasses have occurred as a result of critical substratum pressures and concentrated seepage in the form of sand boils or piping it is practically impossible to predict." If, however, data related to underseepage and crevassing does exist, it appears possible to predict the occurrence of crevassing probabilistically, given the occurrence of piping or sand boils.

A pre-flood event condition which also influences the occurrence of piping or boiling is the amount and availability of substratum storage capacity on the landside of the levee. If a large storage capacity is available and a flood occurs, there may be a lag time of several days before seepage problems occur, simply because the substratum storage volume must be filled before the pressure under the top stratum can be built up. By that time the flood may have dissipated. On the other hand, if the storage volume is already filled or nearly filled by previous storms, seepage related problems may be coincident with the present flood event.

Seepage flow and hydrostatic heads landward of a levee can be estimated from theoretical considerations, piezometric data and knowledge of the underlying strata. Obviously the accuracy of such methods dependens on the degree of uncertainty in the parameters used in the formulations and the sensitivity to those parameters excluded.

Not all factors which influence the seepage flow and pressure lend themselves to theoretical analysis. Some of these factors include stratification of the foundation, lense deposits, and nonuniformity of the top stratum. However, some of the influences which may be evaluated are as follows:

- semi-infinite unconfined aquifer (Ref. 2-12) - for a sudden rise in the water stage from an initial steady state level of H_0 to H_1 (See Figure 2-8a), the change in head at a point x away from the river bank is written:

$$h^2(x, t) = H_0^2+(H_1^2-H_0^2)\mathrm{erfc}\left(\frac{x}{2\sqrt{Dt}}\right) ,$$

where: $D = (k_f-h)/E$,

k_f = horizontal permeability of aquifer,

$h = 0.5\ [H_0 + h(x,t)]$,

E = specific yield of aquifer,

and erfc (•) is the complementary error function;

- finite unconfined aquifer (Ref. 2-12) - for a sudden rise in the water stage from an initial steady state level of H_0 to H_1 in the river (See Figure 2-8b), the change in head at a point x away from the river bank is written:

$$h^2(x, t) = H_0^2+(H_1^2-H_0^2)\{\sum_{n=0}^{\infty}(-1)^n[\mathrm{erfc}(\frac{2Ln+x}{2\sqrt{Dt}} + \mathrm{erfc}(\frac{2Ln+2L-x}{2\sqrt{Dt}})]\},$$

  where L is the horizontal distance from the river bank to the barrier boundary.

Another cause of internal erosion, and one which does not readily lend itself to analytical evaluation, is animal burrowing and activity (Ref. 2-13). Burrows of animals (squirrels, beavers, muskrats) in levees may increase seepage and provide a path for water to flow during high water stages.

2.2.4 Settlement and Subsidence

Levees depend to some extent on freeboard to compensate for the lowering of crest height due to settlement and subsidence. It was pointed out in Reference 2-1 that levees with minimal or no compaction, or where embankment or foundation materials are undrained or composed of materials of high compressibility, will often experience a significant amount of postconstruction settlement. This settlement can result in losses of freeboard as much as 15 percent of the total levee height. These settlement losses will contribute to increased chances of overtopping and/or stability problems.

Another very important hazard which causes failure of some types of levees (particularly levees protecting highly organic lands used for agriculture) is subsidence of the levee and protected areas. In one study of the Sacramento-San Joaquin Delta area (Ref. 2-14), subsidence rates for islands and tracts protected by levees is as much as three inches per year. These subsidence rates have resulted in protected lands being below normal water levels by as much as 10 to 20 feet, thereby increasing the pressure on levees significantly.

Primary causes of subsidence were found to be soil oxidation and shrinkage. Additional causes, some of which may be substantial in localized areas, are wind erosion, burning, man-caused compaction, removal of soil, geologic (tectonic) subsidence and withdrawal of gas or ground water.

2.2.5 Earthquake

Earthquake ground motion can cause sliding failure either as a result of the change in material mechanical properties by liquefying, and/or an increase in loading by imposing an addition driving force in the horizontal direction.

Other possible impacts on levees resulting from earthquake ground shaking include (Ref. 2-15):

- compaction and settlement of levees or foundations;
- lateral spreading of levees or foundations;
- slumping;
- ground cracking;
- lurching of levees;
- erosion or overtopping by earthquake generated waves (seiches).

The potential hazards caused by earthquakes are greatest during high water when levees are already under high stress. The likelihood of such a combination of events is greatest for wet levees in areas such as the Sacramento-San Joaquin Delta. However, Mississippi River levees during flood season are also vulnerable for extended periods of time.

2.2.5.1 Inertia Load

The acceleration of the soil in an earthquake is another potential source of failure. Conventionally, the soil is simply assumed to be accelerated and this is an added driving force. With levees, the possibility of site amplification and the influence of water entrapped in the levee must be considered. The site amplification analysis requires a first mode approximation for the levee as a shear beam above the soil level where the ground motion is assumed imposed. Levee profiles will in general involve relatively long periods for casual construction, such as found in the Sacramento-San Joaquin Delta. Engineered fills, such as earth dams, produce stiffer materials and thus shorter periods along with decreased ability to deform without cracking.

2.2.5.2 Liquefaction

At this time, the state of knowledge of liquefaction does not allow the definition of the volume of material that loses its strength through increase in pore pressure. Hydraulically placed sands, for example, can lose their strength (friction) with a sufficient level or duration of vibration or both. One measure of the potential to fail is the number of blow counts it takes to move a standard probe one foot in the field. In effect, if the soil is highly likely to liquify, the blows of the sampling device on the soil will indicate this potential and the number of blows per foot will be small.

Liquefaction is an "either-or" phenomenon; either it does or does not occur for a given earthquake motion at a given site. Apparently, only sandy soils are prone to liquefaction, and it must, therefore, be determined whether a site has susceptible soil.

Seed and Idriss (Ref. 2-16) and more recently Seed, Idriss, and Grango (Ref. 2-17) presented a simplified procedure for evaluating the liquefaction potential for sand deposits. The procedure expresses the ratio of the average cyclic shear stress, τ_h, developed as a result of earthquake ground motion to the effective over burden stress, σ'_o, in terms of the maximum acceleration felt at the site. The relationship is written:

$$\tau_h/\sigma'_0 \simeq 0.65 a_m \frac{\sigma_0}{\sigma'_0} r_d ,$$

where: a_m = maximum ground acceleration,

σ_o = total overburden pressure,

σ'_o = effective overburden pressure,

r_d = is a stress reduction factor varying from 1.0 at ground surface to 0.90 at 30 feet and 0.75 at 50 feet.

Values of this ratio are then correlated with site soil parameters, such as the corrected standard penetration test (SPT) data for sites which have and have not liquified during earthquake. The SPT data is the number of blow counts per foot of penetration at different locations and depths. The correlated blow count is written:

$$N_1 = C_N N,$$

where C_N = the correction factor as a function of overburden pressure,

N = Standard penetration test (SPT) blow count at the particular point in the field being investigated.

The SPT blow counts, N, which measures resistance to liquification, varies from point to point within a layer. This means that for a given earthquake load, portions of a layer may liquify, while other portions may not. A useful tool in the probabilistic slope stability analysis of a levee section or reach would be an estimate of the percentage of a layer which liquifies during a given earthquake event. If, for example, 50 percent of a layer liquifies during a particular ground motion, then the average shear strength of the whole layer for use in the slope-stability analysis would be halved.

The delineation between the soil resistance that is adequate, and that which is inadequate, to prevent liquefaction for a given ground motion is shown in Figure 2-9. This delineation was empirically developed from field observations. The line of demarcation between liquefaction and non-liquefaction is obviously not fixed and could be considered a random variable, with the line shown in Figure 2-9 simply representing a mean value relationship between the strength parameter, N_1, and the cyclic stress ration causing liquefaction.

The linear portion of the mean value relationship is written:

$$m_{N_1} = 87.7\tau_h/\sigma_0' \; .$$

Assuming a coefficient of variation of 0.20, the standard deviation of N_1 is:

$$\sigma_{N_1} = (0.2)(87.7)\tau_h/\sigma_0' = 17.5\tau_h/\sigma_0' \; .$$

With this information, field data on the distribution of SPT blow counts in a given layer, and the distribution of σ_0', the probabilities of various percentages of a layer liquifying may be estimated for a given maximum ground acceleration. For example, the probability of at least 50 percent of a layer liquifying given an earthquake ground acceleration, a_m, and effective overburden is written:

$$P[N_{1R(50)} - N_{1L} \leq 0 \,|a_{max}, \sigma_0'] = \int_{N_{1R(50)}}^{\infty} f(N_{1L} \,|a_{max}, \sigma_0') dN_{1L},$$

where $N_{1R(50)}$ = fifty percentile corrected blow count as measured in the field,

N_{1L} = the corrected blow count corresponding to liquefaction for a given ground acceleration.

One such field study determined that the distribution of SPT blow counts in a sand layer was such that $N_{1R(25)} = 7.56$, $N_{1R(50)} = 10.8$, $N_{1R(75)} = 16.2$, and $N_{1R(100)} = 41.0$. The mean value of N_{1L} for σ_o' equal to 1,640 pounds per square foot was estimated to be 11.9, with a standard deviation of 2.38. Assuming a normal distribution and an earthquake with $a_m = 0.2g$, there is a 99.97 percent chance that at least 25 percent of the layer liquifies. There is a 99.7 chance that at least 50 percent of the layer liquifies. There is a 94.6 percent chance that at least 75 percent of the layer liquifies, but there is only a 0.02 percent chance that 100 percent of the layer will liquify.

If earthquakes are a hazard to a particular levee system, then this type of information becomes a necessary building block in the overall seismic risk assessment.

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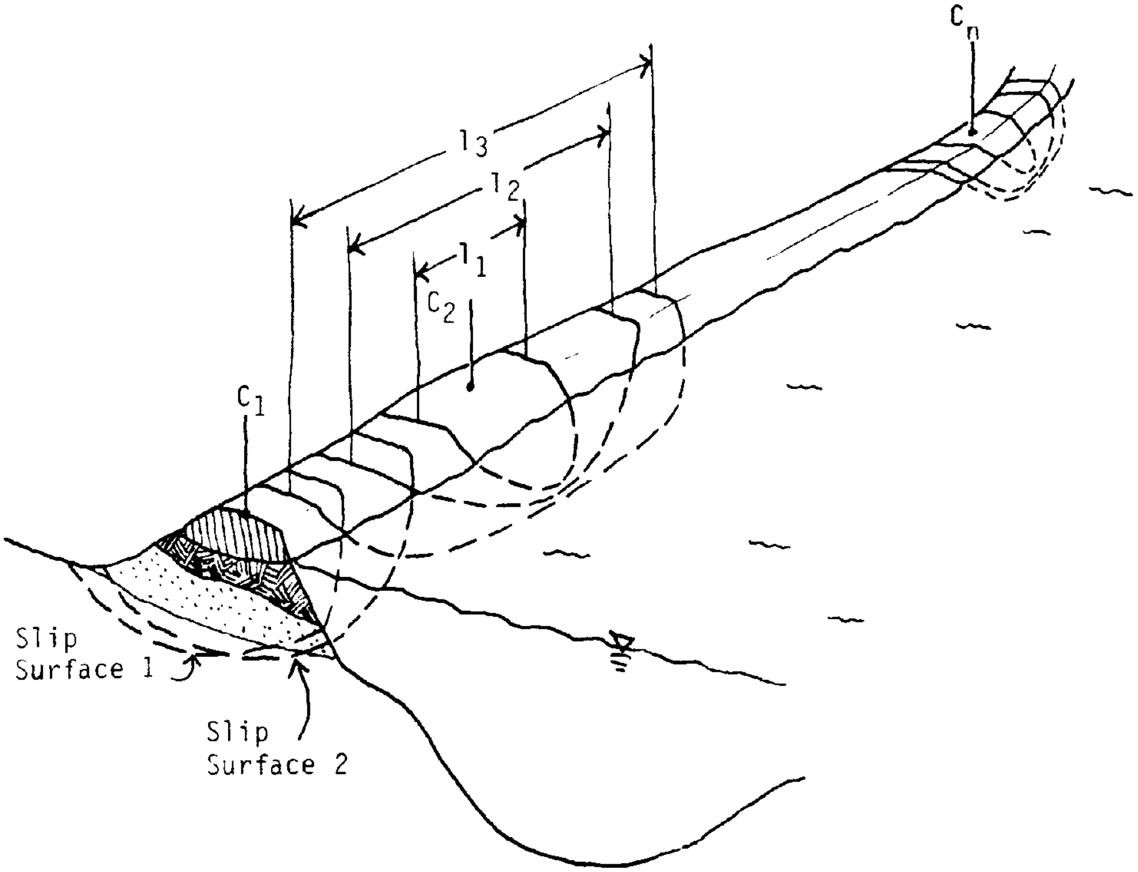


FIGURE 2-1 POSSIBLE STABILITY FAILURE MODES

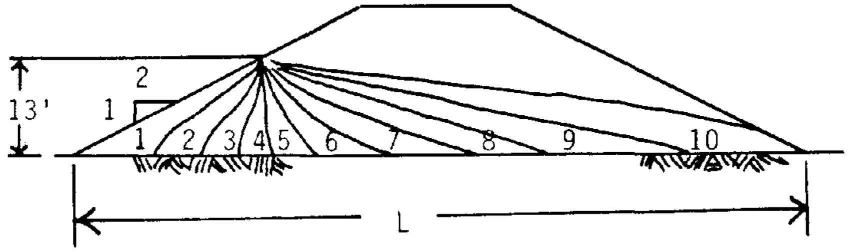


FIGURE 2a TIME MOVEMENT OF ZONE OF SATURATION

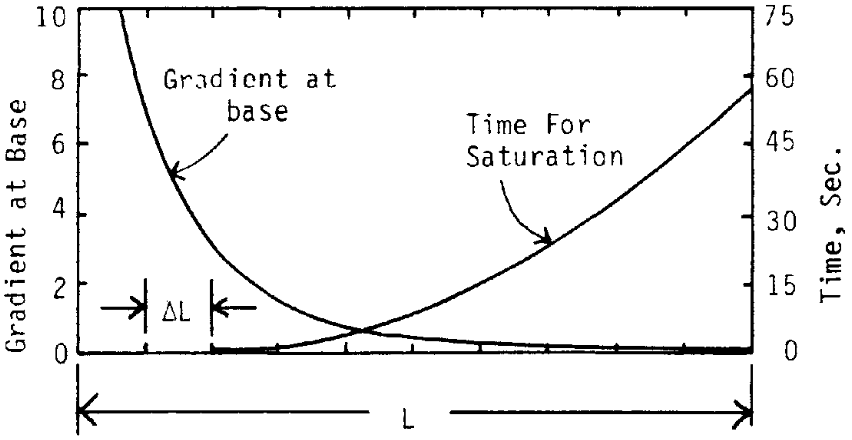


FIGURE 2b SATURATION LINE SECANT-TIME PLOT

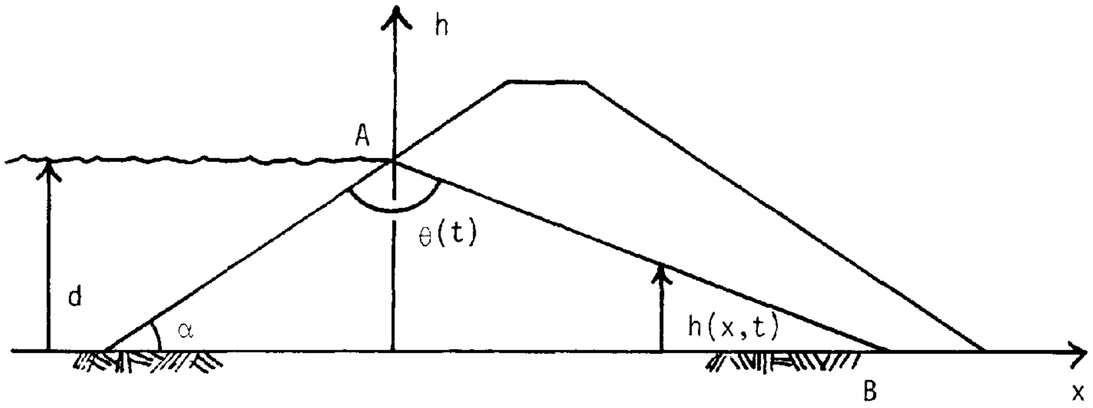


FIGURE 2-3 SIMPLIFIED SATURATION LINE - TIME MODEL

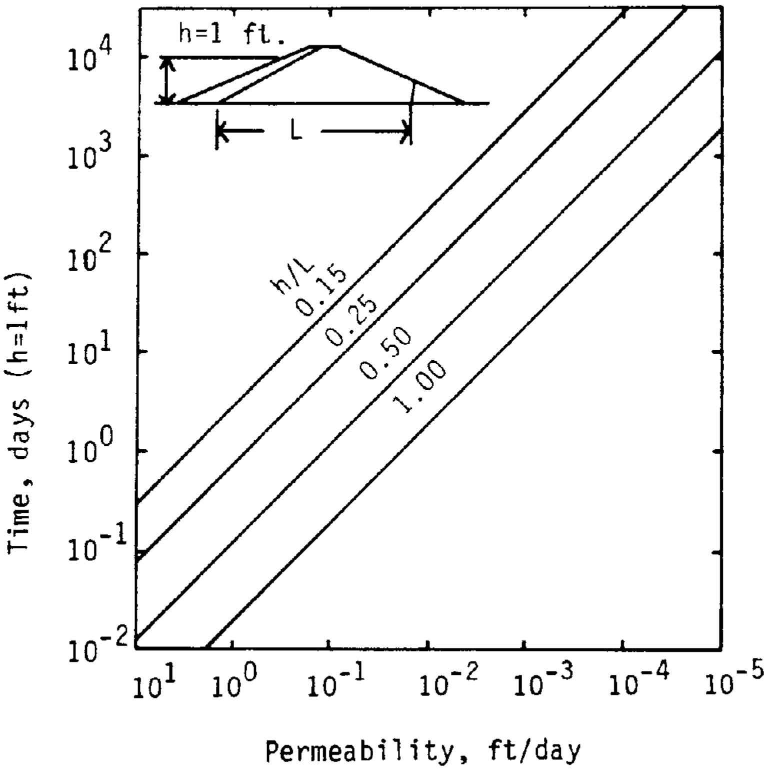


FIGURE 2-4 TIME TO COMPLETE SATURATION

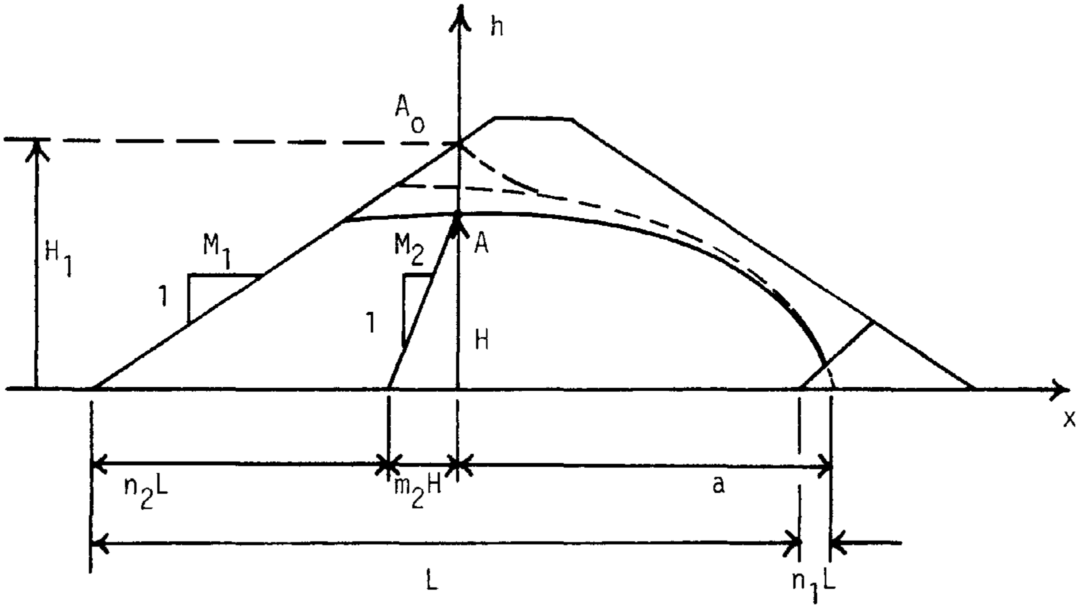


FIGURE 2-5 SATURATION LINE FOR RAPID DRAWDOWN

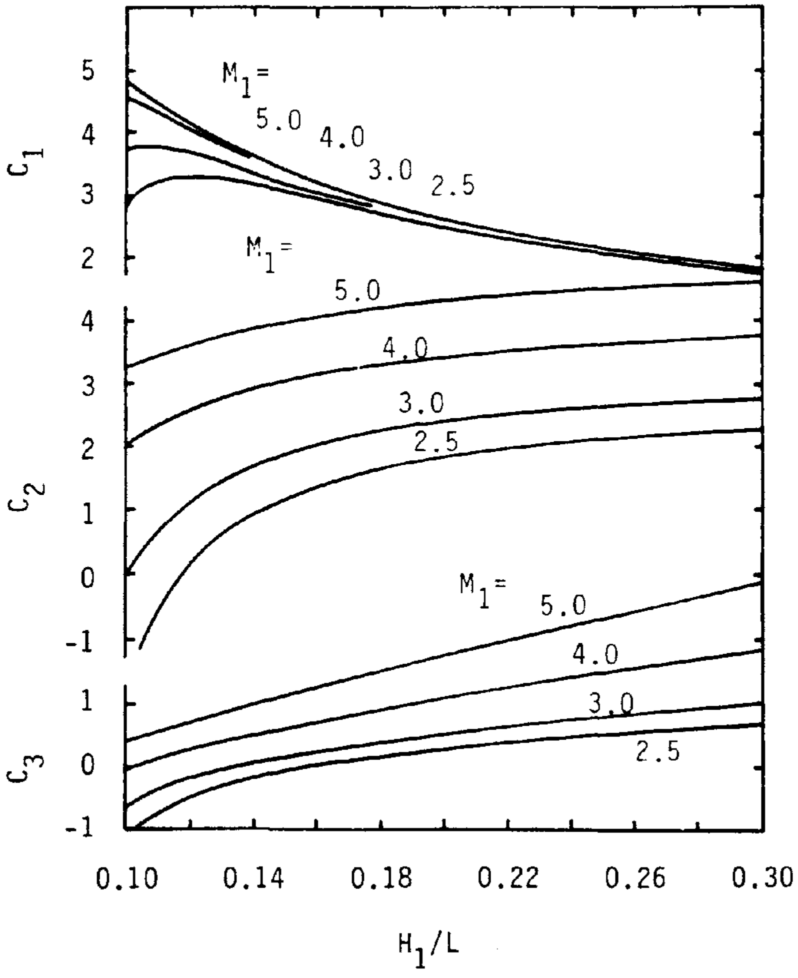


FIGURE 2-6 COEFFICIENTS FOR RAPID DRAWDOWN

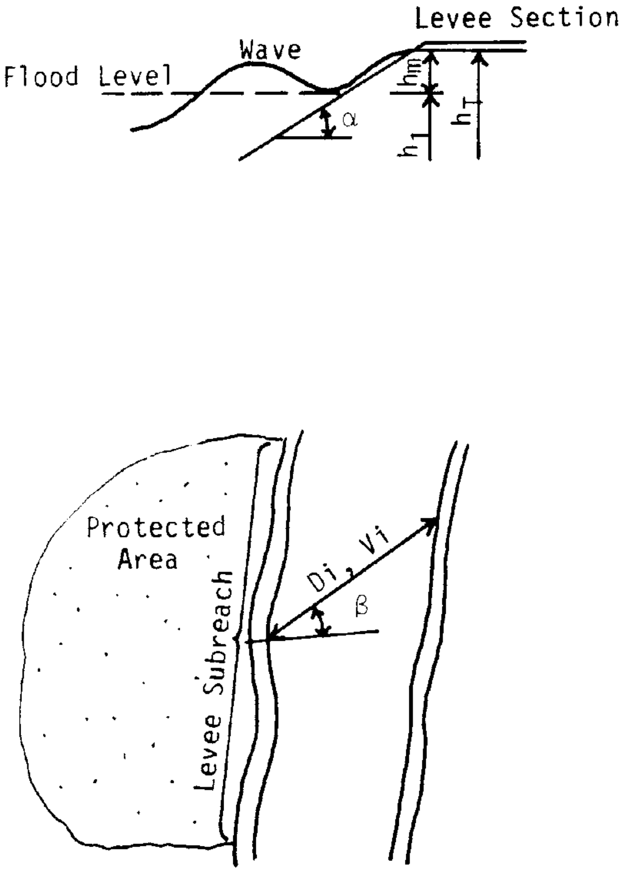


FIGURE 2-7 LEVEE EROSION PARAMETERS

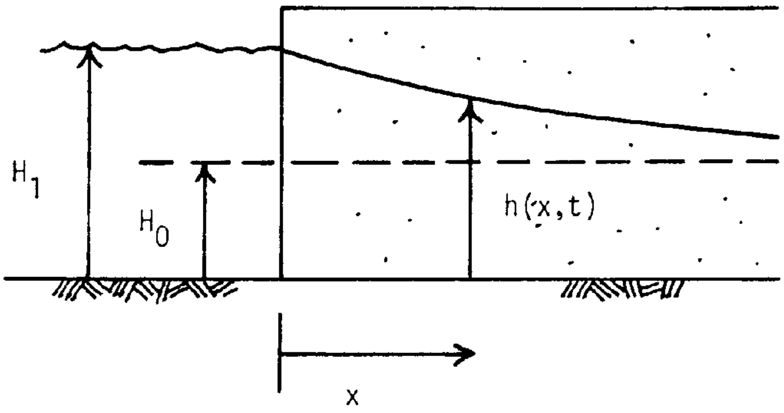


FIGURE 2-8a SEMI-INFINITE UNCONFINED AQUIFER

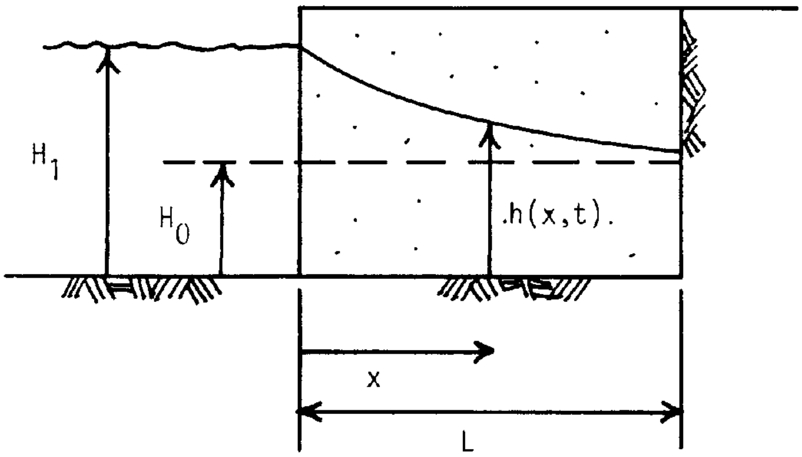


FIGURE 2-8b FINITE UNCONFINED AQUIFER

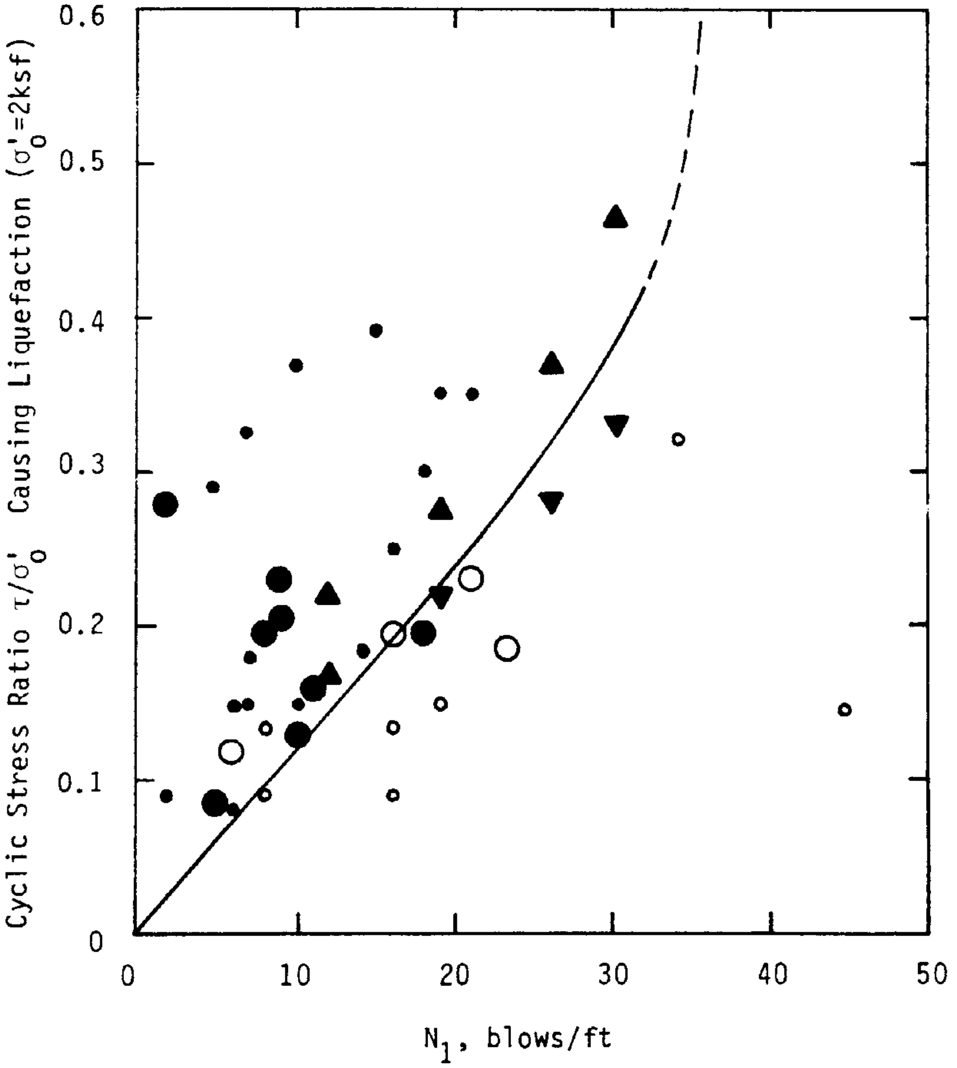


FIGURE 2-9 LIQUEFACTION RELATIONSHIP TO BLOW COUNTS

3.0 STABILITY MODEL

3.1 Probabilistic Considerations

During the course of this study probabilistic stability models were developed for both circular arc and wedge-type landslide failures in three dimensions. The initial work on the probability model utilized a Corps of Engineers levee geometry (see Figure 1-1). Two levee profiles from Woodward Island in the Sacramento-San Joaquin Delta were also studied (Figures 3-1a and b). Woodward Island geotechnical investigations produced a large amount of soil and cross-section geometry data. These data included 10 cross sections with surface geometries and soil profiles, as well as phreatic surface locations. Data from numerous bore holes were obtained and the soil properties of each soil horizon were estimated from these data. Parameters for the Woodward Island soil horizons are listed in Table 3-1. The correlation of cohesion and the tangent of the angle of internal friction was not estimated.

The analysis of the bore hole data indicated that the variation in the parameters for each soil horizon is random. Data for each soil horizon were combined to obtain the estimated means and coefficients of variation listed in Table 3-1. The correlation of soil properties along the levee was estimated based on the assumption that each pair of data was jointly normally distributed with a correlation coefficient that decayed exponentially with the distance between the sample points. The sample likelihoods for each pair of data points were multiplied and the constant term in the exponential decay expression was determined by maximizing the sample likelihood.

Uncertainty in the estimate of this decay parameter is large, but not unreasonable, given the type of casual construction and rehabilitation of the Woodward Island levees over the past 100 years, or so. A second case study (Ref. 3-1) indicates smaller coefficients of variation to be characteristic of carefully controlled engineered construction.

A computer program was developed (see Appendix) which obtains the probability of landslide failure of given length along a levee. Characteristics of the program are discussed in Section 3.2. It is noted that this program was designed to provide reasonable estimates of failure probabilities for use in levee systems analysis. It was not developed to compete with various other computer programs which estimate safety factors in conventional geotechnical studies.

The probability model significantly extends that used by Vanmarcke (Ref. 3-1) by virtue of including, not only a cylindrical, but also an ellipsoidal shape of the slip surface. In addition, the model has the ability to consider wedge failures that do not include passive earth pressure, and includes possible hydrostatic and ground acceleration effects from earthquakes.

3.2 The Basic Three-Dimensional Model

The essential characteristics of the analytical model are shown in Figure 3-2, using levee Profile C, (Figure 1-1). A circular arc failure surface is assumed to exist perpendicular to the levee axis. The arc may intersect the soil on the riverside of the levee profile below the water surface so that hydrostatic load may exist. The arc of the circle can be made very large to approximate a wedge-type of failure. Note that this is not a general wedge failure analysis, since it does not include passive earth pressure influence at the toe. Single slices can be considered or the failure surface can be assumed to be either cylindrical or ellipsoidal in shape in the direction of the levee axis. The model also includes the possible influence of a horizontal acceleration to approximate earthquake effects through the use of a static coefficient.

For analysis, the levee is divided into segments, as shown in Figure 3-2. Slices through the levee are considered as shown. Each vertical prism of soil above the assumed failure surface is treated in turn in the analysis. A soil prism can contain up to five soil horizons. A horizon can be damp, saturated, or a damp portion can occur above a saturated portion as defined by the phreatic surface. The mean and variance of soil density (damp and saturated), cohesion, tangent of the angle of internal friction, and the influence of pore pressure are considered in the analysis for each horizon in accordance with Lambe and Whitman (Ref. 3-2). It is assumed that during failure all segments are fully mobilized along the failure surface so that the block of soil initially moves as a rigid body.

The simplicity of the model is advantageous in that it allows the consideration of both circular arc failures and wedge-type failures in one model for several conditions, including hydrostatic loads, horizontal acceleration loads, variations in the phreatic surface, variations in geometry, rapid drawdown, and failures in both the riverside and landside faces.

A mean safety factor and a probability of failure assuming that the random variable "safety factor" is lognormally distributed are computed for each analysis. Initial studies utilized a normally distributed safety factor; but when it was observed that the coefficient of variation of the safety factor was large for some soils (see Table 3-1), a change was made to the lognormal model.

Results of one such analysis are shown in Figure 3-3. Note that the probability of failure generally decreases with an increase in the mean safety factor, but there are exceptions. As a consequence of the increase in variance, the probability of failure can increase while the mean safety factor increases, and vice versa. It is also important to note that an infinite number of possible failure surfaces exist, each with its own probability of failure. The properties of the failure surfaces are highly correlated so that the most critical failure surface is the one with the largest probability failure, not the smallest mean safety factor. Many failure surfaces can sensibly have the same probability of failure. Thus, critical zones of failure exist rather than a single critical surface, or arc, as determined in conventional analyses. That is, if probabilities of failure are rounded-off to values consistent with the uncertainty in the data, many different failure surfaces have the same likelihood of failure.

Failure probabilities are conditional on the radii and centers of rotation of the slip surfaces. To find the unconditional probability of failure, the total probability theorem is used:

$$P[F] = \sum_{\text{all } i} P[F|S_i]P[S_i],$$

where S_i is slip surface, i. Although $P[S_i]$ is unknown, the unconditional probability of failure is just the weighted average conditional probability of failure, given S_i, and will always be less than the maximum conditional probability of failure:

$$P[F] \leq \underset{\text{all } S_i}{\text{Max}} P[F|S_i].$$

Therefore, a conservative and simple approximation to the probability of slip surface failure is to determine the maximum conditional probability by trial and error and use that.

The very large variability in the safety factor was also of interest. The coefficient of variation of the safety factor was on the order of 0.6 to 0.7 for the material properties listed in Table 3-1. This magnitude of the coefficient of variation precluded the use of the normal distribution to model the safety factor. Note that the coefficient of variation of the safety factor was dominated by the coefficient of variation of cohesion.

Using the developed model, the analysis of a levee section consists first of a search of possible centers of slip and radii based on a single slice. The analysis then considers the extent of failure. Typical results are shown in Figures 3-4 and 3-5. The most likely failure length is one of the basic results of this type of analysis.

Vanmarcke (Ref. 3-1) used level crossing theory in examining the extent of failure. This study uses the concept of a critical length. The critical length is defined as that length beyond which correlations essentially need not be considered. If a levee is 5,000 feet in length and the critical length is 1,000 feet, then five critical lengths exist in the levee and five Bernoulli type trials may be considered in estimating the landslide failure probability of the 5,000 foot system. The critical length is necessarily subjectively defined, but it is a useful intuitive approximation in systems analysis because of its basic simplicity.

3.3 Sensitivity Studies

The analytical model is complex, and involves many parameters, depending on the number of soil horizons considered. It is, therefore, useful to examine the results of an analysis as a function of the properties of key parameters in an effort to identify the dominant ones as well as possibly reduce the amount of field data. The mean of a property is easier to estimate with adequate reliability than the variability. However, the coefficient of variation may be typical of the particular class of soil, while the mean varies and can be established with a few samples.

With the large number of parameters in even a profile with two layers, the sensitivity study was limited to levee Profile C with a cylindrical failure surface analysis and two soil horizons. Each soil horizon is characterized effectively by four parameters, the damp and saturated densities, the cohesion, and the tangent of the angle of internal friction. The difference between damp and saturated conditions for the latter two parameters was not considered. The objective of the sensitivity study was to investigate the influence of different levee variables, as well as the variability of each of the soil parameters on the mean safety factor and probability of failure, since it is the most difficult value to estimate. Landside subsidence conditions and varying phreatic surfaces were considered.

3.3.1 Influence of Soil Parameter Variability

As expected, the shape of the failure probability curves is not altered by changes in the coefficients of variation of the soil parameters. The coefficient of variation of the cohesion had a significantly larger influence than those of the other parameters. This is consistent with the observed influence of the cohesion on the safety factor for the soils considered.

The influence of the coefficient of variation of cohesion on the probability of failure is shown in Figure 3-4. Here, all other coefficients of variation are equal to 0.2. Similarly, the influence of the coefficient of variation of the tangent of the internal friction angle is shown in Figure 3-5. The dominance of cohesion in the strength properties of the levee materials is shown by the relative magnitudes of the probability of failure.

In summary, the influence of a change in the coefficients of variation of all the other soil parameters (density, friction) was less than that of cohesion.

3.3.2 Influence of The Phreatic Surface

Studies were made of the influence of the phreatic surface using levee Profile C (Figure 1-1). In the first set of analyses, the phreatic surface was located at five different levels, from the crest of the levee on the riverside to below the levee in the subsoil, as shown in Figure 3-6. The soil properties for the levee horizons are given in Table 3-2.

Analyses were made assuming both cylindrical and ellipsoidal failure surfaces, as discussed in Section 3.2. The probability of landslide failure and its corresponding mean safety factor were calculated as a function of phreatic surface location and failure length measured along the levee.

The steady state influences of phreatic surface location are shown in Figures 3-7a,b,c, and d. The assumption of a cylindrical failure surface are depicted in Figures 3-7a and 3-7b. Probabilities of failure are seen to be very sensitive to the location of the phreatic surface, whereas the mean safety factor is relatively less variable. Note that the probabilities of failure are on a logarithmic scale in Figures 3-7b. End zone contribution to the total resisting moment is seen to decrease with increase in rupture lengths. Similar results were obtained assuming an ellipsoidal failure surface, Figures 3-7c and 3-7d. Note that the zone of "most likely" failure length is narrower with an ellipsoidal failure surface than with a cylindrical failure surface and that this zone broadens greatly for higher phreatic surfaces.

The influence of a rapid rise in the phreatic surface was also studied. If, for example, the water level rises rapidly from elevation 7.3 feet to 18.2 feet as shown in Figure 3-8, the phreatic surface as a function of time can be approximated by several straight lines. Analyses were made of the probabilities of failure and safety factors for both cylindrical and ellipsoidal failure surfaces. The results are shown in Figures 3-9a,b,c,and d. Note that the time between initial and final phreatic surfaces depends on the permeability and geometry of the cross section.

3.3.3 Influence of Landside Subsidence

To study the influence of subsidence on failure (using a cylindrical failure surface), analyses were made with two different phreatic surface conditions and five landside subsidence conditions. The geometry configurations used are shown in Figure 3-10a and the results of the analyses are shown in Figures 3-10b,c,and d. The probability of failure for maximum subsidence was almost 50 percent greater than for the original configuration.

3.3.4 Riverside and Crest Erosion

Studies of levee slope stability as a function of both riverside and crest erosion were made using levee Profile C. The water surface was assumed to be at the top of the levee. The crest erosion conditions considered are shown in Figure 3-11. It was found that the effect of both riverside and crest erosion on the probability of failure was minimal. This is intuitively obvious in the sense that a change of between 0.5 and 1 foot near the center of a 20 to 30 foot high earth structure or on one face will not significantly affect any of the terms in the resisting moment or driving moment equations.

3.3.5 Rapid Drawdown

Two different phreatic surfaces (Fig. 3-12a) were assumed prior to a rapid drawdown in order to examine riverside levee slope stability. Levee Profile C (Figure 1-1) was used in the analysis along with a cylindrical failure surface. Drawdown was analyzed in accordance with Reference 3-2. The results of the analyses are shown in Figure 3-12b, and c. The relatively high probability of failure due to a complete drawdown condition shows why it is cause for concern in geotechnical engineering. The difference in "most likely" rupture lengths is due to the greater coefficient of variation in the safety factor for the higher phreatic surface.

3.3.6 Horizontal Earthquake Acceleration

The influence of a horizontal earthquake acceleration of 0.05g on levee Profile C was studied using both a cylindrical and an ellipsoidal failure surface. Four different phreatic surface conditions were considered (Figure 3-6). The analysis was accomplished by a slight modification of the computer program to include horizontal inertia forces from each segment of each soil column in the soil mass. The inertial effects of the water on the riverside face of the levee were not considered.

The results of the studies are shown in Figures 3-13a and b for the two failure surface assumptions. The effect of an earthquake acceleration is to increase the probability of failure for the different phreatic surfaces by an almost constant amount. The probability of failure approximately doubles and the mean safety factor is reduced by a factor of about two as a consequence of a 0.05g horizontal acceleration.

3.4 Comparison of Present Study with Vanmarcke's Methodology

As a check on the developed analytical methodology, an example presented by Vanmarcke (Reference 3-1) was studied. The methods differ in the correlation decay function, but are otherwise similar. Vanmarcke assumed an exponential decay using the square of the distance between locations, while this study assumes a linear relationship with distance in the exponential decay. The difference between the two decay functions is not large from a practical point of view, since the two functions employ different coefficients. The analytical model employed in the present study also includes a further linearization of the influence of correlation of material properties.

The levee profile used in the comparison is shown in Figure 3-14a and the soil properties are given in Table 3-3. The first analysis was made without a phreatic surface (drained levee condition) using a cylindrical as well as an ellipsoidal failure model. A conventional slip-circle analysis was also made. The mean safety factor was computed at 1.17.

Using the data presented in Table 3-3 and a 250 foot long cylindrical failure surface, the mean safety factor was found to be 1.21, and the probability of failure was calculated to be 0.090. This probability is compared to 0.086 calculated by Vanmarcke. Using an ellipsoidal failure surface and a rupture length of 300 feet, the probability of failure was 0.049 and the mean factor of safety was 1.30. Figure 3-14b is a plot of the probability of failure versus failure length for the two failure surface assumptions. Figure 3-14c contains a similar plot for mean safety factor.

3.5 Woodward Island Studies

Limited analytical studies were made for two levee cross sections of Woodward Island. The geometries are shown in Figures 3-1a and b. The soil properties for both sections were assumed to be the same for the same soil horizons.

The first part of this study examined the influence of the soil property variations on the safety factor and the probability of failure. As expected, it was found that the most critical failure surfaces, as defined by the largest probability of failure, depended on both the mean safety factor and the variability of that factor so that the critical failure surface was not necessarily associated with the minimum safety factor.

Although the minimum safety factor may not define the "most likely" failure surface, it is important to note that a failure zone exists in which many surfaces have very similar failure probabilities. This being true, from a practical engineering point of view, it is not necessary to determine the mathematically critical surface, since any arc in the broad failure zone will have sufficiently similar properties for engineering purposes.

Typical analytical results are shown in Figures 3-15a,b,c, and d, in which the mean safety factor and the probability of failure are plotted against failure length. It is seen that the influence of the flood level, on the mean safety factor is much smaller than it is on the probability of failure.

The probability of wedge failure along the base of the levee had an extremely small value, beyond the range of validity of the basic data.

3.6 Conclusions

- The levee length beyond which correlation influences can be neglected is herein called the critical length. This length is based on the decay of the probability of failure with failure length. Each such critical length in a levee reach can be considered to be independent in response to the hazards or loads. The critical length is a convenient approximation in the analysis of system performance.

- A "most likely" failure length exists in each critical length of levee, but this length is not sharply defined. Many lengths have about the same probability of failure. Similarly, a wide variety of slip-surface descriptions have about the same probability of failure. A shorter "most likely" failure length zone is associated with an assumed ellipsoidal failure surface, while a longer length is associated with a cylindrical failure surface.

- The probability of failure is a better index of safety than the safety factor, if the slip surface penetrates through soils with differing properties and large variabilities. The difference in characteristics between an ellipsoidal and a cylindrical failure surface depends on the soil properties. Differences are more pronounced with highly variable soil horizons.

- Small variations in levee geometry have a minor influence on stability.

- Small variations in the location of the phreatic surface have a minor influence on levee performance. Large variations in phreatic surface, as induced by a long term increase in water level or a rapid drawdown, result in major increases in the probability of failure.

- Sensitivity studies indicate that the variability of the safety factor and thus the probability of failure in these studies is dominated by the large variability of the cohesion. Minor variabilities can be neglected. It appears likely that the coefficient of variation of soil properties can be estimated subjectively from two factors, the natural variability of the soil and the degree of control evidenced in levee construction. Casual construction is associated with much larger coefficients of variation than carefully controlled engineered construction.

3.7 References

3-1 Vanmarcke, E.H., "Reliability of Earth Slopes," Journal of the Geotechnical Engineering Division, ASCE, Vol. 103, No. GT11, Nov. 1977, pp. 1247-1266.

3-2 Lambe, T.W. and R.V. Whitman, Soil Mechanics, John Wiley and Sons, Inc., New York, N.Y., 1969.

Table 3-1

WOODWARD ISLAND SOIL PROFILE PARAMETERS

	Horizon 1		Horizon 2		Horizon 3		Horizon 4		Horizon 5	
	Mean	COV	Mean	COV	Mean	COV	Mean	COV	Mean	COV
Damp Density (pcf)	95.0	0.10	90.0	0.10	65.0	0.10	105	0.10	125	0.10
Saturated Density (pcf)	42.6	0.10	37.6	0.10	7.60	0.10	47.6	0.10	62.6	0.10
Cohesion (pcf)	150	0.70	200	0.45	150	0.60	200	0.35	160	0.30
Tangent [Angle of Internal Friction]	0.532	0.30	0.445	0.30	0.510	0.30	0.625	0.30	0.649	0.30

TABLE 3-2

SOIL PROPERTIES FOR PHREATIC SURFACE STUDY

	Top Horizon		Bottom Horizon	
	Mean	COV	Mean	COV
Damp Unit Weight (pcf)	95.0	0.13	90.0	0.43
Submerged Unit Weight (pcf)	32.6	0.70	27.6	1.1
Cohesion (psf)	250	0.70	240	0.20
Tangent [Angle of Internal Friction]	0.51	0.16	0.4	0.60

Table 3-3

SOIL PROFILE PARAMETERS FOR VANMARCKE'S EXAMPLE

	Horizon 1		Horizon 2		Horizon 3	
	Mean	COV	Mean	COV	Mean	COV
Damp Density (pcf)	130	0.05	115	0.05	110	0.05
Saturated Density (pcf)	132.5	0.05	115	0.05	110	0.05
Cohesion (psf)	0.001	0.01	1000	0.18	480	0.18
Tangent [Angle of Internal Friction]	0.84	0.20	0.001	0.10	0.001	0.10

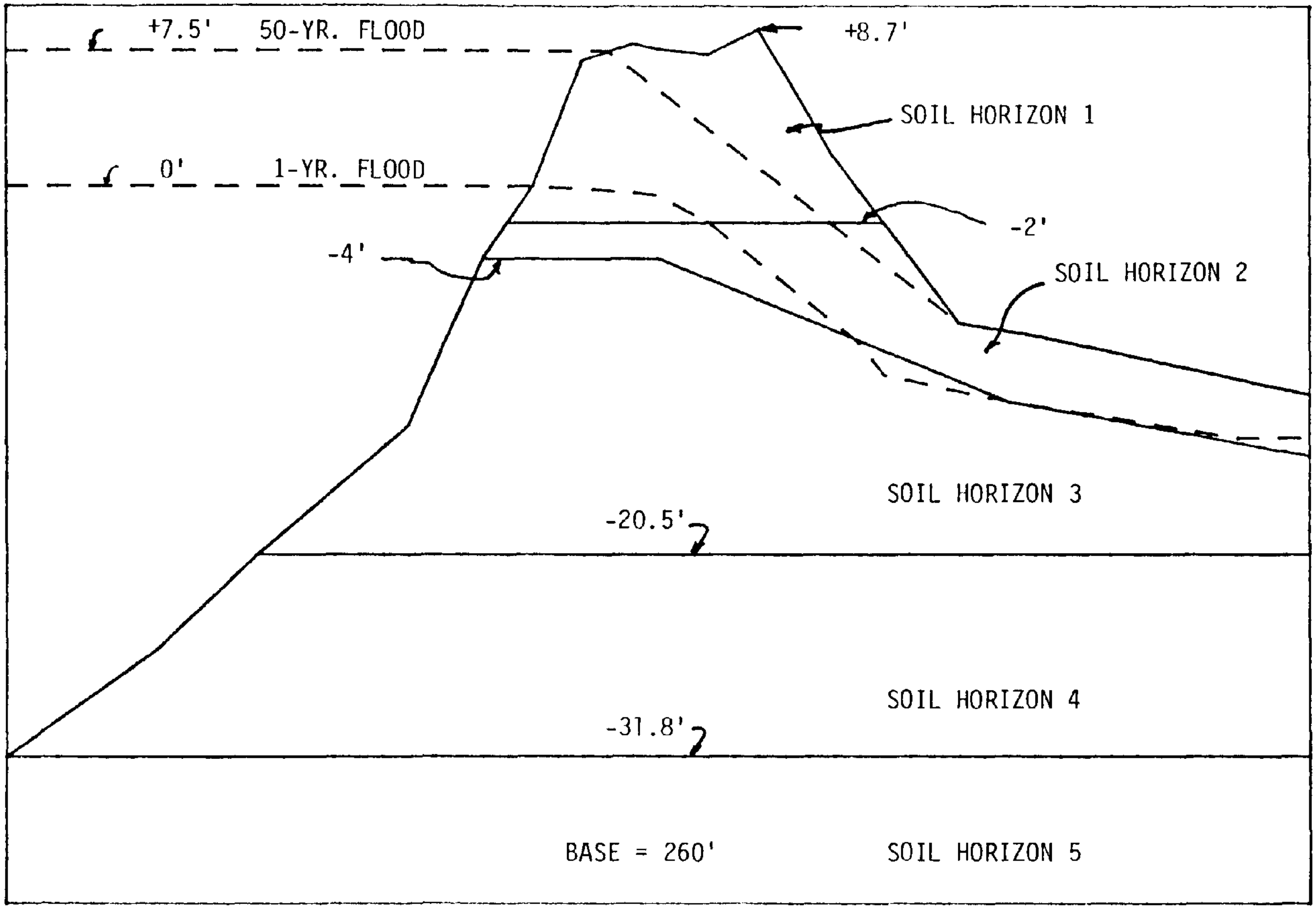


FIGURE 3-1a WOODWARD PROFILE #1

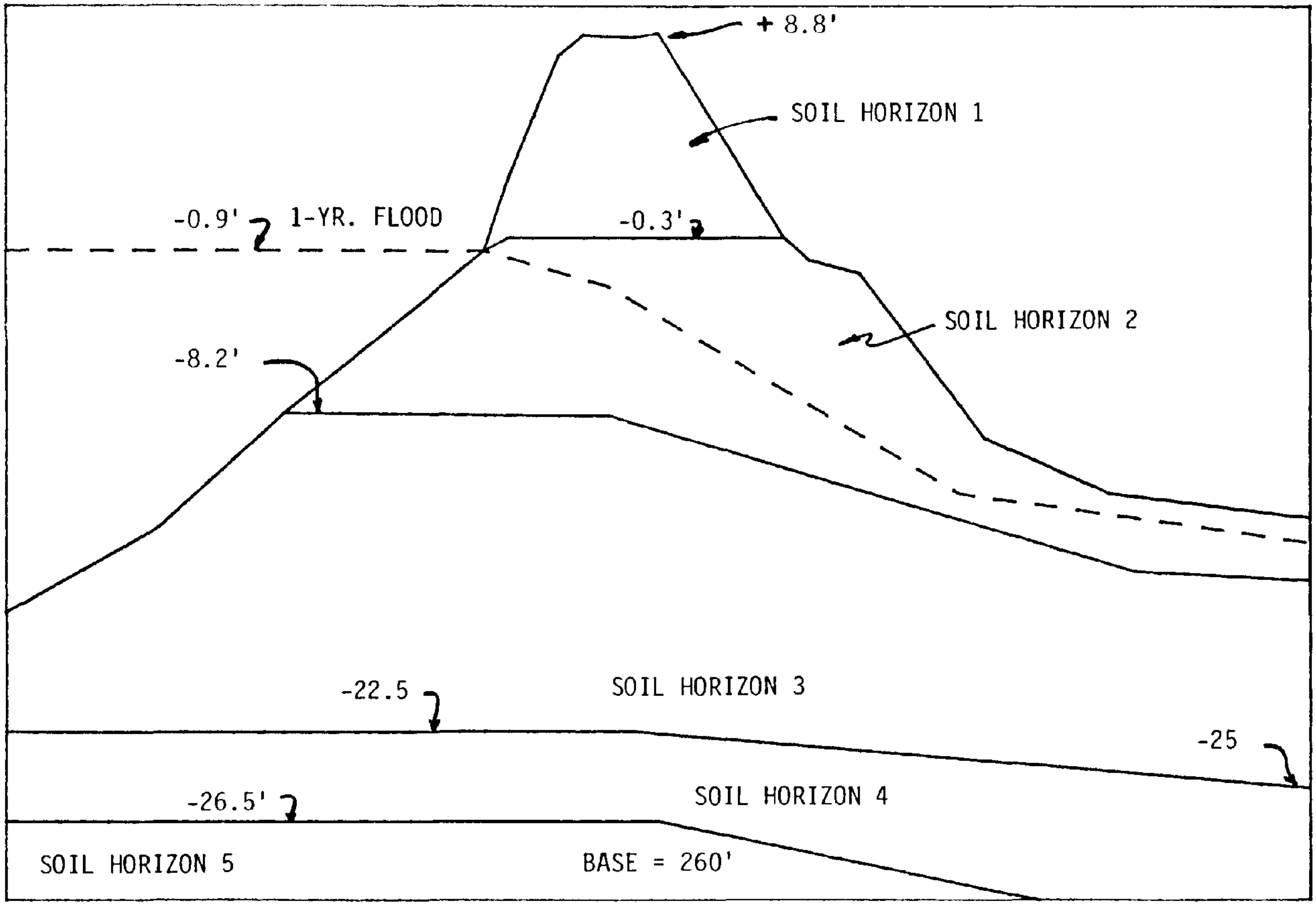


FIGURE 3-1b WOODWARD ISLAND PROFILE #2

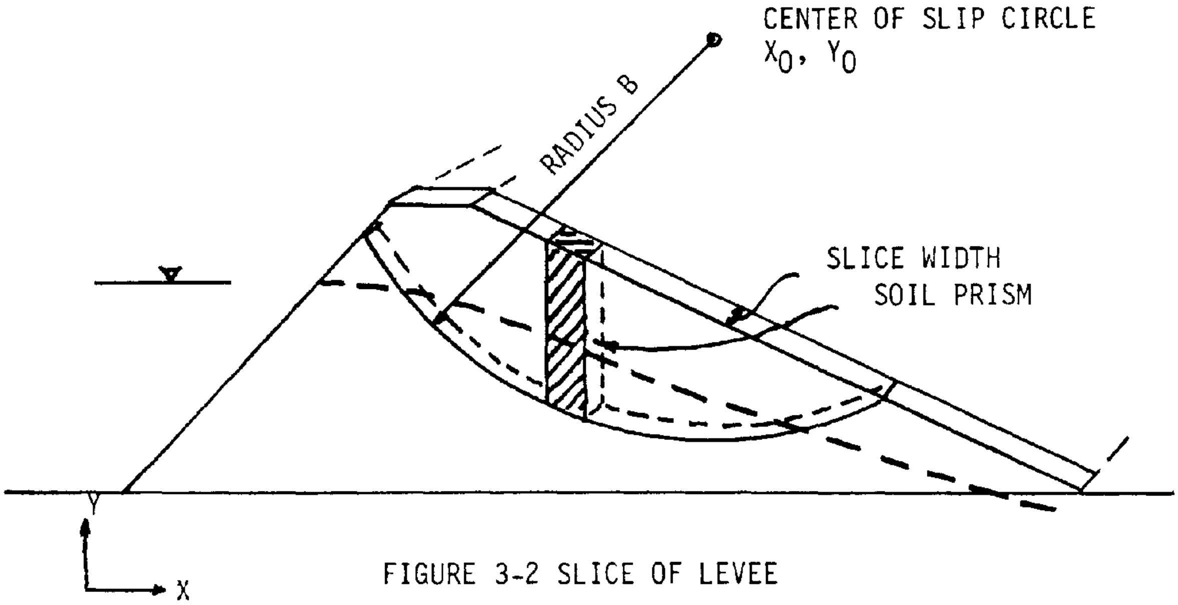
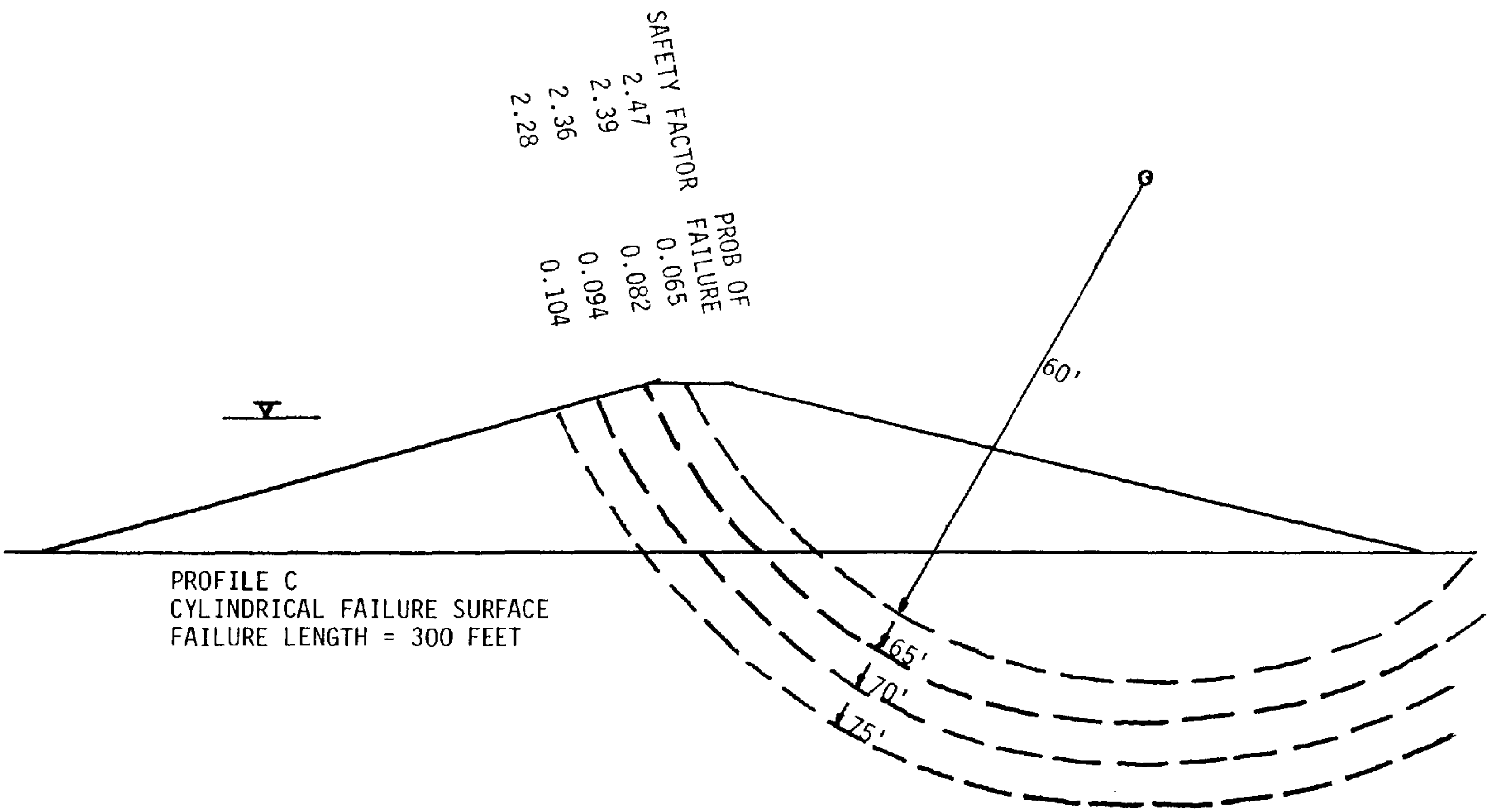


FIGURE 3-2 SLICE OF LEVEE



SAFETY FACTOR	PROB OF FAILURE
2.47	0.065
2.39	0.082
2.36	0.094
2.28	0.104

FIGURE 3-3 TYPICAL RESULTS OF ANALYSIS

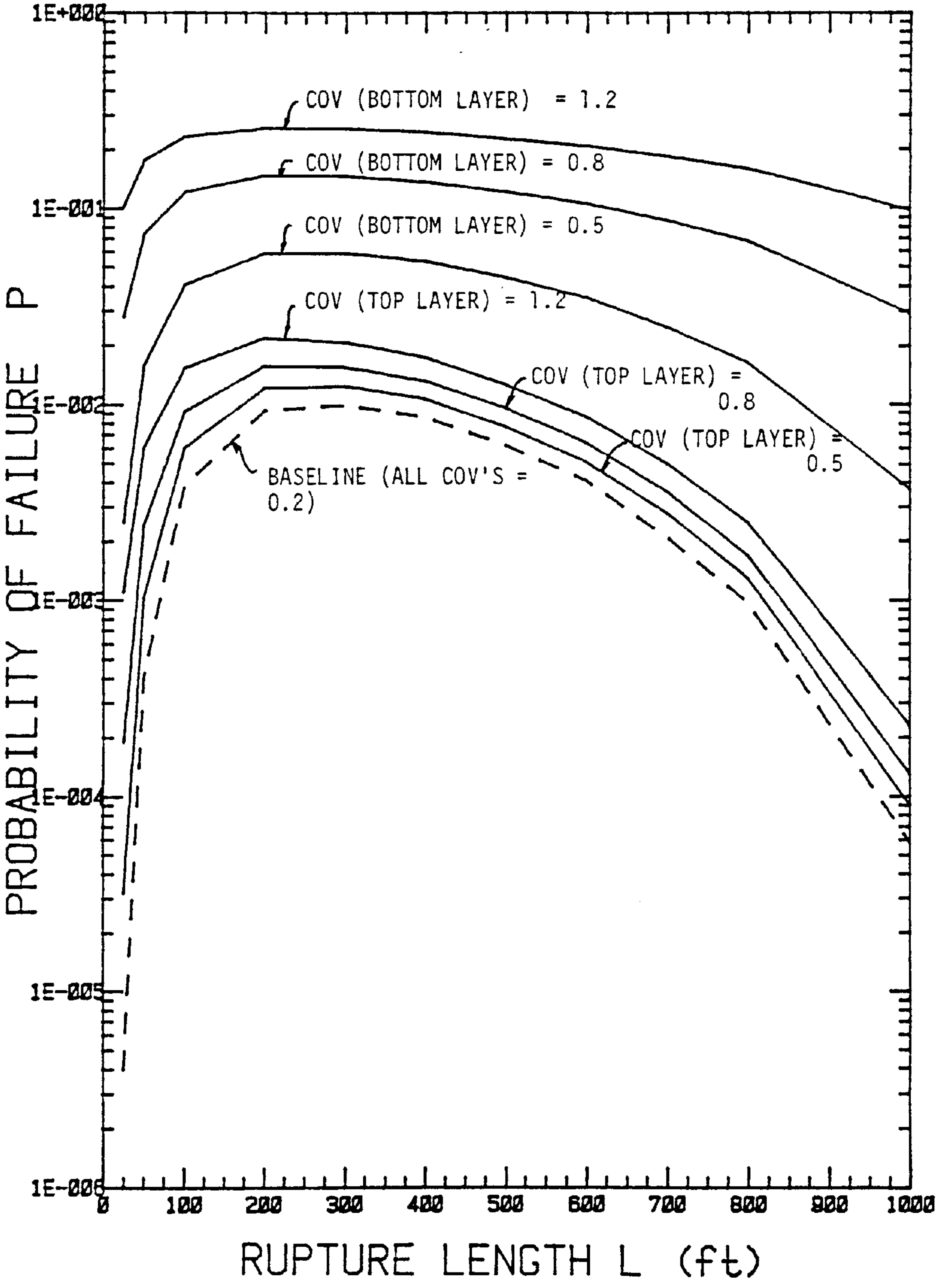


FIGURE 3-4 PARAMETRIC STUDY: INFLUENCE OF COEFFICIENT OF VARIATION OF COHESION ON PROBABILITY OF FAILURE (CYLINDRICAL FAILURE SURFACE)

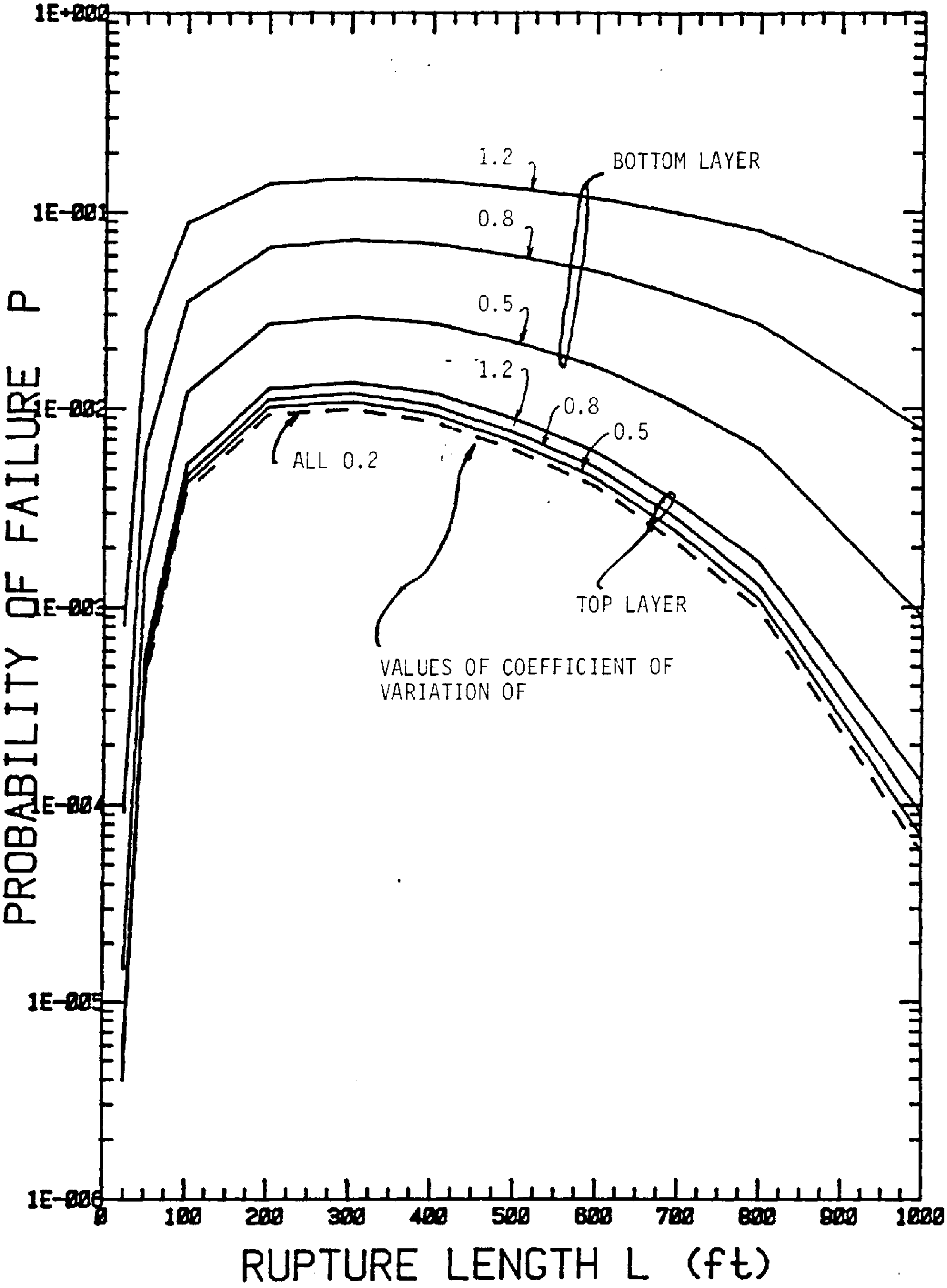


FIGURE 3-5 PARAMETRIC STUDY: INFLUENCE OF COEFFICIENT OF VARIATION OF TAN Ø ON PROBABILITY OF FAILURE (CYLINDRICAL FAILURE SURFACE)

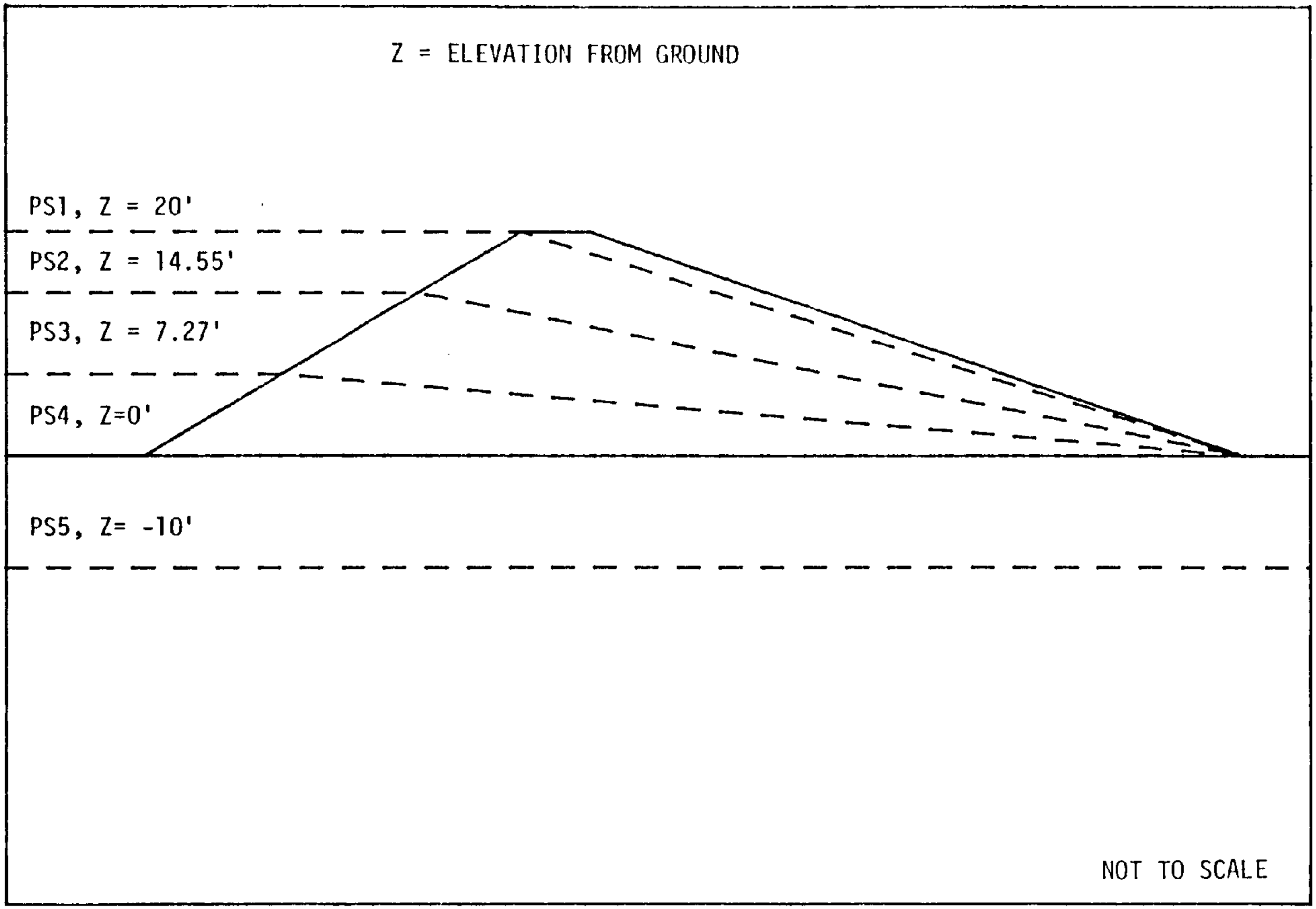


FIGURE 3-6 LOCATION OF PHREATIC SURFACES (PS) USED IN LONG TERM ANALYSES

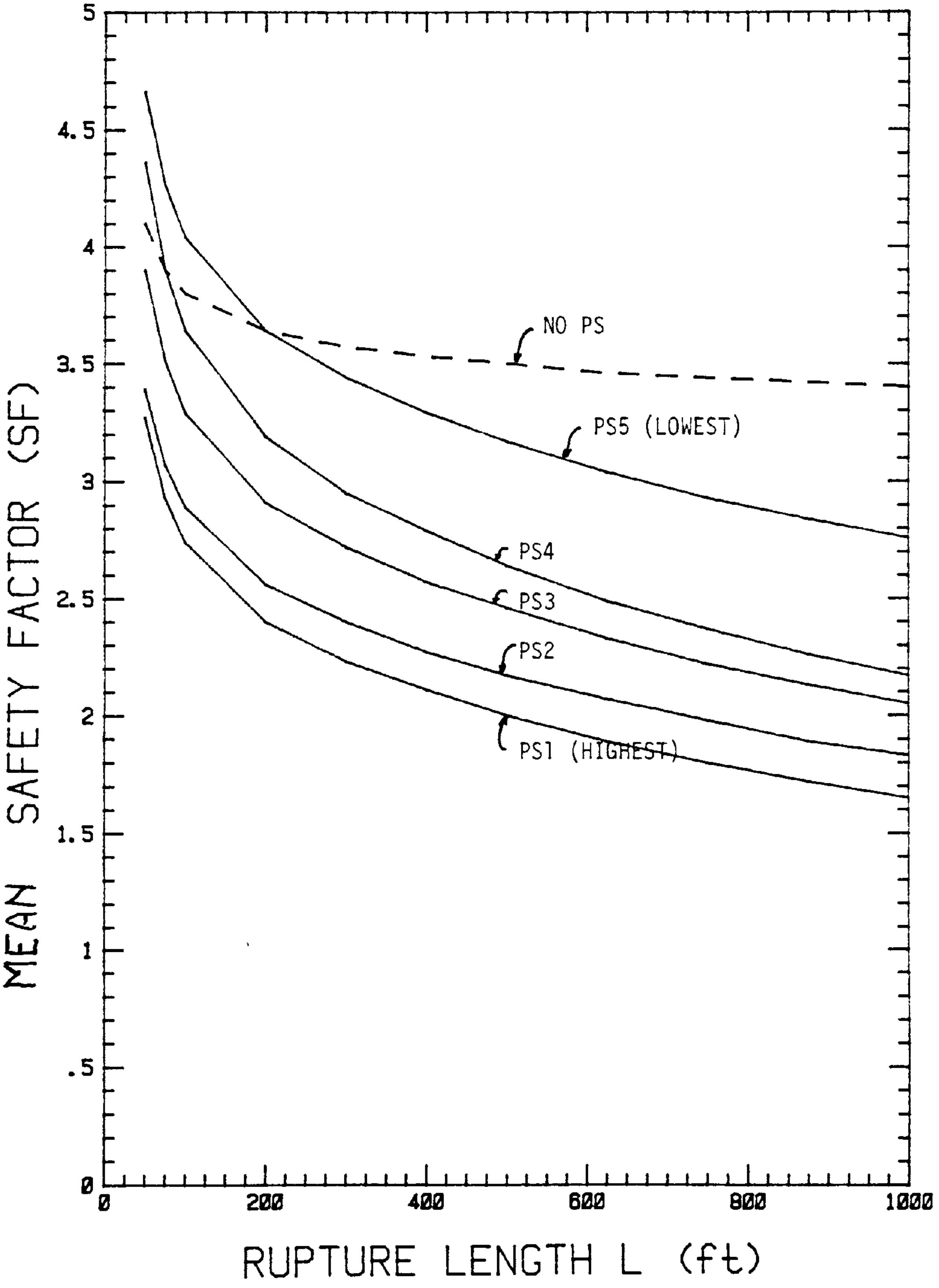


FIGURE 3-7a EFFECT OF LONG TERM PHREATIC SURFACE LOCATION ON MEAN SAFETY FACTOR (CYLINDRICAL FAILURE SURFACE)

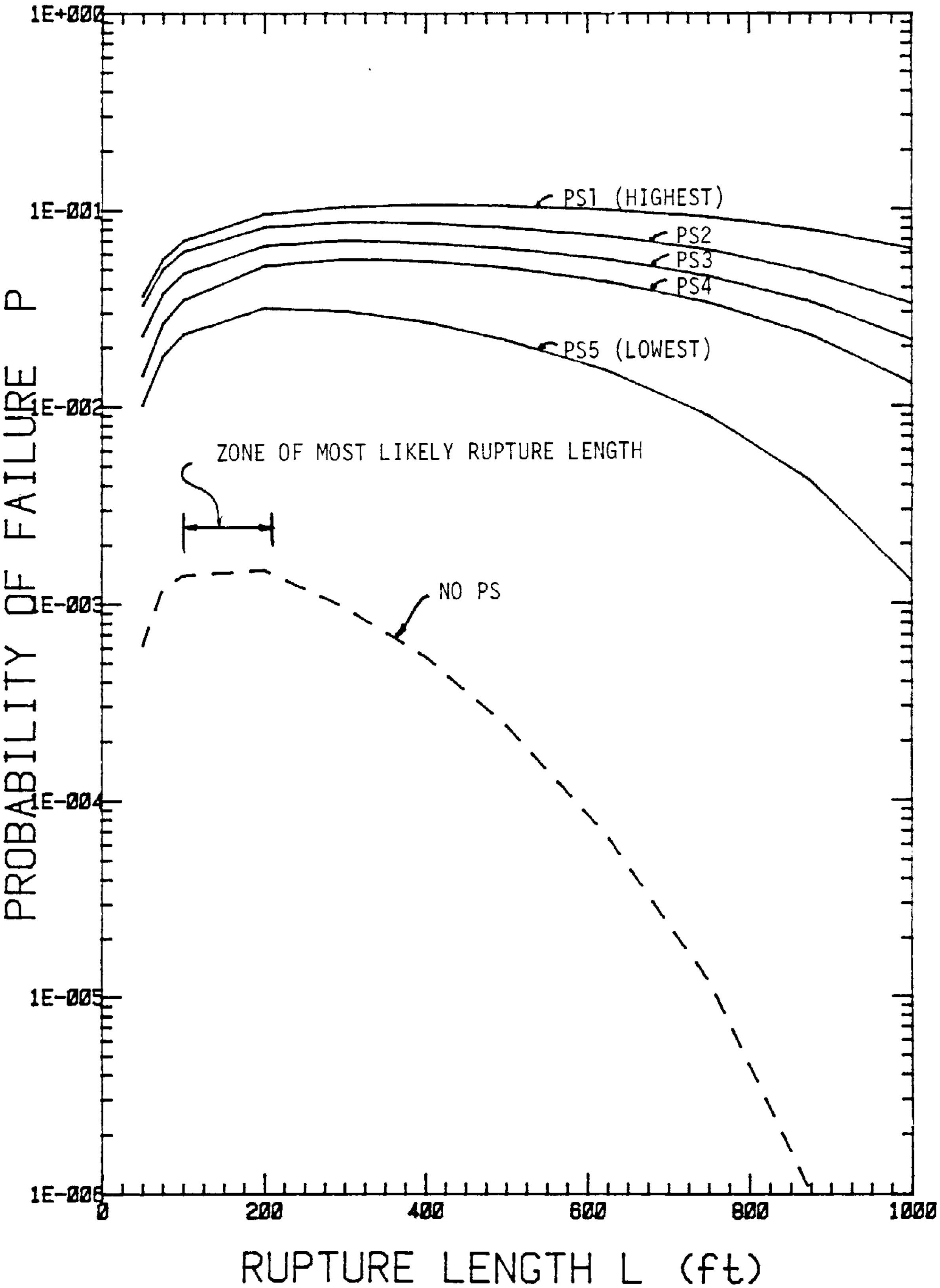


FIGURE 3-7b EFFECT OF LONG TERM PS LOCATION ON PROBABILITY OF FAILURE (CYLINDRICAL FAILURE SURFACE)

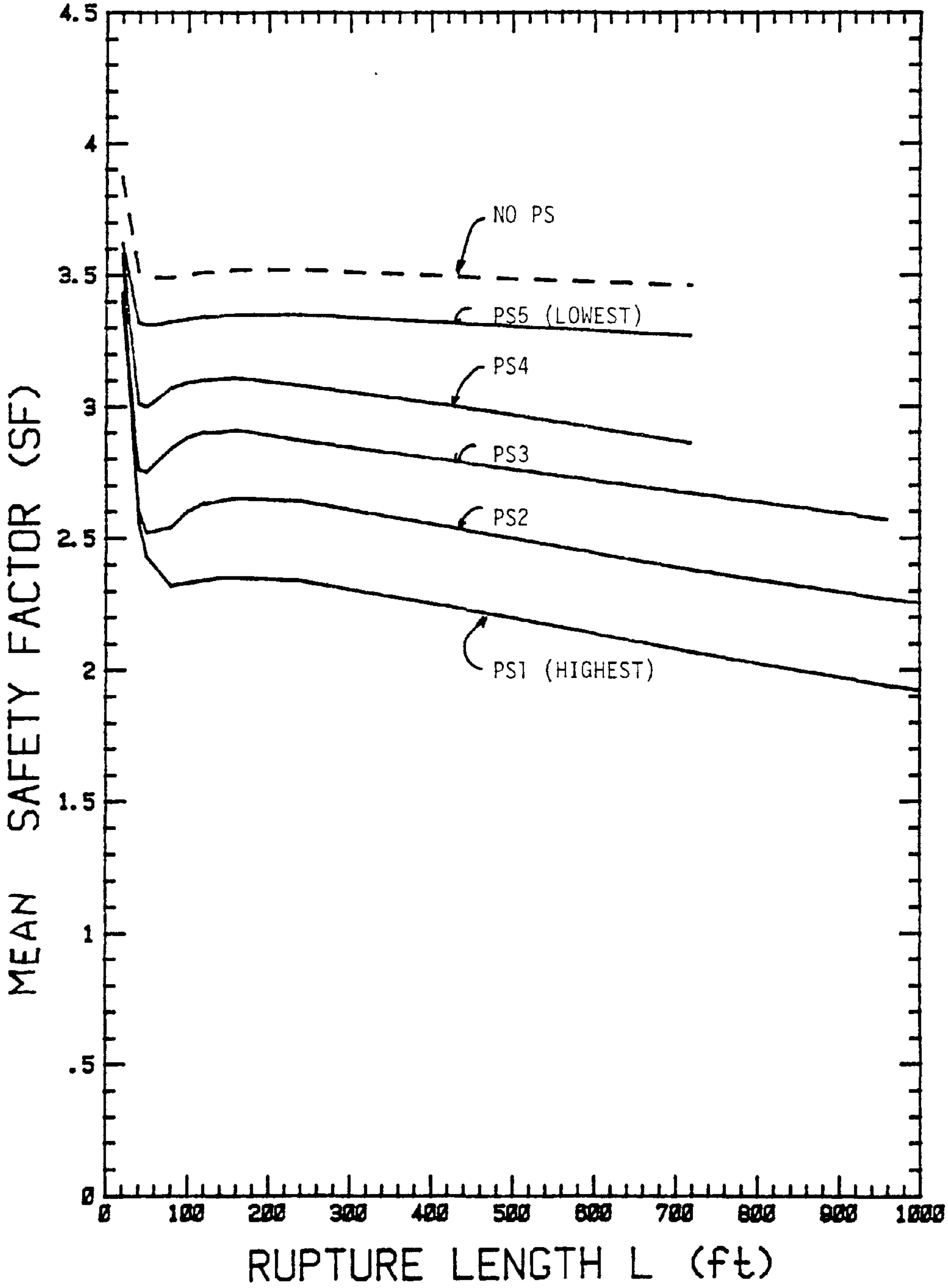


FIGURE 3-7c EFFECT OF LONG TERM PS LOCATION ON THE MEAN SAFETY FACTOR (ELLIPSOIDAL FAILURE SURFACE)

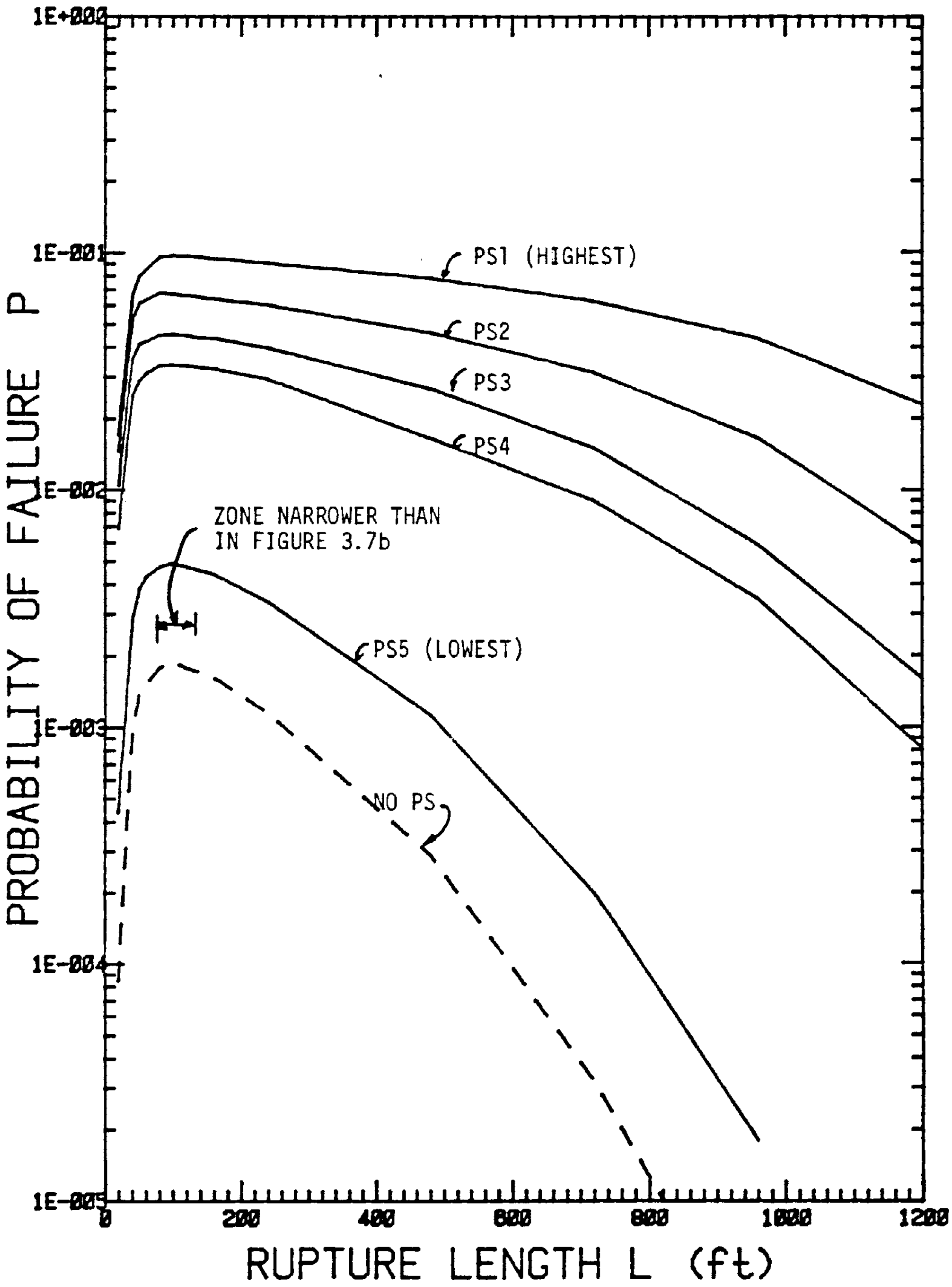


FIGURE 3-7d EFFECT OF LONG TERM PS LOCATION ON THE PROBABILITY OF FAILURE (ELLIPISOIDAL FAILURE SURFACE)

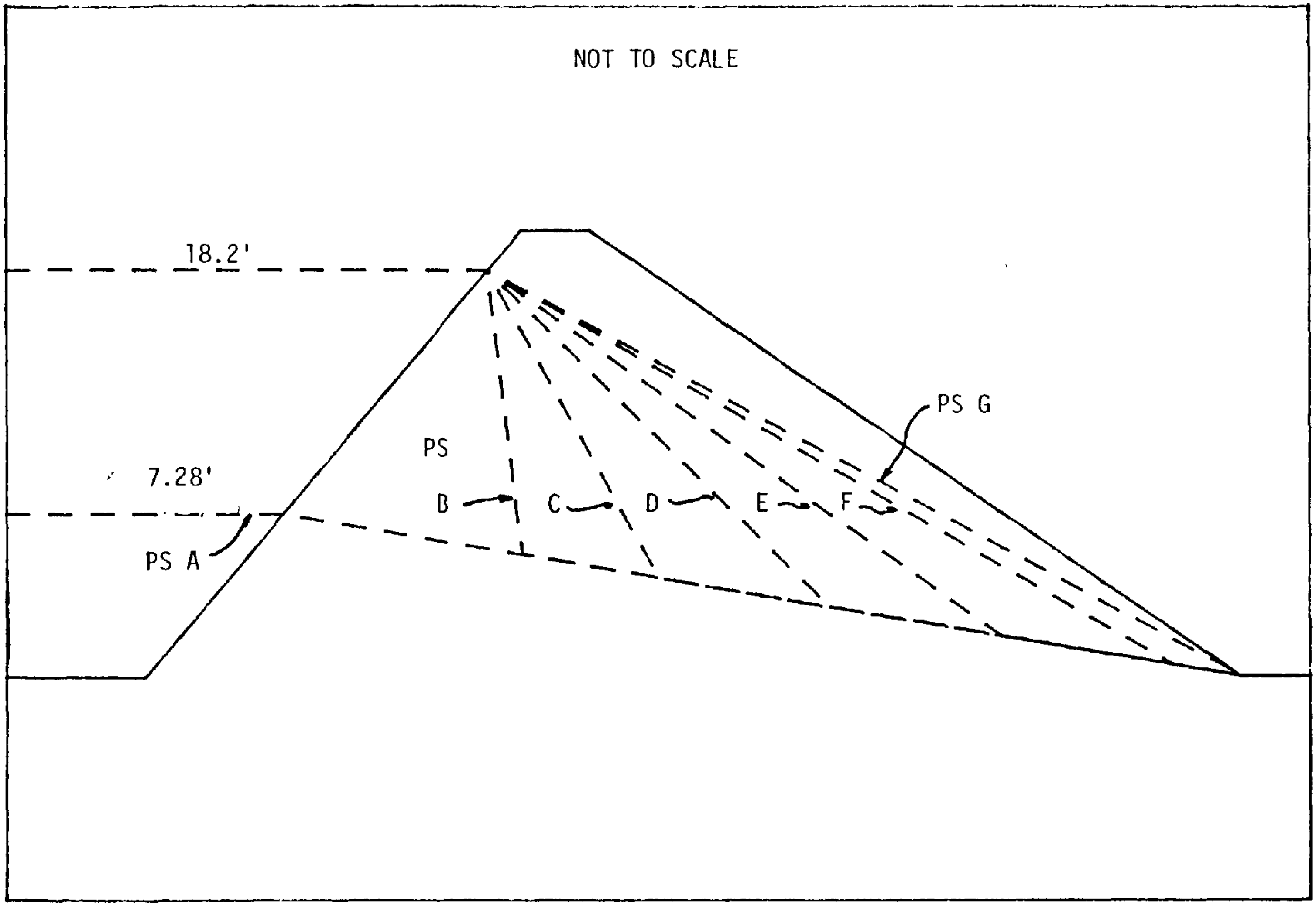


FIGURE 3-8 INITIAL, INTERMEDIATE, AND FINAL PHREATIC SURFACES USED TO STUDY THE EFFECT OF A RAPID RISE IN WATER LEVEL

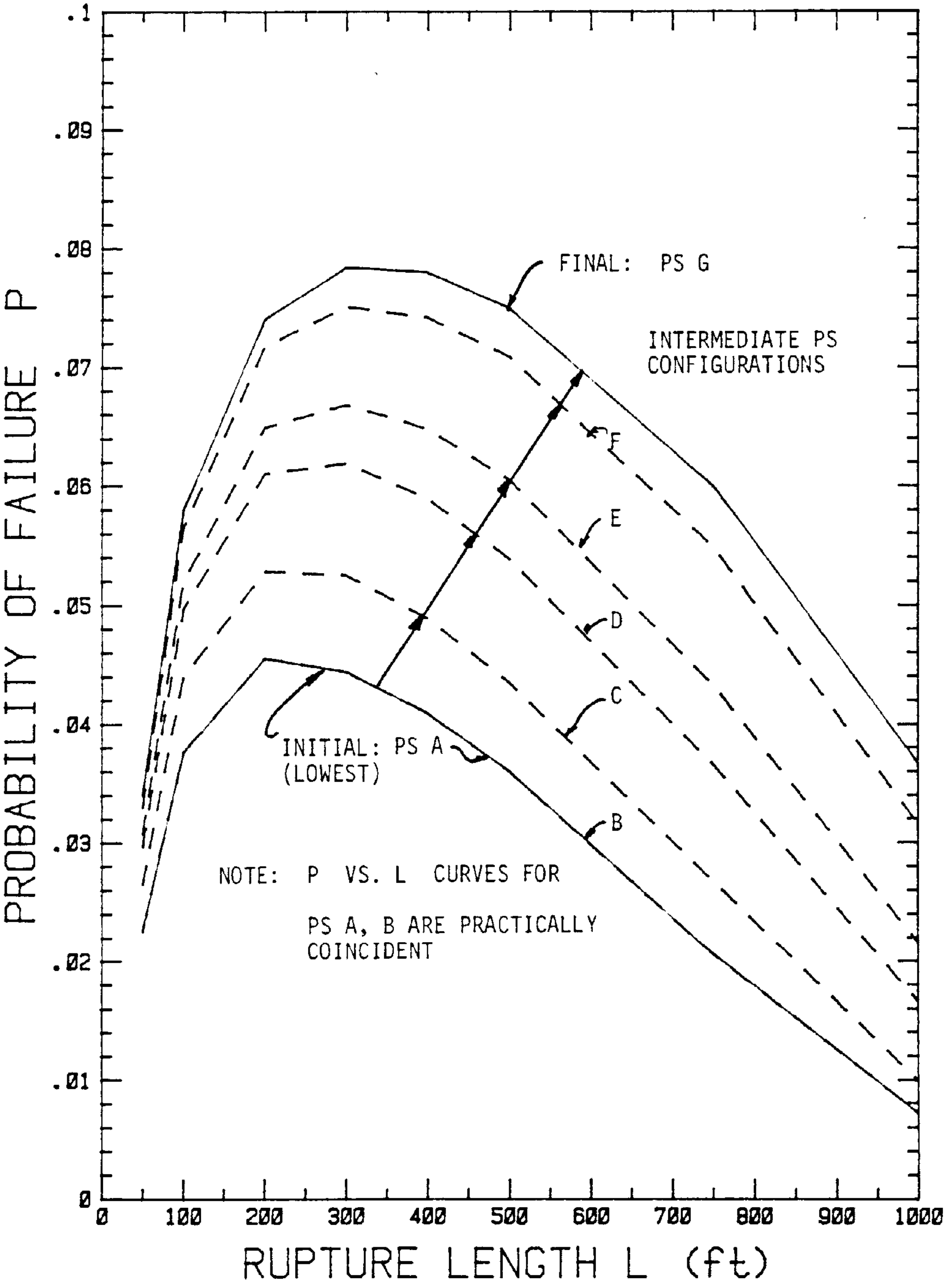


FIGURE 3-9a EFFECT OF RAPID RISE IN PS ON THE PROBABILITY OF FAILURE FOR A CYLINDRICAL FAILURE SURFACE

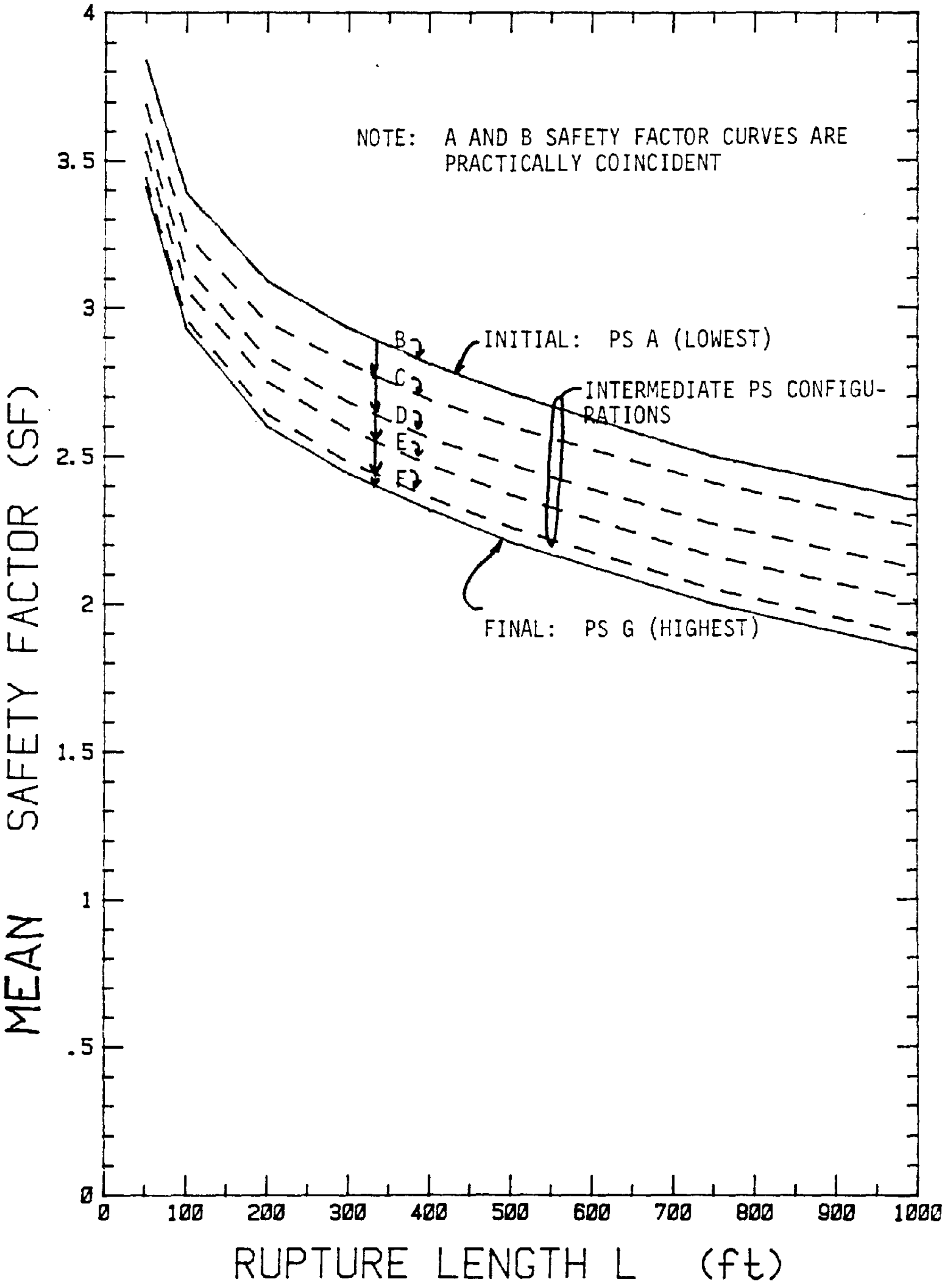


FIGURE 3-9b EFFECT OF A RAPID RISE IN PS ON THE MEAN SAFETY FACTOR FOR A CYLINDRICAL FAILURE SURFACE

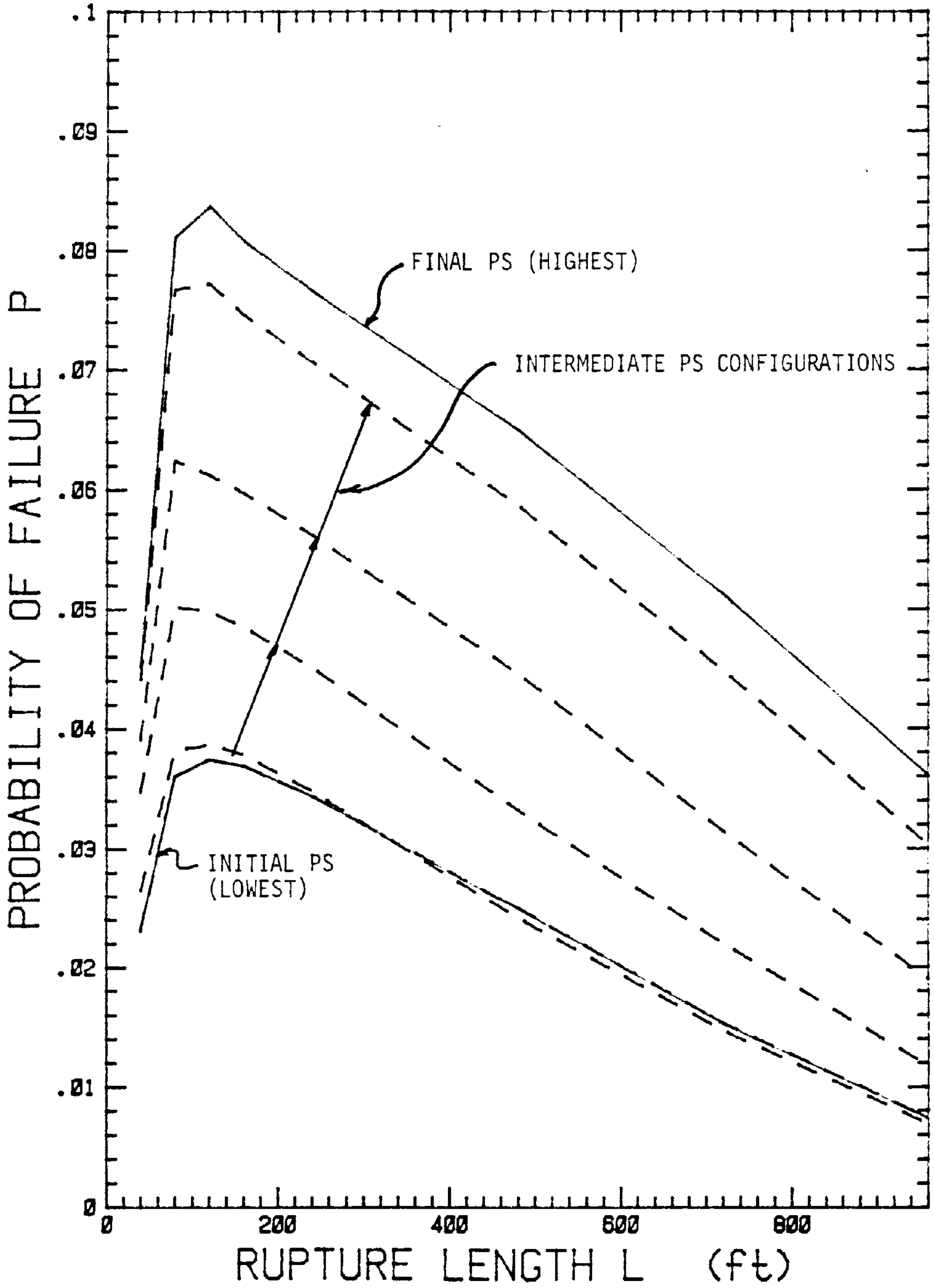


FIGURE 3-9c EFFECT OF A RAPID RISE IN PS ON THE PROBABILITY OF FAILURE FOR AN ELLIPSOIDAL FAILURE SURFACE. NOTE THE SHARP PEAK RELATIVE TO FIGURE 3-9a.

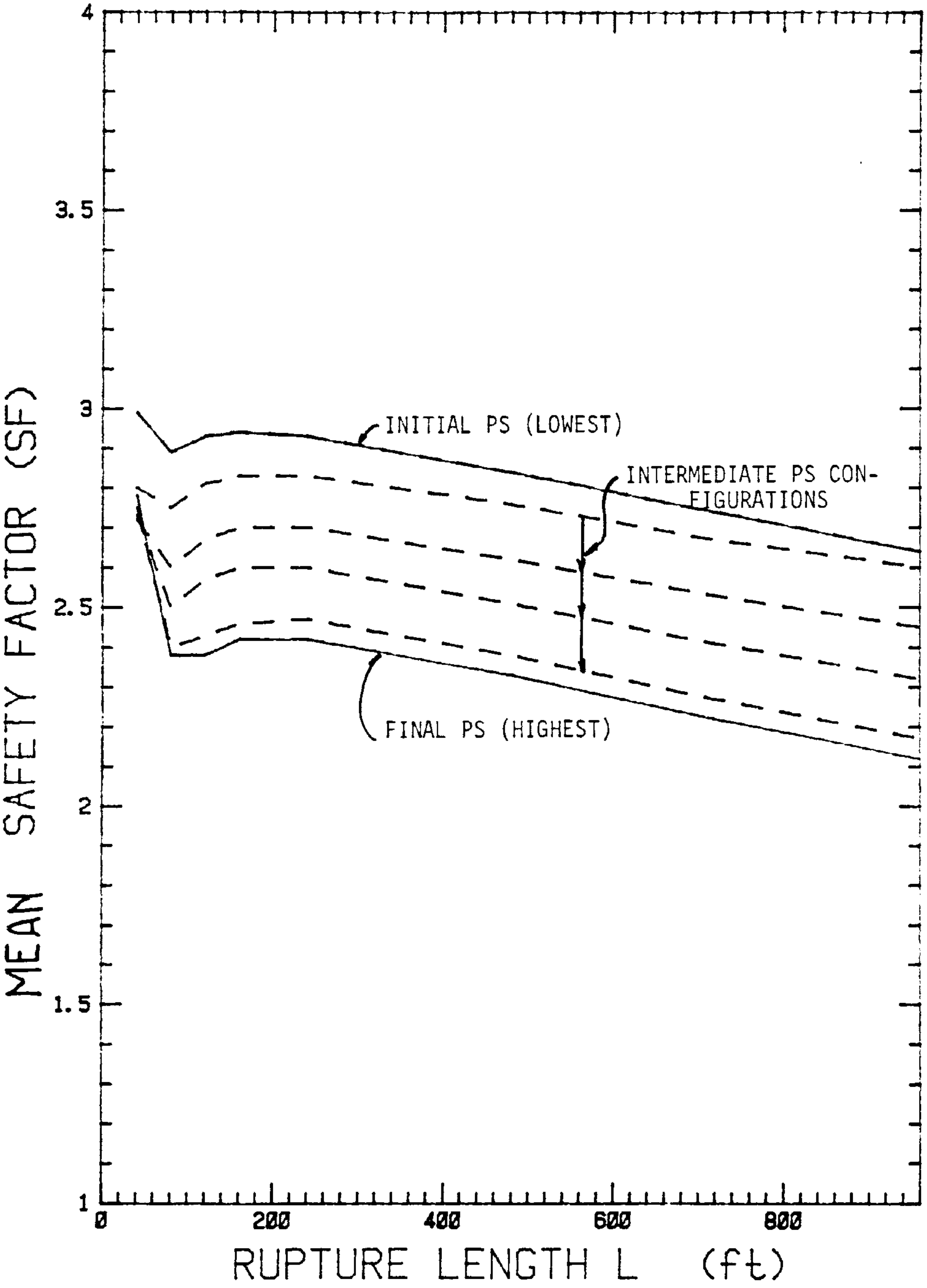


FIGURE 3-9d EFFECT OF A RAPID RISE IN PS ON THE MEAN SAFETY FACTOR FOR AN ELLIPSOIDAL FAILURE SURFACE

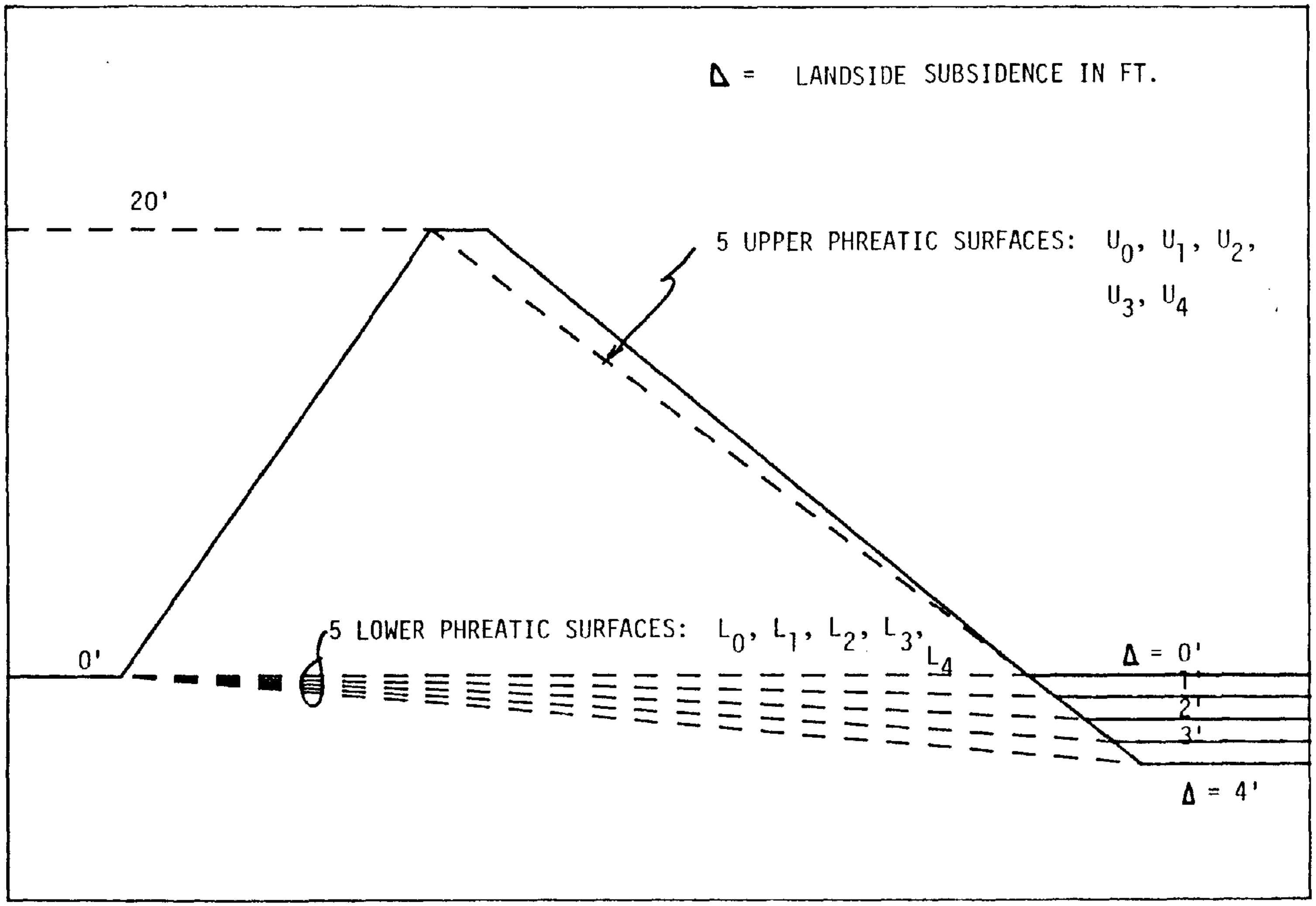


FIGURE 3-10a CONFIGURATIONS USED IN THE STUDY OF LANDSIDE SUBSIDENCE

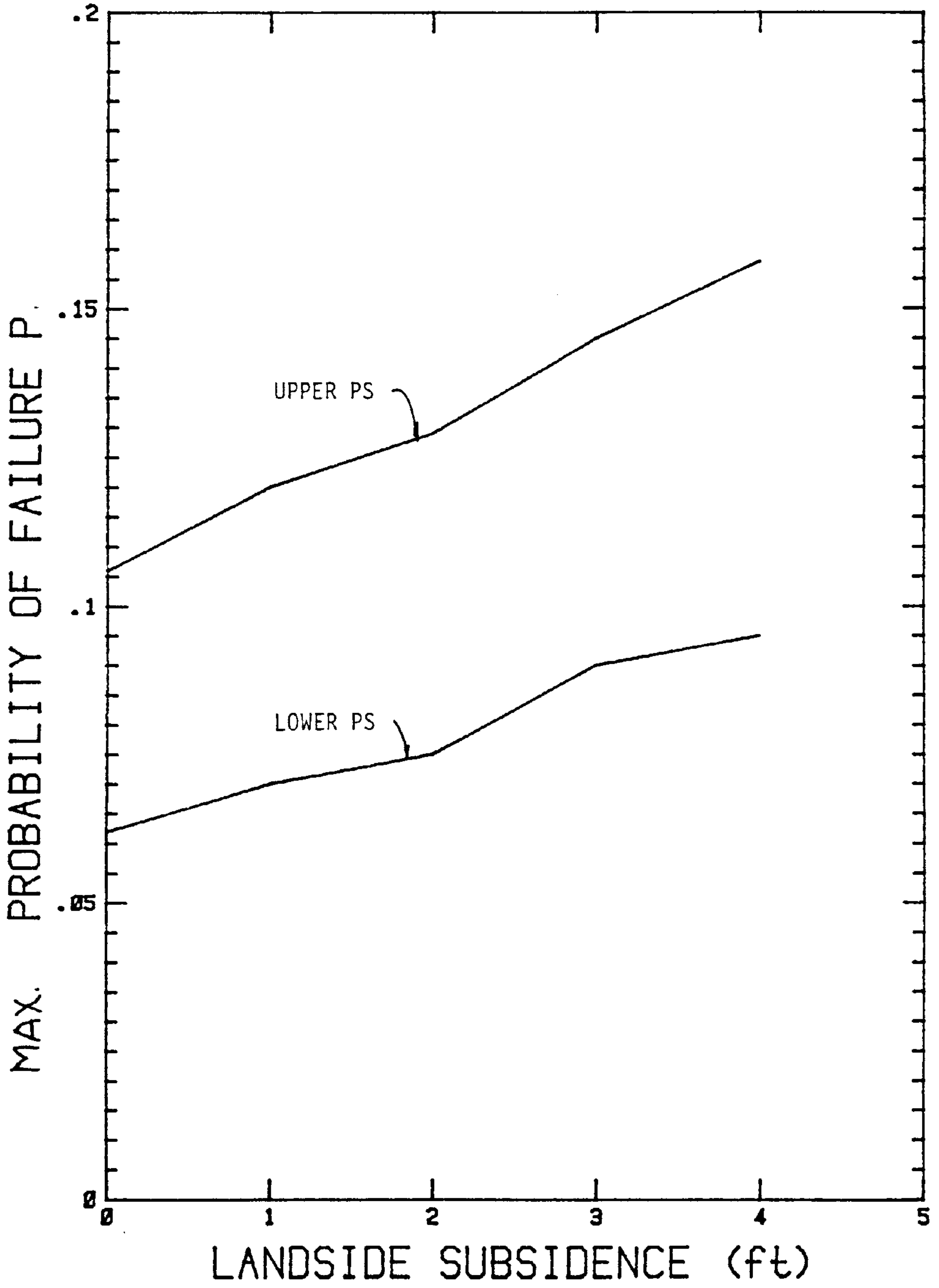


FIGURE 3-10b EFFECT OF LANDSIDE SUBSIDENCE ON THE PROBABILITY OF FAILURE

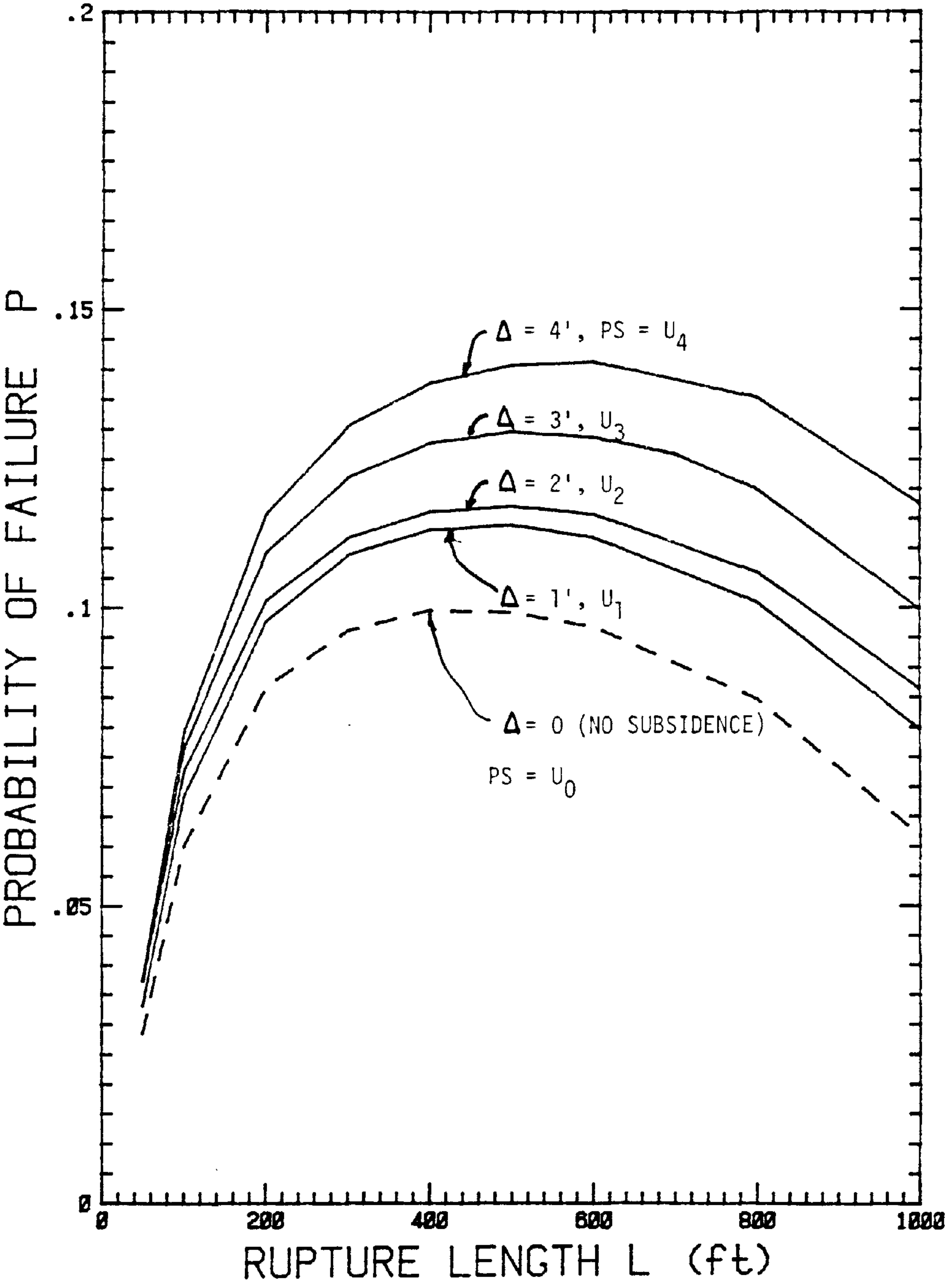


FIGURE 3-10c EFFECT OF LANDSIDE SUBSIDENCE, Δ, ON THE PROBABILITY OF FAILURE FOR A CYLINDRICAL FAILURE SURFACE AND THE UPPER PS

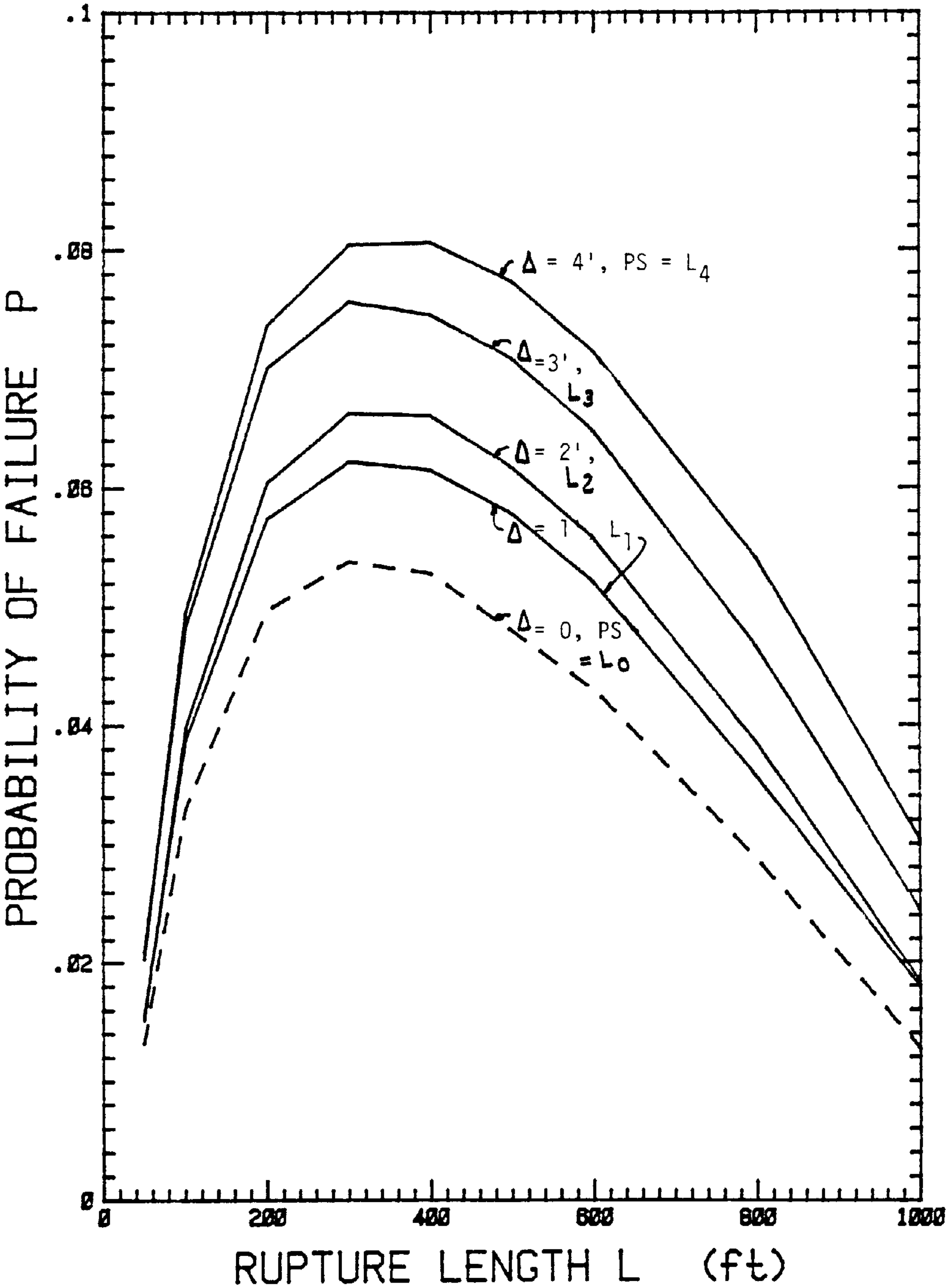


FIGURE 3-10d EFFECT OF LANDSIDE SUBSIDENCE, Δ, ON THE PROBABILITY OF FAILURE FOR A CYLINDRICAL FAILURE SURFACE AND THE LOWER PS

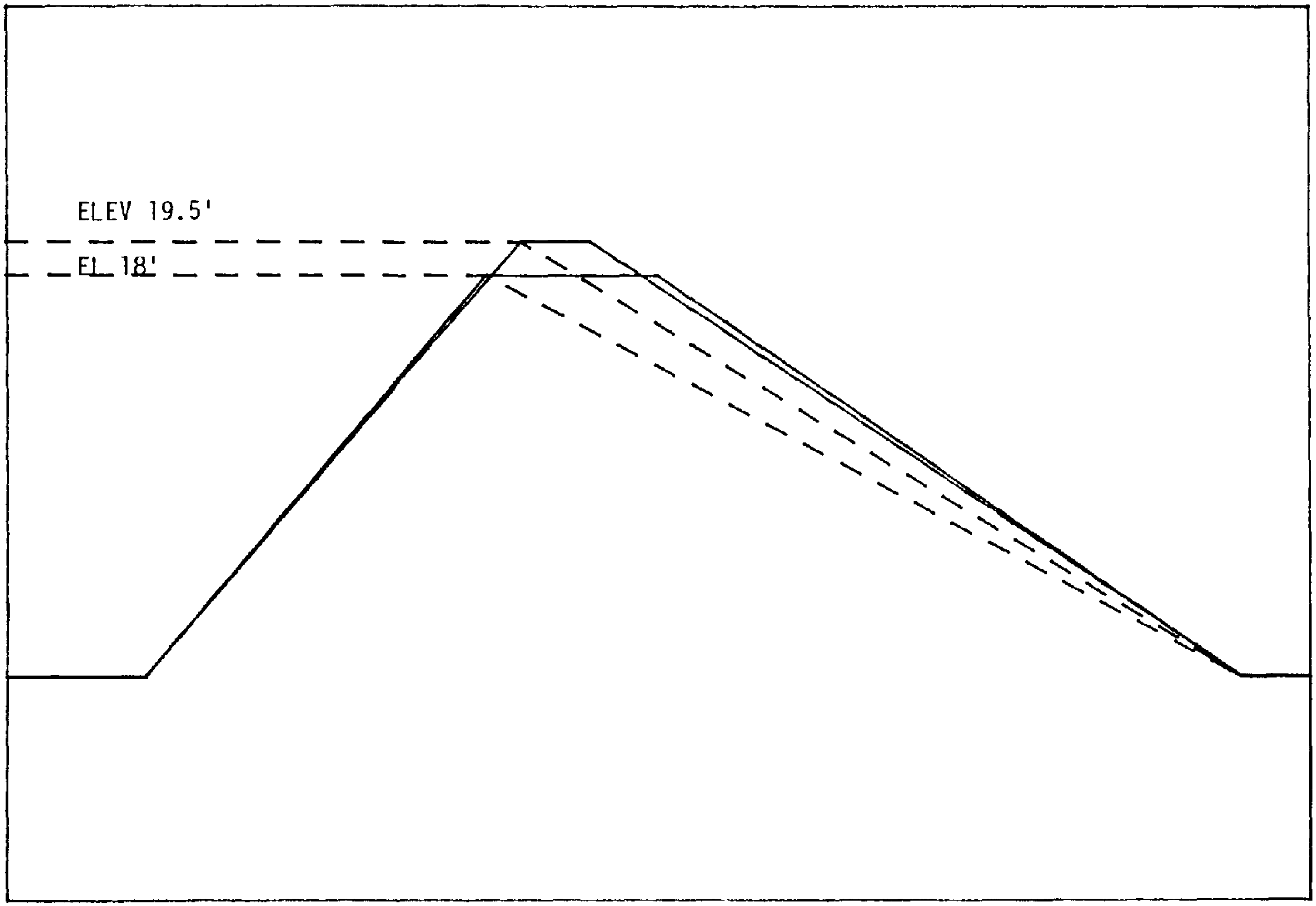


FIGURE 3-11 CREST EROSIONS CONSIDERED

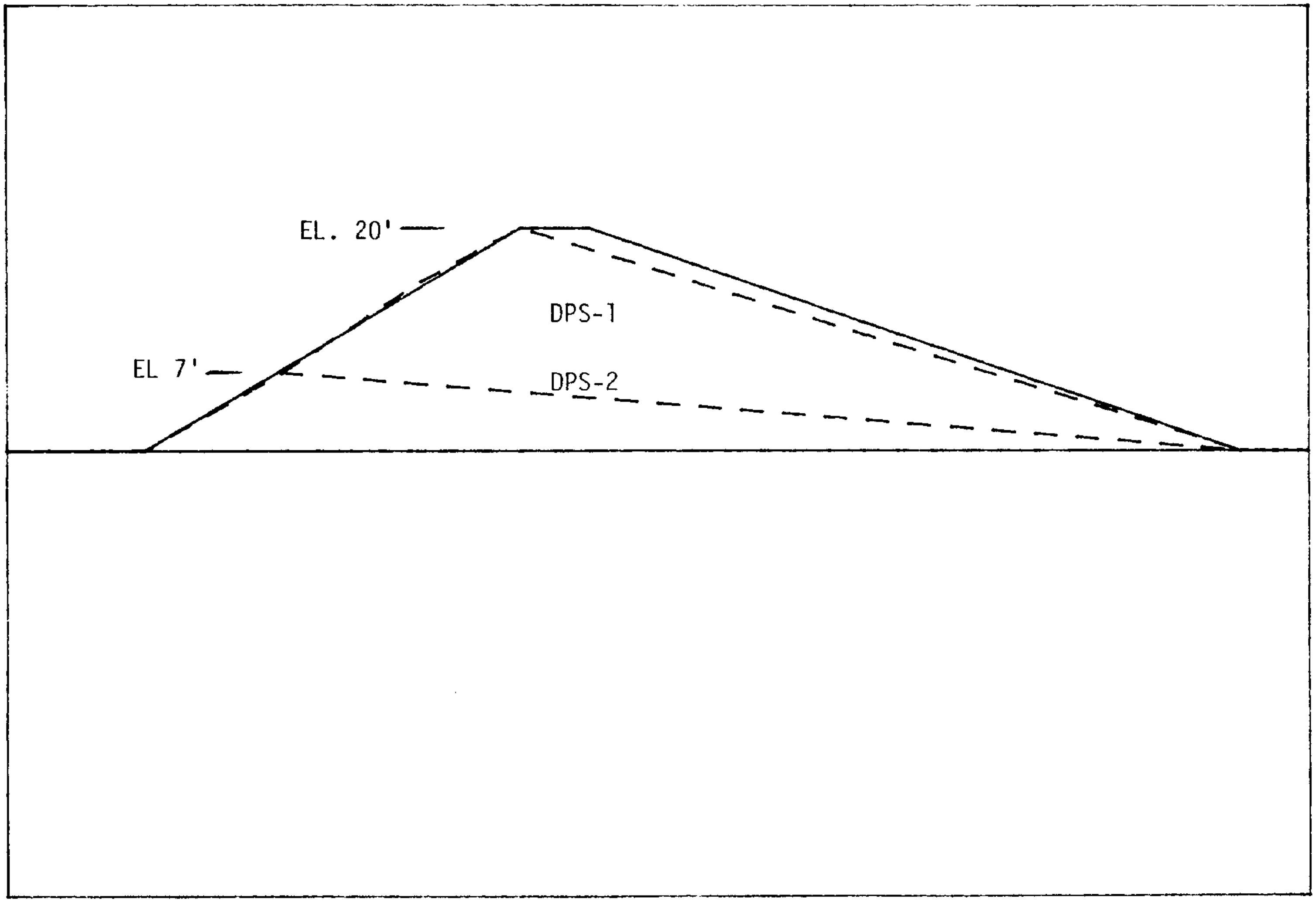


FIGURE 3-12a PHREATIC SURFACES USED IN THE RAPID DRAWDOWN STUDIES

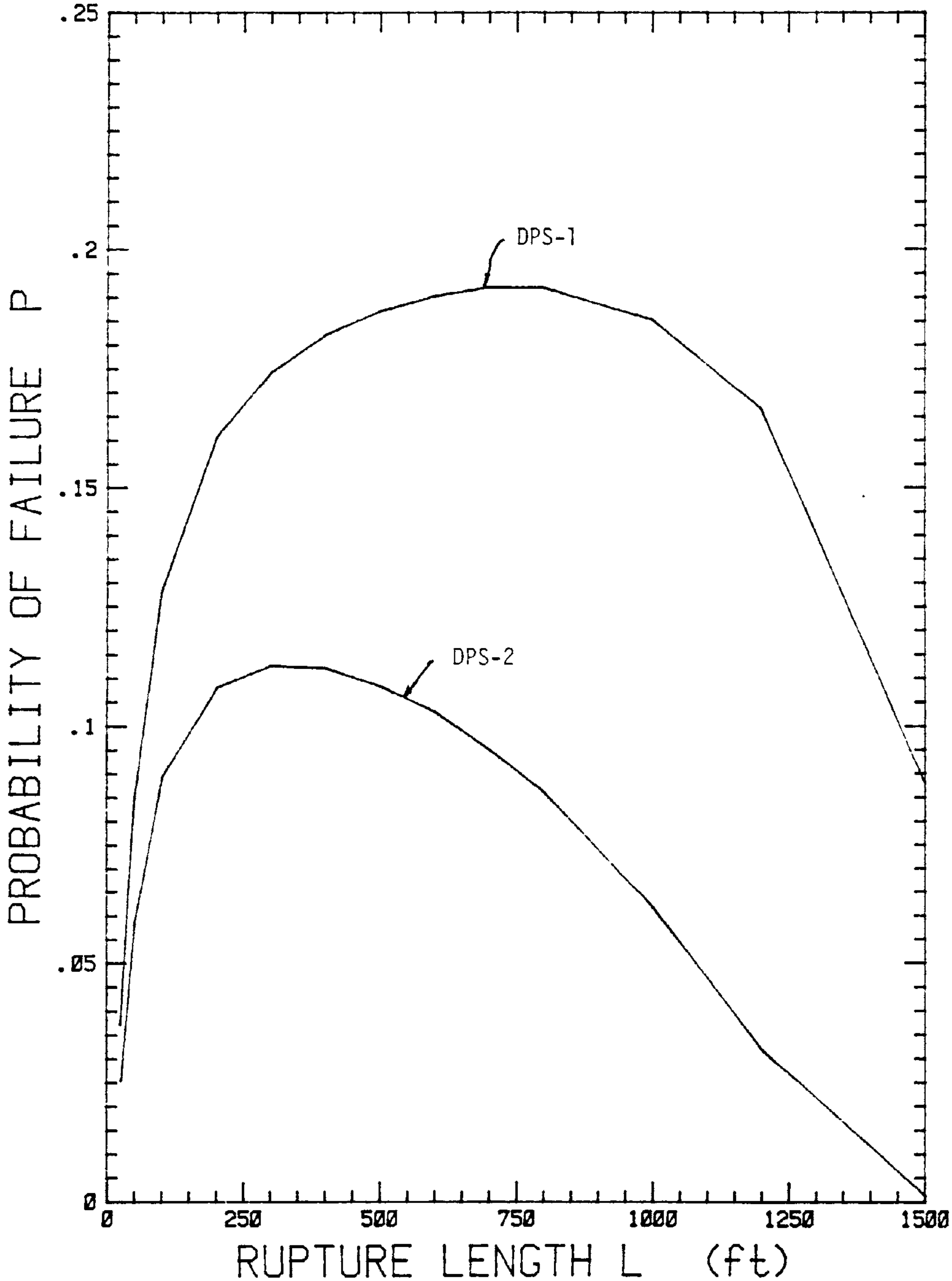


FIGURE 3-12b EFFECT OF RAPID DRAWDOWN ON PROBABILITY OF FAILURE FOR A CYLINDRICAL FAILURE SURFACE

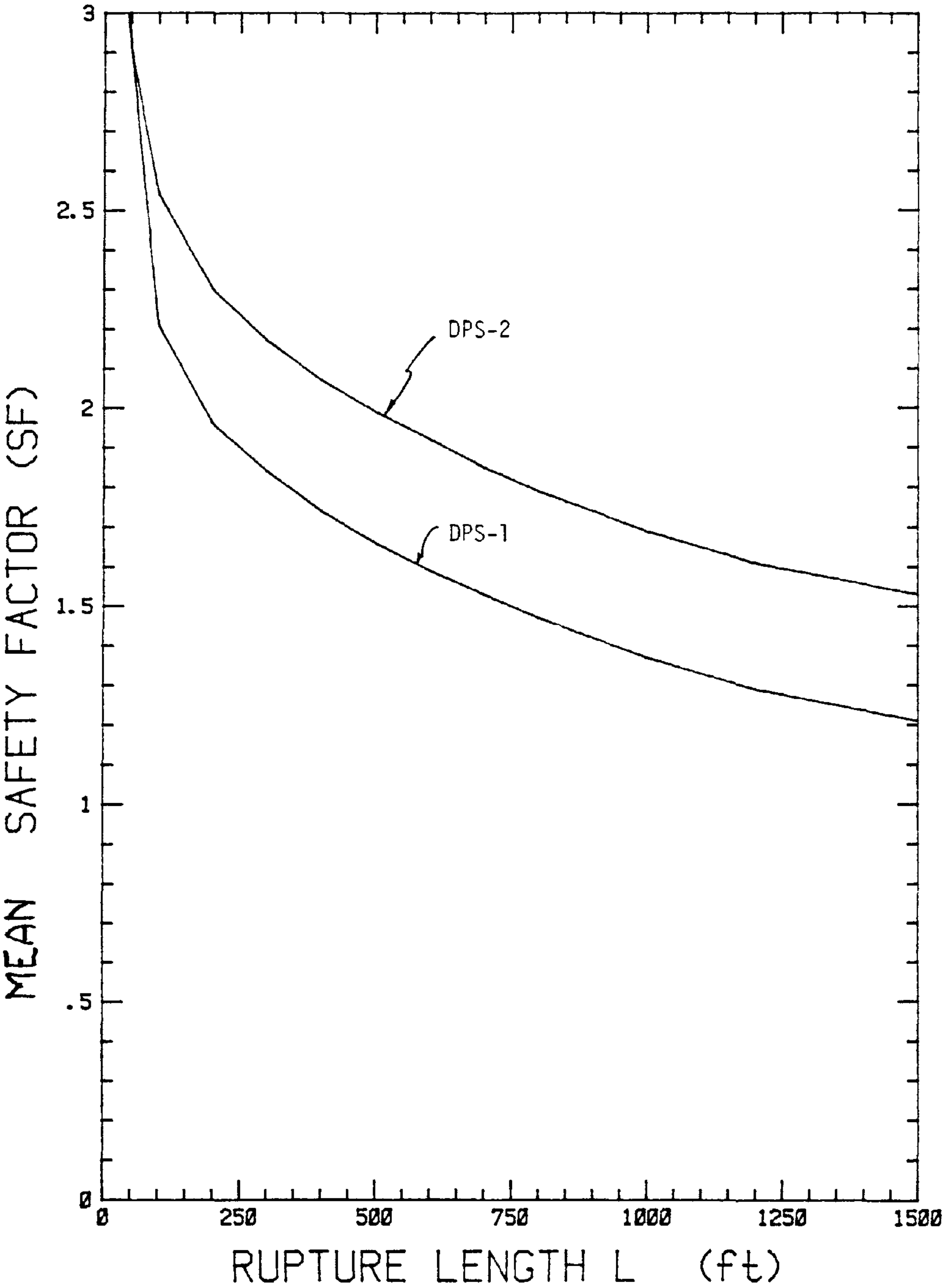


FIGURE 3-12c EFFECT OF RAPID DRAWDOWN ON MEAN SAFETY FACTOR FOR A CYLINDRICAL FAILURE SURFACE

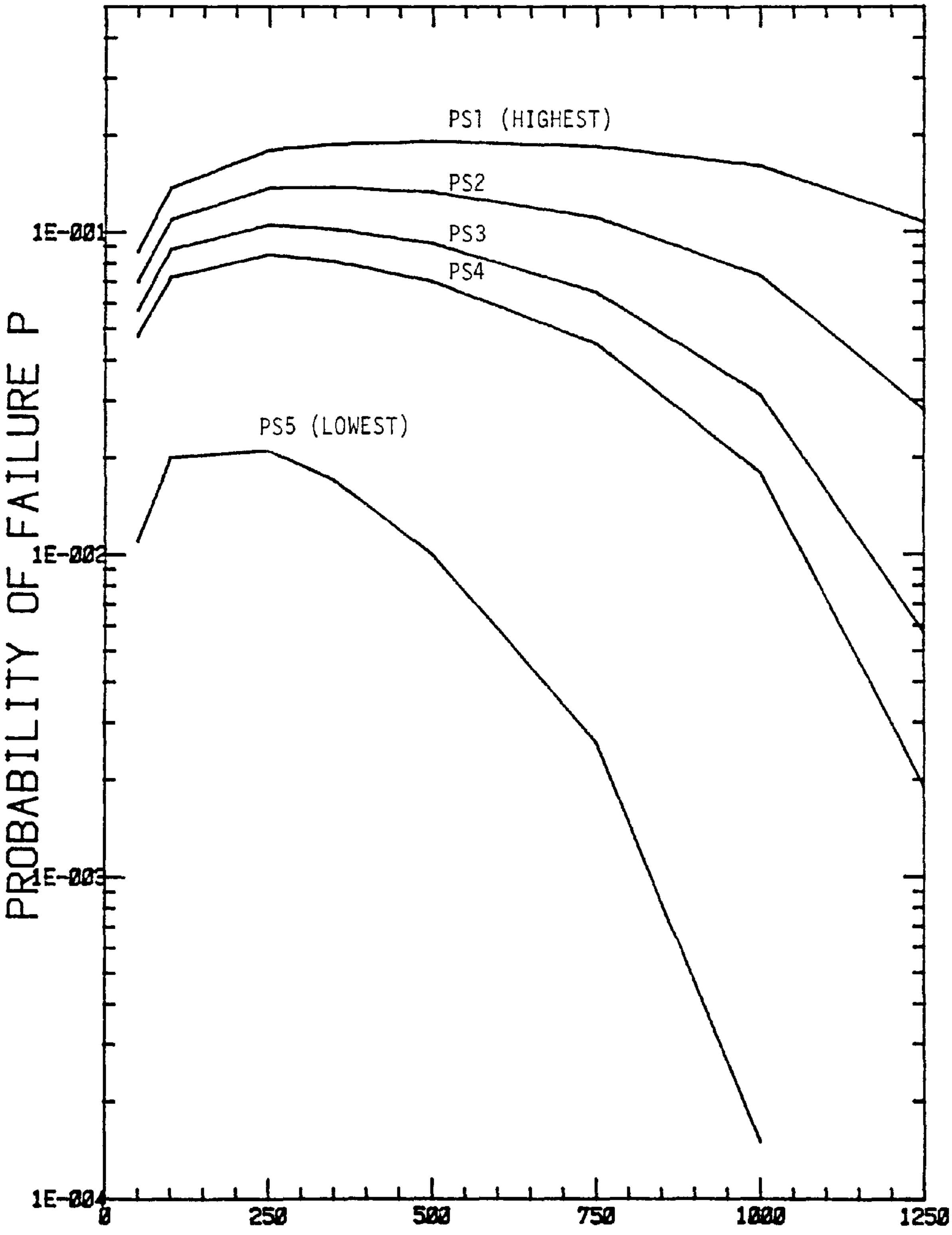


FIGURE 3-13a EFFECT OF PSEUDO SEISMIC LOADING ON PROBABILITY OF FAILURE FOR VARIOUS PS LOCATIONS, CYLINDRICAL FAILURE SURFACE

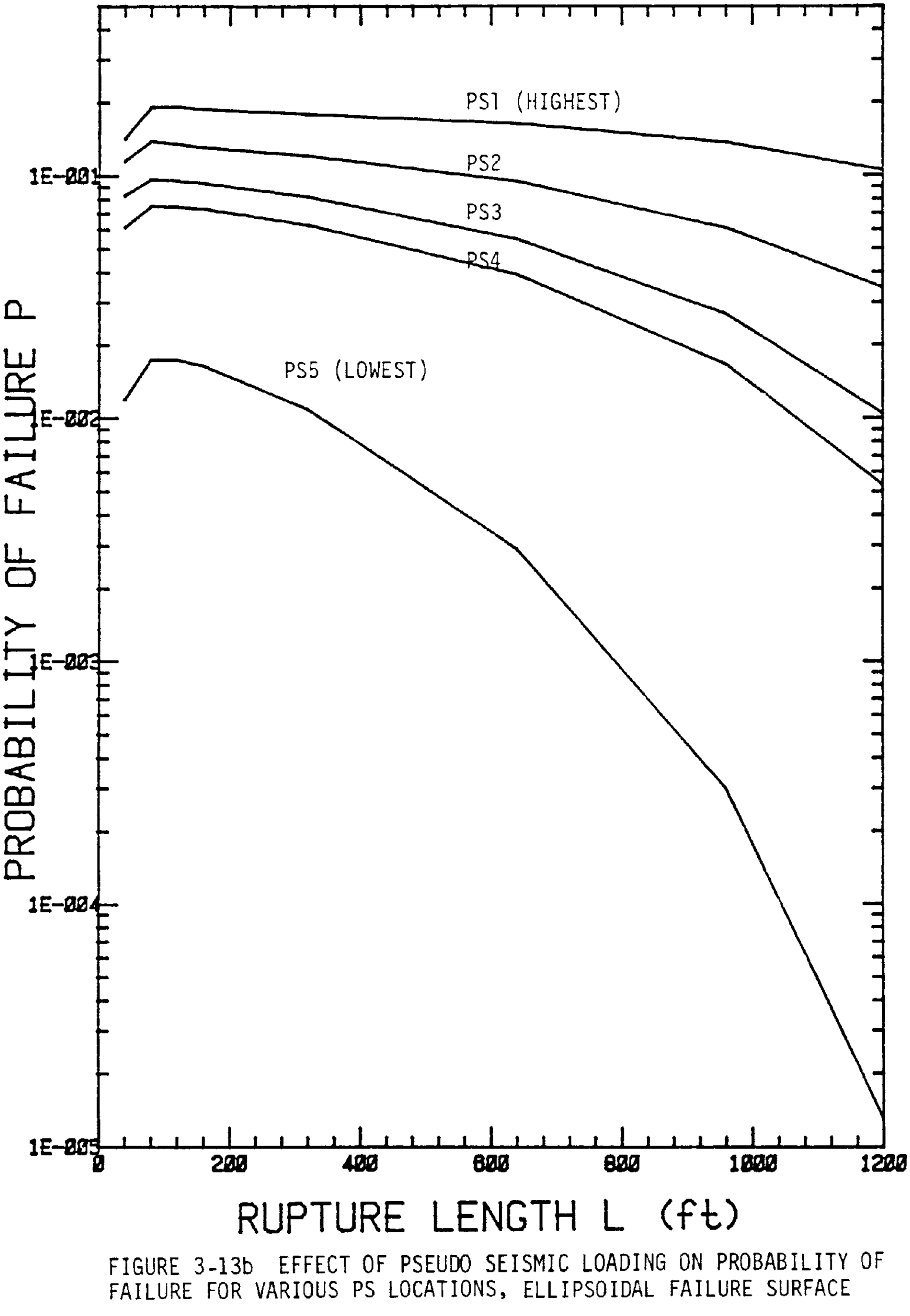


FIGURE 3-13b EFFECT OF PSEUDO SEISMIC LOADING ON PROBABILITY OF FAILURE FOR VARIOUS PS LOCATIONS, ELLIPSOIDAL FAILURE SURFACE

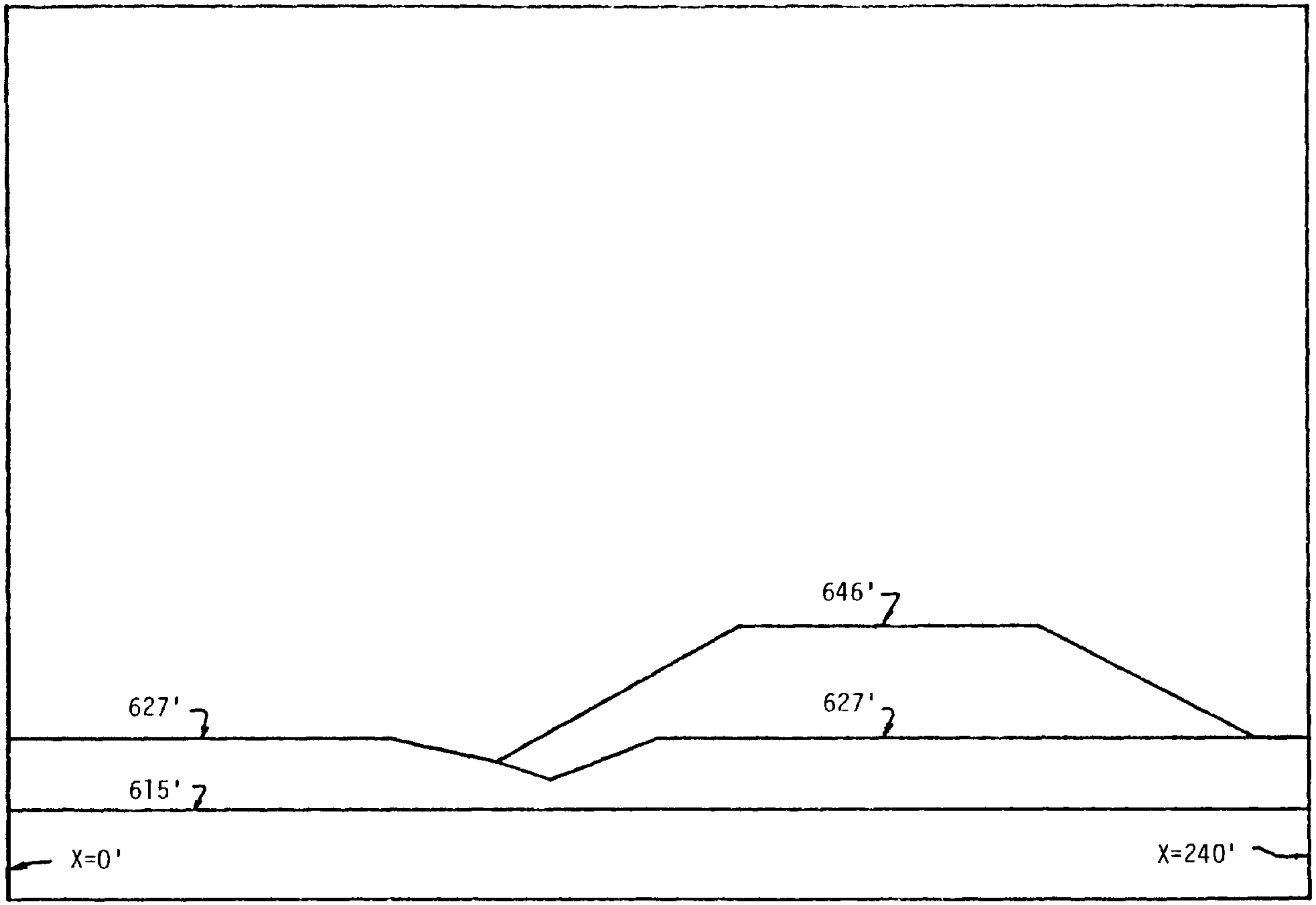


FIGURE 3-14a GEOMETRY USED IN VANMARCKE'S EXAMPLE

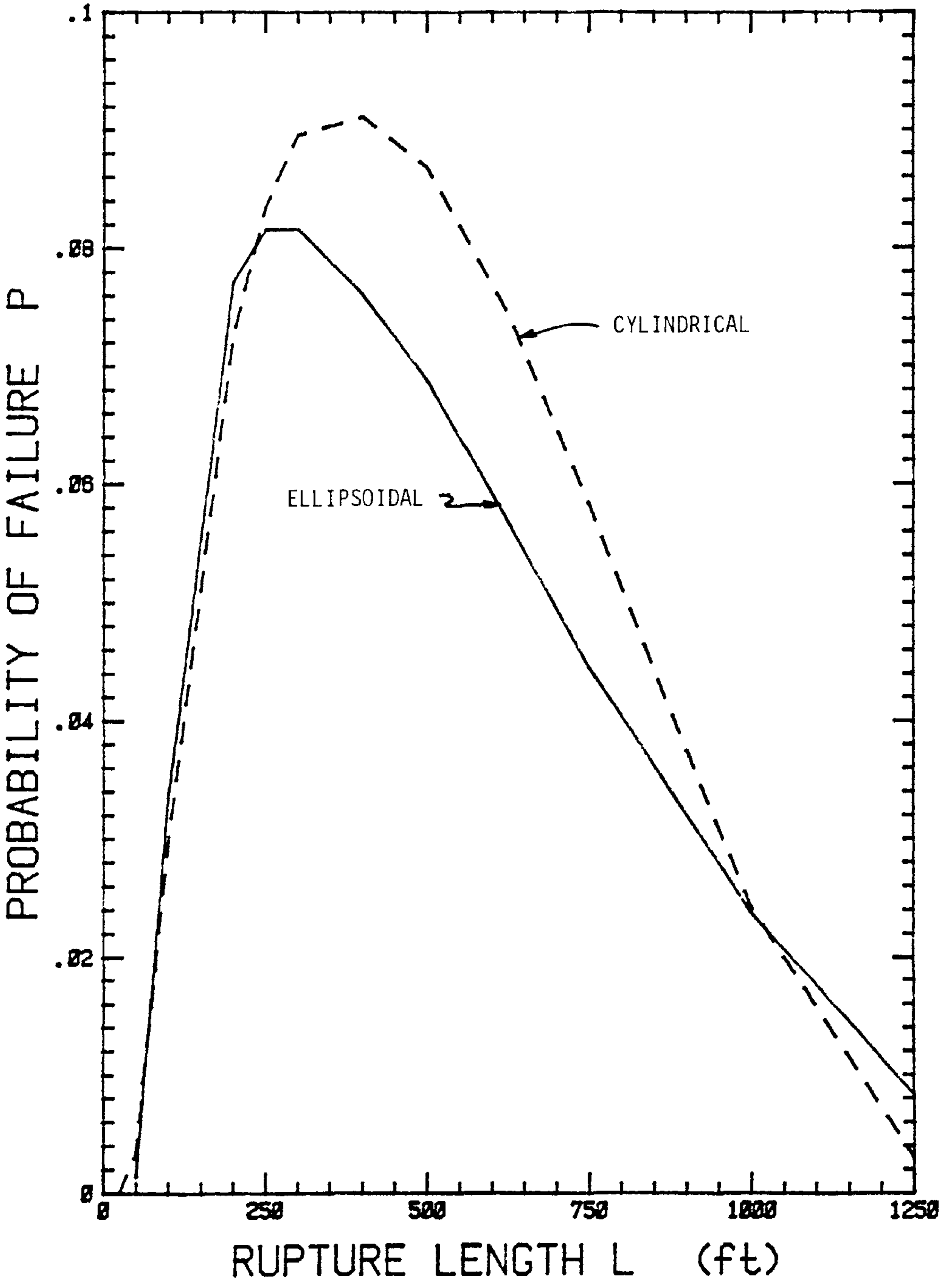


FIGURE 3-14b INFLUENCE OF FAILURE SURFACE ASSUMPTION ON PROBABILITY OF FAILURE WITH VANMARCKE'S EXAMPLE

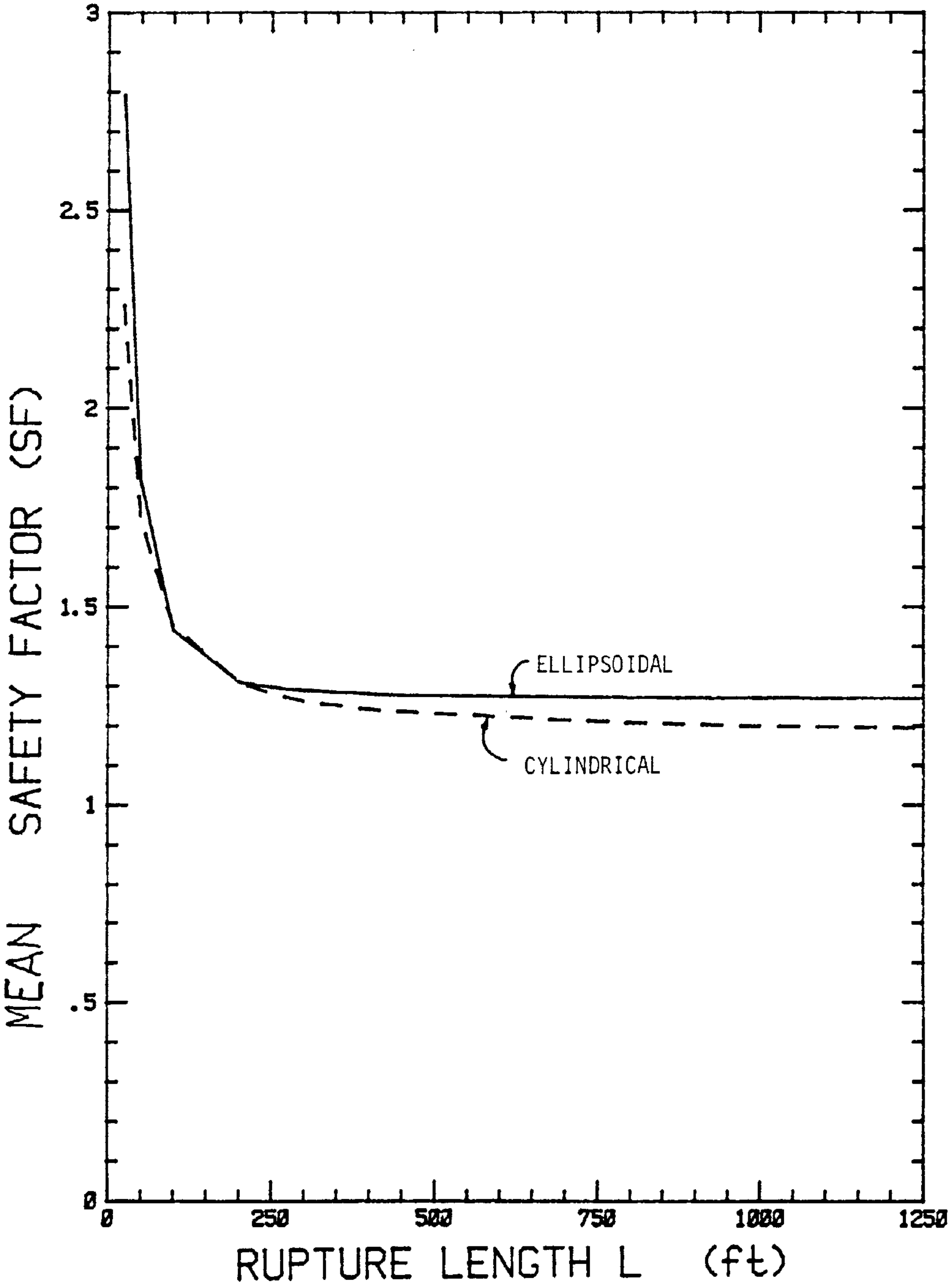


FIGURE 3-14c INFLUENCE OF FAILURE SURFACE ASSUMPTION ON MEAN SAFETY FACTOR FOR VANMARCKE'S EXAMPLE

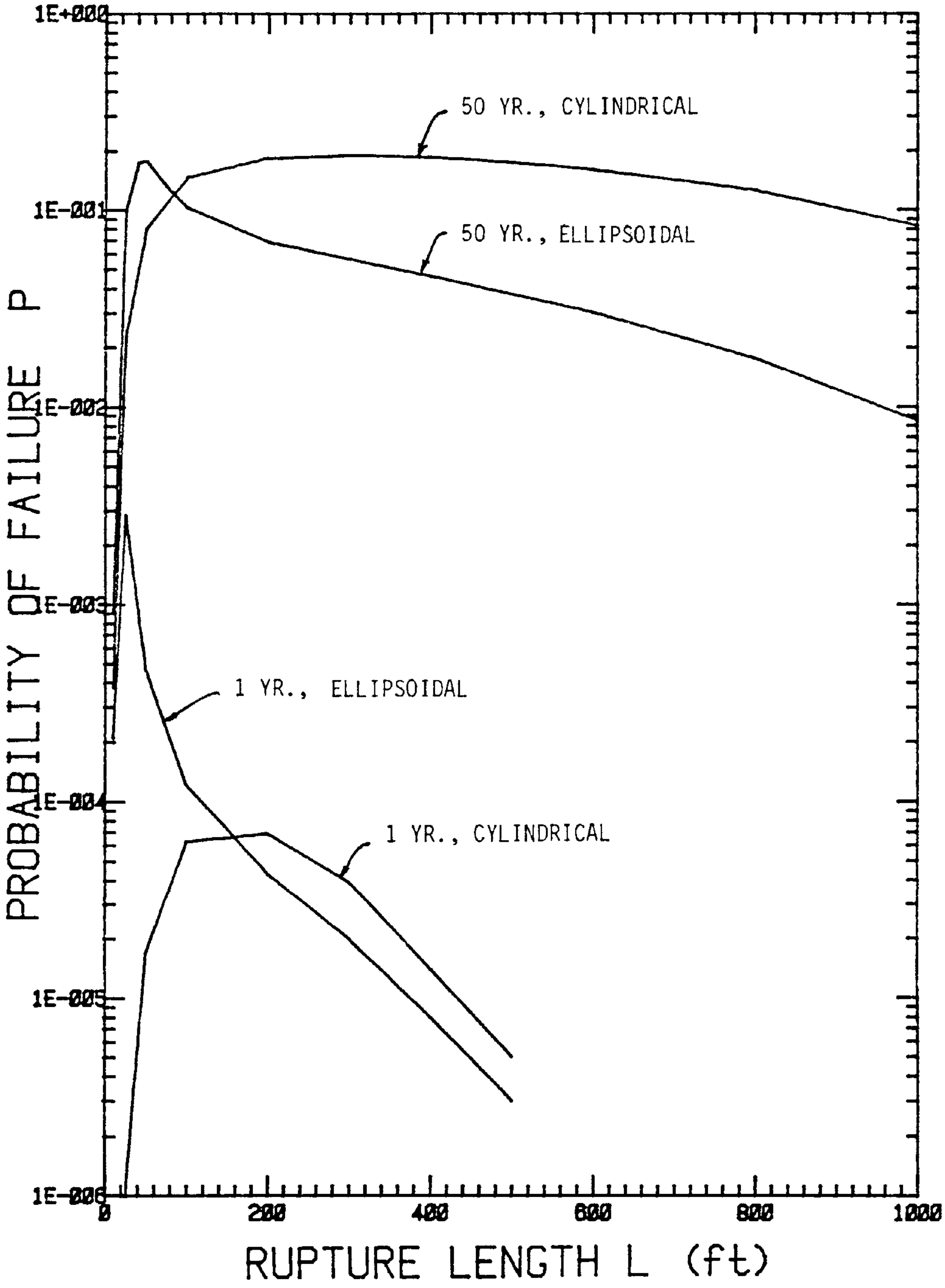


FIGURE 3-15a INFLUENCE OF FLOOD LEVEL ON PROBABILITY OF FAILURE FOR WOODWARD PROFILE #1

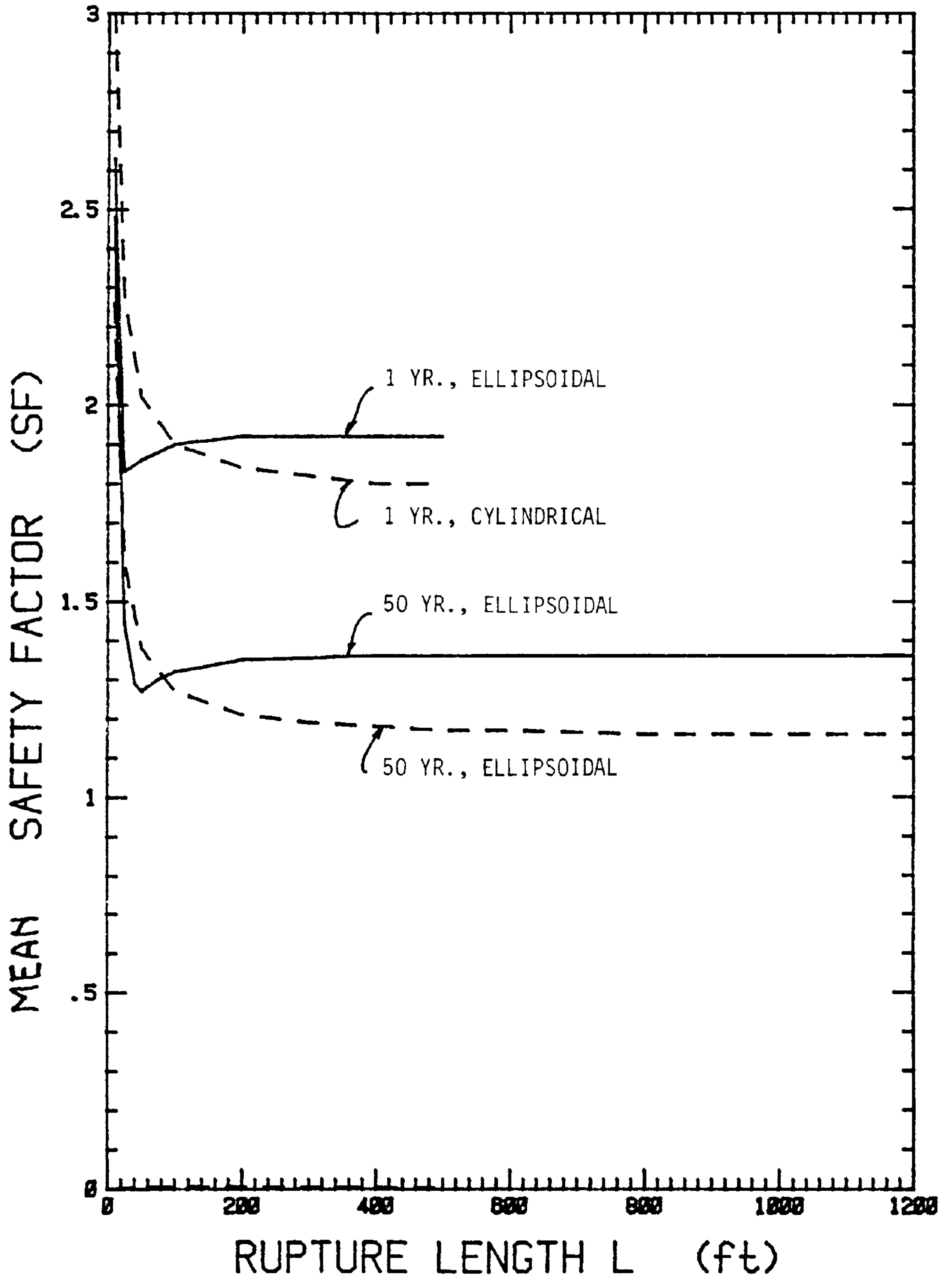


FIGURE 3-15b INFLUENCE OF FLOOD LEVEL ON MEAN SAFETY FACTOR FOR WOODWARD PROFILE #1

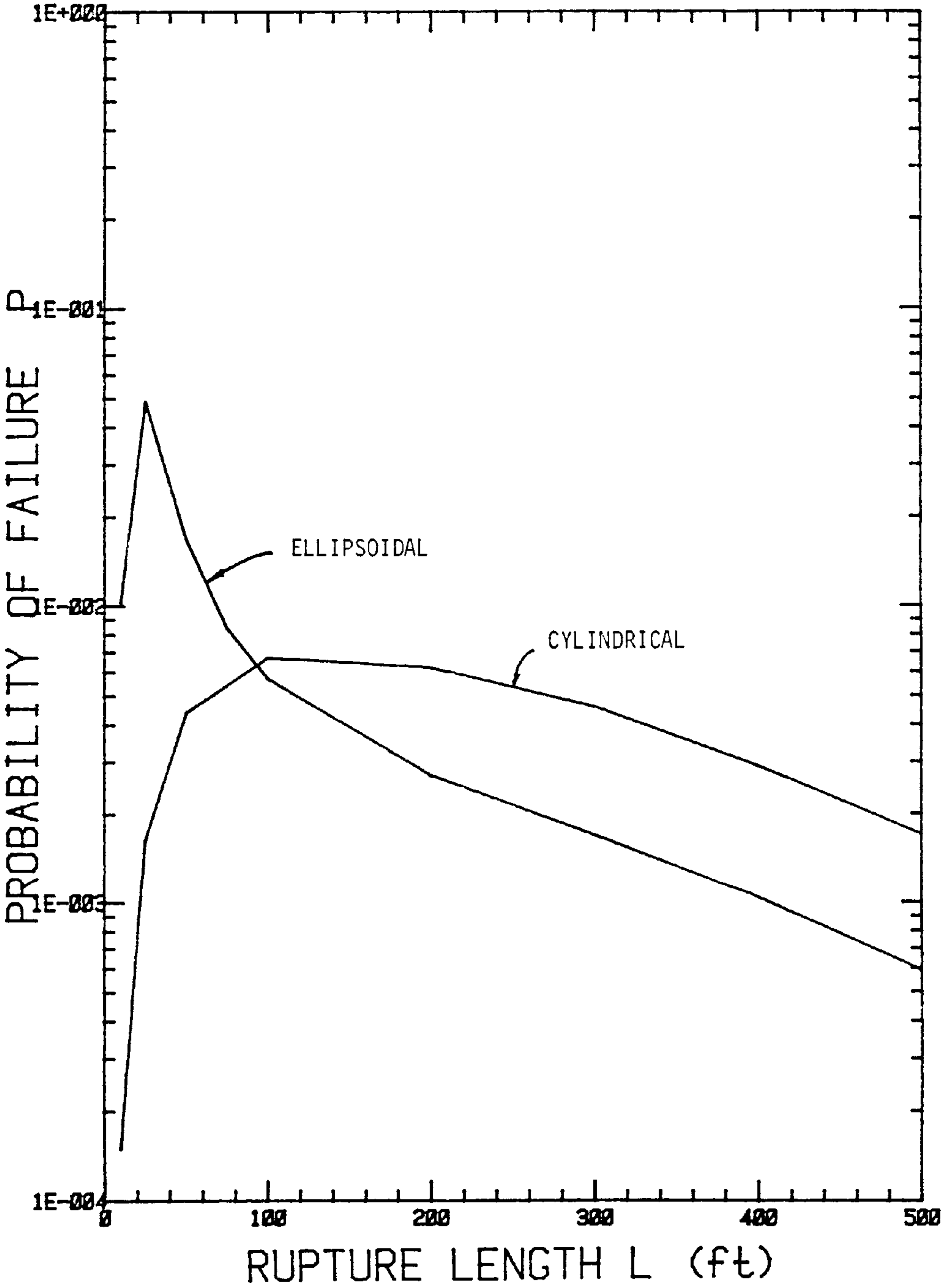


FIGURE 3-15c WOODWARD PROFILE #2

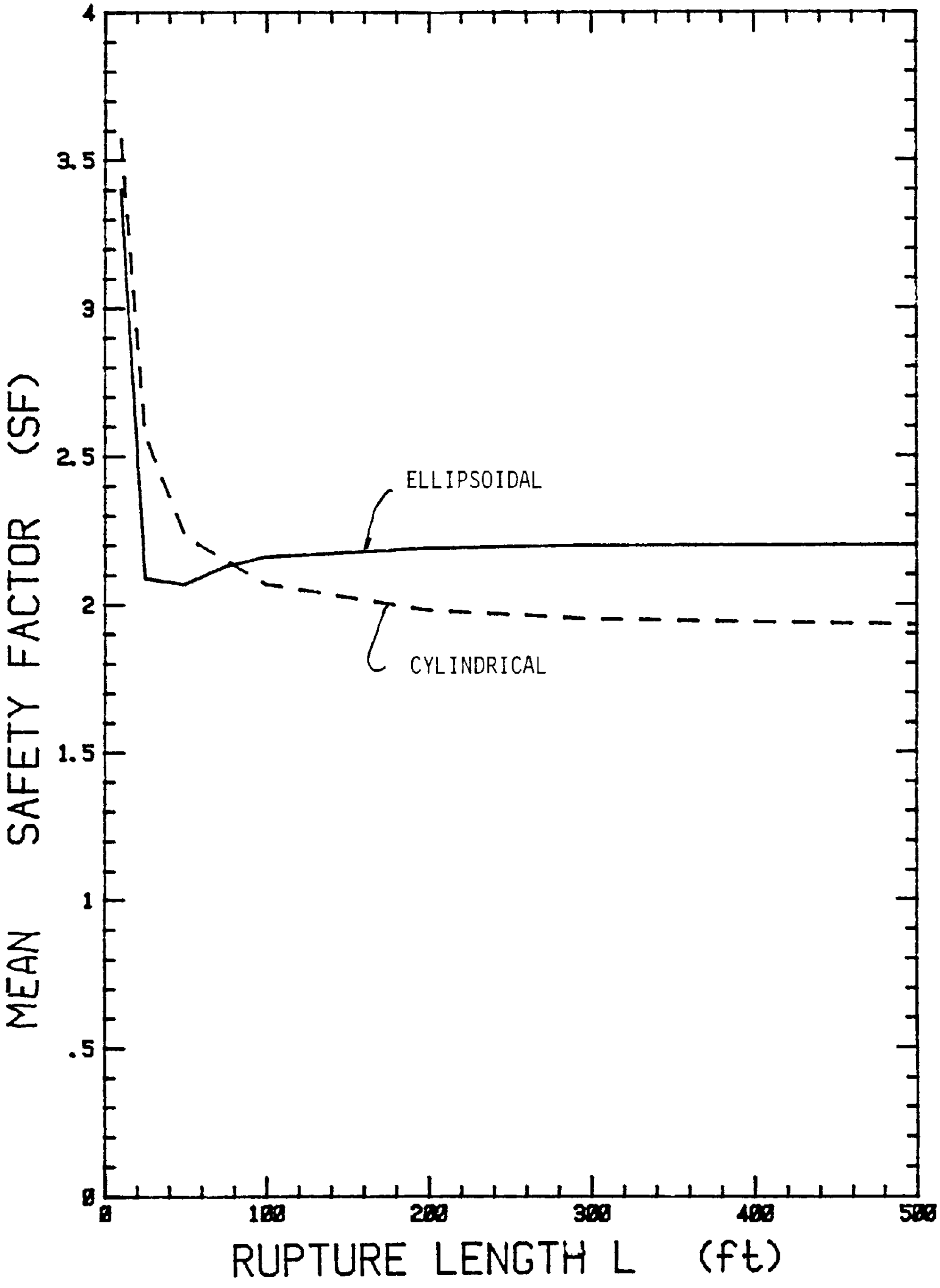


FIGURE 3-15d WOODWARD PROFILE #2

4.0 Systems Analysis and Scenarios

4.1 Systems Analysis Applied to Levees

Levee systems consist of components, such as embankments broken down into subreaches), hardware (e.g. closures, pumps, etc.), and operation and maintenance personnel. The system is surrounded by a physical and social environment, and suffers from aging.

Henley and Kuromoto (Ref. 4-1) point out that there are two basic approaches for analyzing causal relations in a systems analysis: forwards and backwards. Forward analyses start with failure events and try to identify all possible consequences. Failure events are generally related to:

- human error, such as design error, operator error, maintenance error or neglect;
- materials problems, such as low strength;
- the environment, such as earthquakes, subsidence, animal burrowing, flooding, etc.

On the other hand, backward analyses begin with a possible system failure (e.g., levee breach) and trace backwards searching for possible causes.

Event and decision trees are forward analyses, whereas backward analyses are typified by the fault tree. Generally, both of these approaches are used cooperatively to attain a complete systems reliability analysis. The backward analysis is used to identify the causal relationships leading to a specific failure, the failure being the top event of the fault tree (levee breach). The forward analysis assumes different sequences of events and specifies a number of scenarios ending in the system failure. The information which must be developed in order to write good scenarios are component layout, component failure characteristics and system specifications.

Component failures are classified as primary failure, secondary failures, or command faults. A primary failure occurs when a component is in a non-working state caused by natural aging (e.g., erosion, subsidence, etc.) and in need of repairs to return to the working state. A primary failure may occur at loads below the design allowable load condition. A secondary failure is the same as a primary failure except that the failure is due to excessive demands caused by such events as earthquake, water stages greater than the design flood level, etc. In the terminology of fault tree analysis, primary and secondary failures are known as basic failures. Note that these failure classifications may be dependent. For example, if an earthquake shakes a levee whose material strength has been weakened over the years by rodents, or eroded by wave action, then the failure is a combination of primary and secondary events.

A command fault is defined as a component being in the non-working state due to improper operation. For example, a closure is not closed in time to prevent a less than design flood from inundating behind a levee, or a closure is inadvertently closed causing water from a tributary behind a levee to flood the protected area.

An example of how multiple, dependent hazards can be handled for a levee is given by Duckstein and Bogardi (Ref. 4-2). They present a methodology for determining the reliability of levee systems which takes into account four types of failure hazards: overtopping, subsoil failure (boils), slope stability, and erosion. The loads include peak flood level, duration, and volume. The flood height can be assumed constant but random at all sections, or varying according to backwater effects and wind waves.

The resistance of each section is then determined for each of these loads and is expressed in terms of the flood parameter that triggers the failure. Resistance values are determined by direct measurement (levee profiles, soil properties) and analysis (seepage, stability). In general, the flood parameters governing these four types of failure are different.

The reliability model outlined in Reference 4-2 takes into consideration the stochastic character of the flood load, the random resistance of each section of the levee reach, and the different modes of failure. Failure of a levee section occurs if either:

$h > H_1$: overtopping,
$h > H_2$: subsoil failure (boils),
$h > H_3$ and $w > W$: slope stability failure,
$h + x > X$: wave erosion,

where
h = peak flood level,
w = flood exposure (the area of the stage hydrograph),
x = wave height and run-up,
H_1 = crest height,
H_2 = flood height corresponding to onset of boils,
H_3, W = respectively, the smallest <u>necessary</u> flood height and the largest <u>allowable</u> flood exposure for slope stability failure,
X = the highest dynamic water level (peak static level + wave + run-up) necessary for erosion failure.

The failure event is for a given levee section written as:

$$F = [h > H_1] \cup [h > H_2] \cup [h > H_3 \cap w > W] \cup [(h + x) > X].$$

For ease of computing the failure probability the failure event can be divided into disjoint events:

$$F = A \cup B \cup C \cup D,$$

where
$$A = [h \leq H_3] \cap [h + x > X)],$$
$$B = h \geq \min [H_1, H_2],$$
$$C = [H_3 < h \leq \min (H_1, H_2)] \cap [h + x > X],$$
$$D = [H_3 < h \leq \min (H_1, H_2)] \cap [h + x \leq X] \cap [w > W].$$

Subdividing the levee into subreaches, each with its own failure event defined, the system failure event is then defined as:

$$F = F_1 \cup F_2 \cup . . . \; F_n.$$

Letting
$$H = \min (H_{1,i}, H_{2,i}),$$
$$H_3 = \min (H_{3,i}),$$
$$t = \min (W_i), \qquad \text{for } H_{3,i} < h < H,$$

the conditional probability of failure of the levee system, given H, H_3, and t, is written:

$$P_{F|H,\, H_3,\, t} = 1 - F_h(H) + \int_{H_3}^{H} \int_{t}^{\infty} f(h, w)\,dw\,dh.$$

4.2 Scenarios in Levee Systems Analysis

Scenarios are simply a series of events that we imagine happening in the future. We construct scenarios in our every day lives, but rarely are they as developed or elaborate as those prepared by researchers working for the government or industry for military, political, and economic forecasting.

The term "scenario writing" denotes a technique which attempts to set up a logical sequence of events in order to show how, starting from the present (or any other given) situation, a future state might evolve, step by step. For the purposes of technological forecasting, time does not always have to be introduced explicitly, but may only be intervals of time, such as one year, ten years, etc.

Scenario writing is particularly suited to dealing with several aspects of a problem more or less simultaneously that may be interrelated. By the use of a relatively extensive scenario, the analyst may be able to get a "feel" for events and for the branching points dependent upon critical choices. These branches can then be explored more or less systematically.

Scenarios force the analyst to deal with details and dynamics which he might easily avoid treating if he restricted himself to abstract considerations. Typically, no particular set of the many possible sets of details and dynamics seems especially worth treating, so none are treated, even though a detailed investigation of even a few arbitrarily chosen cases can be helpful.

Various methods have been employed to structure scenarios, including morphological analysis, event-tree analysis, cross-impact analysis, brainstorming, etc., and yet the one which appears to be most useful to decision makers regarding levee systems is the event tree. Not only can environmental events be constructed, technological events and consequential events can also be evaluated.

4.3 References

4-1 Henley, E. J. and H. Kuromoto, Reliability Engineering and Risk Assessment, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1981.

4-2 Duckstein, L. and I. Bogardi, "Application of Reliability Theory to Hydraulic Engineering Design," Journal of the Hydraulics Division, ASCE, Vol. 107, No. HY7, July, 1981.

4-3 Bowles, D. S., L. R. Anderson, and R. V. Canfield, "A Systems Approach to Risk Analysis for an Earth Dam."

5.0 CONSEQUENCES AND DECISION MODELING

5.1 Consequences

Flooding is natural. However, when flooding comes in contact with developed areas, losses occur. Efforts to mitigate flood losses take many forms including flood-plain construction of levees. Flood-plain management should undertake to minimize the costs associated with flood-plain occupancy by optimizing the initial cost of development, the cost of flood protection, the cost of residual flood damage, and the cost of relief and rehabilitation.

Tangible benefits from flood mitigation include prevention of flood damage and land enhancement from more intensive use of protected land. The primary benefit from prevention of flood damage is the difference in expected damage throughout the life of a land use project with and without flood mitigation. Primary benefits include decrease or elimination of:

- costs of replacing or repairing damaged property;
- costs of evacuation, relief, and rehabilitation of victims, and emergency flood-protection measures;
- losses resulting from disruption of business;
- loss of crops, and/or cost of replanting crops.

Unfortunately, levee constuction activities often encourage over-development in flood hazard zones, thereby increasing the potential consequences when and if a levee is breached or overtopped during storm run-off.

Reference 5-1 states that there are approximately 160 million acres of land in flood plains, with more than 6 million dwellings and structures. In a recent six-year period there occurred 193 major natural disasters, of these approximately 80 percent involved flooding. It has further been estimated (Ref. 5-2), that levee overtopping or failure is involved in approximately one third of all flood disasters. In 1978 the total flood damage was estimated at 3.8 billion dollars, and the average annual property loss during the 1970's was 1.7 billion dollars.

In an example of a single incident, a recent break in a Sacramento-San Joaquin Delta levee flooded 6,100 acres of prime farm land to a depth of twelve feet, causing an estimated direct loss of 10 million dollars (Ref. 5-3). The cost of closing the breach and dewatering the protected land was estimated at 6.6 million dollars, with a crop loss estimated at 3.25 million dollars. It was further estimated that 210,000 tons of quarry rock and 340,000 cubic yards of silt will be required to close the 600 foot long by 85 foot deep breach.

In addition to the direct consequences of property damage and repair costs, there are many indirect consequences which should not be overlooked in the overall flood mitigation decision process. For example, a similar break in another Delta levee caused 11,000 acres to be inundated by 150,000 acre-feet of water (Ref. 5-4). The inrushing water allowed salt water to encroach on the Delta from Suisan Bay. In an attempt to flush the salt from the Delta, since many communities rely on the Delta waters for fresh water, state and federal water projects began to release additional fresh water from surrounding reservoirs and curtailed fresh water pumping for consumption. Within ten days over 300,000 acre-feet of water were released from reservoirs in order to cleanse the Delta and restore the hydraulic barrier between fresh and salt water. Even with this large inflow of extra water, the Delta could not be entirely flushed and the bulk of the salt had to be removed over the next several weeks by pumping. In addition, unmeasurable damage was caused to the San Francisco and Delta fisheries, wildlife, and water users in southern California. Although the Sacramento-San Joaquin Delta is unique among levee systems, this example indicates that the consequences of levee failure may be felt by many diverse interests both near and far, and that the planning of new levees or rehabilitation of existing levees necessitates the inclusion of all consequences, not just the obvious ones.

5.2 Decision Making

Consequences are variable with magnitudes assigned probabilities of occurrence. For example, the length and depth of a breach cannot be known ahead of time. Repair costs are a function of these dimensions and are, therefore, uncertain. Often, only the expected value of these consequences is estimated, with no indication of the variability in the estimate. For expected value decision making this procedure is adequate. However, if there is any degree of risk aversion in the decision making body, it is essential to estimate the variability, as well as the expected value.

The impact of the difference between expected-value decision making and risk-adverse decision making is illustrated in the following example. Suppose there are two different insurance situations the Federal Insurance Agency (FIA) can find itself in. The first is a situation in which the FIA is asked to issue flood insurance policies for a community of 10,000 homes which is protected by a levee designed to the 100-year flood (disregarding the geotechnical risk of failure at a lower level, the chance of overtopping is any year is 0.01). The probable number of times this community will be flooded in the next five years, for example, is governed by the binomial distribution. If a flood does occur in this community, all 10,000 homes will be flooded (the chance of this happening at least once in a five-year period is 0.049). If each is insured to 100,000 dollars, this represents a potential loss to FIA of 1,000,000,000 dollars. However, from an actuarial point of view, we find that the expected number of damaged homes over a five-year period is only 500, representing an expected monetary loss of 50,000,000 dollars. Thus, the actuarial premium should be 1,000 dollars per year on the average for each homeowner in this community.

In the second situation, the FIA is asked to insure homes in five separate communities, geographically independent from one another, each with 2,000 homes and each protected by a 100-year levee. In a five-year period, the probable number of times any one of these communities will be flooded is again governed by the binomial distribution. As with the first situation, if a levee is overtopped, all 2,000 homes in that community will be flooded. Therefore, over a five-year period the total expected number of damaged homes in the five communities is 500 with an expected monetary loss (assuming 100,000 dollars per home) of 50,000,000 dollars, just as in the first situation. However, the chance of flooding 10,000 homes or more in the five-year period drops dramatically to 0.000044.

Although there is a greater chance of some homes flooding in the second case (0.22 vs. 0.049), there is a much greater chance of sustaining catastrophic levels of monetary loss in the first case (0.049 vs. 0.000044). Therefore, a relatively new insurance program, such as the National Flood Insurance Policy (NFIP), with an unestablished reserve to cover the type of catastrophic loss represented by the first situation, should be adverse to the extreme risks implicit in the use of the expected monetary value approach.

The graph in Figure 5-1 shows two utility curves representing two different risk attitudes. The straight line represents an expected value utility curve and is the rational one to use if a large enough reserve were available. The curved line represents a typical risk adverse utility curve and is the type that should be used to establish insurance premiums for a new insurance program. If a risk adverse utility curve were adopted, it would mean that the insurance premiums in the first situation should be higher than the second situation, or that the required levee design level in the first situation should be more restrictive than in the second, or both. Requiring that the design level of the levee in the first case be such that the chance of the catastrophic loss is the same as in the second case would mean a design flood equal to the 100,000 year event. Economically, this may not make sense, and a more balanced solution would be more appropriate (also note that the uncertainty in determining the 100,000-year event is tremendous). In either case, if no flooding occurs over a period of years and the reserve is built up, the utility curve for NFIP approaches the expected monetary loss value.

5.3 References

5-1 AIA Research Corporation, Design Guidelines for Flood Damage Reduction, Federal Emergency Management Agency, Washington, D.C., 1981.

5-2 National Research Council, A Levee Policy For The National Flood Insurance Program, National Academy Press, Washington, D.C., 1982.

5-3 "California Levee Break Costly," Engineering News Record, McGraw-Hill, September 2, 1982 (p.18).

5-4 Teerink, J.R., "The Delta Experience With A Drought And Levee Failure", presented to the California Water Commission, Sacramento, September 1, 1972.

5-5 Linsley, R. K., and J. B. Franzini, Water Resources Engineering, Second Edition, McGraw-Hill Cook Company, 1972, pp. 602-632.

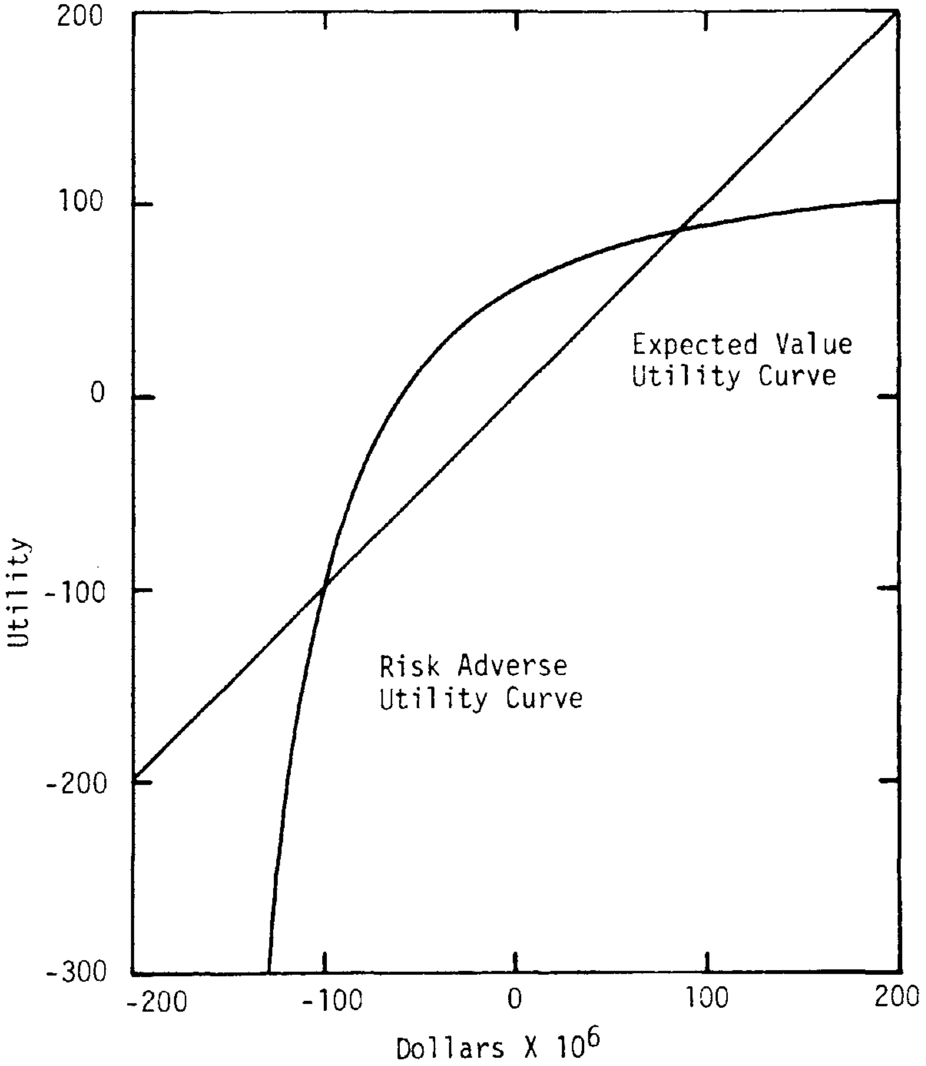


FIGURE 5-1 UTILITY CURVES

A. APPENDIX

A.1 Levee Stability Computer Programs

These computer programs were developed on the Hewlett-Packard 85 and 86 computers in Basic language. Program SLOPE 86 inputs the levee geometry and horizon material properties. Program SEEK86EQX searches for the critical circle in a given levee configuration. Program SUPERSTB, calculates the probability of failure and corresponding safety factor for a levee with rupture length, L, for either a cylindrical or ellipsoidal failure surface. The programs SEEK86EQX and SUPERSTB have the capability to analyze hydrostatic and/or earthquake effects, the latter being accounted for by the inclusion of a horizontal load from a constant pseudo-earthquake acceleration.

The basic analytical methodology for determination of the mean factor of safety is simple and conventional, but several important assumptions of a probabilistic nature are made that need a brief explanation. First, in calculating the effective weight of a soil prism composed of several soil horizons and an estimated phreatic surface, the mean effective density of each successive layer from the top down to the failure surface is used as in conventional analysis. The variance of weight is simultaneously calculated from the mean density, the coefficient of variation of density, and the geometry with the additional assumption that the successive random variables (weight) are perfectly correlated. In the levees of primary interest, this appears to be a reasonable assumption, but there are no data to support the assumption of unity correlation coefficient.

The computations for each successive soil prism yield cohesion capacity along the inclined failure surface (mean and variance), friction capacity (by combining the mean and variance of with the mean and variance of the tangent of the angle of internal friction, assuming independence between the weight and the friction properties), and loading influence (mean and variance). The analysis involves a great many soil prisms and each has its own mean and variance for each of the above factors. For simplicity, it was assumed that the coefficient of variation of total mass was about the same for all prisms so that the mean coefficient of variation of all of the soil prisms could be used to characterize the entire soil mass. The problem here is one of unknown correlation of properties from prism to prism.

Owing to the large coefficients of variation of the soil properties, the safety factor was assumed to be lognormally distributed. With soils whose properties have a small coefficient of variation, of the order of 0.2, the safety factor can be assumed to be normally distributed.

Finally, some field data on the variation of soil properties along the levee were available. It was assumed that each test boring represented about 100 square feet in horizontal area or a square about 10 feet on a side. The correlation coefficient of soil properties between 10 foot square areas of soil was assumed to be of the form exp(-CX) in which C was taken to be 0.015, based on a maximum likelihood estimate using paired data. X is the distance between prisms in units of 10 feet.

```
10 REM **SLOPE86**  : MARCH 6, 1983
20 REM PREPARE EMBANKMENT SECTION FOR CALCULATION
30 OPTION BASE 1
40 COM Z(5,400),N(5,400),X(400),Y(400),W(400) ,SHORT U(400),V(400).H(400),F0(4
)
45 COM SHORT G1(5),G2(5),T(10),C(10),V1(10),V2(5),V3(5),V4(10)
50 PRINTER IS 401,80
51 MASS STORAGE IS ":D700"
55 ON KEY# 1,"1) RAW-GEO" GOTO 90
60 ON KEY# 2,"2) PRO-GEO" GOTO 610
62 ON KEY# 3,"3) IN-SOIL" GOTO 1600
64 ON KEY# 4,"4) SEEKEQX" GOTO 2200
65 ON KEY# 5,"5)SUPERSTB" GOTO 81
70 CLEAR @ DISP "CONT 70" @ KEY LABEL @ WAIT 5000 @ GOTO 70
80 REM ***************************************************************
81 CHAIN "SUPERSTB"
85 REM ***************************************************************
90 ! ***** GEOM01 *******
100 ! READ RAW GEOMETRY OF EMBANKMENT SECTION
110 CLEAR @ PRINT @ PRINT @ PRINT
120 M0=999 @ M9=-999 @ Y0=999
130 DISP "INPUT COORDINATES"
140 DISP "100 PAIRS MAX.END WITH 999,0"
150 FOR I=1 TO 99
160 DISP "X(";I;"),Y(";I;")"
170 INPUT X(I),Y(I)
180 IF X(I)=999 THEN 250
190 IF X(I)<M0 THEN M0=X(I)
200 IF X(I)>M9 THEN M9=X(I)
210 IF Y(I)<Y0 THEN Y0=Y(I)
220 PRINT USING 260 : I,X(I),Y(I)
230 NEXT I
240 X(I)=999 @ Y(I)=0
250 PRINT @ PRINT @ PRINT @ CLEAR @ N1=I @ N2=0
260 IMAGE 2X,2D,5X,4D.DD,5X,M2D.DD
270 MAT N=ZER
280 FOR I=1 TO 5
290 DISP
300 DISP "INPUT BOUNDARY":I;" END WITH 999"
310 FOR J=1 TO 20
320 DISP "N(";I;",";J;")";
330 INPUT N(I,J)
340 IF N(I,J)=999 THEN 370
350 NEXT J
360 N(I,J)=999
370 N2=N2+J
380 NEXT I
390 N3=INT ((N1*2+N2)/32)+2
400 FOR I=1 TO 21
410 PRINT USING 430 ; N(1,I),N(2,I),N(3,I),N(4,I),N(5,I)
420 NEXT I
430 IMAGE 7(4D)
440 GOSUB 1470
450 ASSIGN# 1 TO  F$
460 PRINT# 1 ; "RAW SEC GEO",M0,M9,Y0
470 FOR I=1 TO N1
480 PRINT# 1 : X(I),Y(I)
490 NEXT I
```

```
500 FOR I=1 TO 5
510 FOR J=1 TO 21
520 PRINT# 1 ; N(I,J)
530 IF N(I,J)=999 THEN 550
540 NEXT J
550 NEXT I
555 PRINT "RAW DATA STORED UNDER NAME :";F$;@ PRINT
560 ASSIGN# 1 TO  *
570 MASS STORAGE IS ":D700"
580 PRINT
600 GOTO 70
605 REM ************************************************************************
610 ! *** GEOM04 ******
620 ! PREPARE SECTION GEOMETRY FOR CALCULATION
630 CLEAR @ PRINT @ PRINT @ PRINT
640 DISP "INPUT FILE NAME"
650 INPUT F1$
660 MASS STORAGE IS ":D701"
670 ASSIGN# 1 TO  F1$
680 A$="RAW SEC GEO"
690 READ# 1 ; B$,M0,M9,Y0
700 IF B$=A$ THEN 730
710 GOSUB 1370
720 GOTO 640
730 DISP "INPUT DISCRETIZATION STEP"
740 DISP "(ALL INPUT X's WILL BE SET TO MULTIPLES OF DISCRETIZATION STEP)"
750 INPUT L6
760 DISP "RECORDED MIN-X =";M0
770 DISP "RECORDED MAX-X =";M9
780 DISP "MAY REDEFINE X ORIGIN"
790 DISP "X ORIG";
800 INPUT M5
810 DISP @ DISP "RECORDED MIN-Y=";Y0
820 DISP @ DISP "GIVE A BOTTOM TO THE LAST LAYER"
830 DISP "Y-BASE"
840 INPUT B
850 M5=INT (M5/L6+.5)*L6
860 M0=INT ((M0-M5)/L6+.5)*L6
870 M9=INT ((M9-M5)/L6+.5)*L6
880 PRINT USING "K,K" ; "INPUT FILE NAME= ",F1$
885 PRINT @ PRINT "DISCRETIZATION STEP IS";L6
890 PRINT USING 920 ; "X-MIN= ",M0
900 PRINT USING 920 ; "X-MAX= ",M9
910 REM
920 IMAGE K.4D
930 PRINT USING "K,MDD.D" ; "Y-BASE=",B
940 FOR I=1 TO 100
950 READ# 1 : X(I),Y(I)
960 IF X(I)=999 THEN 990
970 NEXT I
980 REM INTERPOLATION ASSUMES X's ARE ALREADY MULTPLS OF DISCR. STEP
990 FOR L=1 TO 5
995 READ# 1 ; N(L,1)
1000 IF N(L,1)=999 THEN 1240
1010 C=1 @ X9=M0
1020 Z(L,1)=Y(N(L,1)) @ Y9=Z(L,1)
1030  I=0
1040 I=I+1 @ READ# 1 : N(L,I+1)@ IF N(L,I+1)=999 THEN 1170
1050 X0=X9
1060 X9=INT (X(N(L,I+1))/L6+.5)*L6
1070 Y0=Y9
1080 Y9=Y(N(L,I+1))
1090 IF X9-X0=0 THEN 1040
1100 T=(Y9-Y0)/(X9-X0)
1110 FOR J=L6 TO X9-X0 STEP L6
1120 C=C+1
```

```
1130 Z(L,C)=Y0+J*I
1135 ! PRINT X0+J;Z(L,C)
1140 NEXT J
1160 GOTO 1040
1170 IF L=1 THEN 1230
1200 FOR I=1 TO C
1205 IF Z(L.I)<= Z(L-1,I) THEN 1210
1206 PRINT "STRANGE GEOM: ;LAYER";L;" IS ABOVE LAYER";L-1;" AT X= ";M0+L6*(I-1
1207 PRINT Z(L,I);" >";Z(L-1,I)
1208 BEEP 40,150 @ BEEP 200,300 @ GOTO 70
1210 IF Z(L.I)<B THEN Z(L.I)=B
1220 NEXT I
1230 NEXT L
1240 N2=L-1
1250 N3=INT ((C*N2+9)/32)+1
1260 GOSUB 1470
1270 ASSIGN# 1 TO  F$
1280 PRINT# 1 ; "PRO SEC GEO",M0,M9,B,C,N2,L6
1290 FOR D=1 TO N2
1300 FOR I=1 TO C
1310 PRINT# 1 ; Z(D,I)
1315 NEXT I
1320 NEXT D
1330 PRINT " RAW DATA FILE ";F1$;" WAS PROCESSED INTO FILE ";F$
1340 ASSIGN# 1 TO  *
1350 MASS STORAGE IS ":D700"
1360 GOTO 70
1370 REM **********************************************************************
1380 ! WARNING FOR WRONG DATA FILE
1390 DISP @ DISP
1400 DISP "MISMATCHED DATA FILES"
1410 DISP "DATA FILE IS ";B$
1420 DISP "FILE SHOULD BE ";A$
1430 DISP "TRY AGAIN"
1440 RETURN
1450 REM ***********************************************************************
1460 REM FILE CREATOR
1470 DISP "I NEED";N3;" RECORDS TO STORE THIS"
1480 DISP "I NEED 0 RECORDS IF FILE AREADY EXISTS"
1490 DISP "INPUT FILE NAME. NB OF REC"
1500 INPUT F$,N3
1510 MASS STORAGE IS ":D701"
1520 IF N3#0 THEN CREATE F$,N3
1530 RETURN
1600 REM ***************************************************************
1620 ! *** SOILP1 ***
1630 REM READ SOIL PROPERTIES AND READY FOR CALCULATION BY 'STB86'
1640 CLEAR @ PRINT @ PRINT @ PRINT
1650 DISP "NB OF SOIL LAYERS (5 MAX)"
1660 INPUT N2
1670 N3=5
1680 MAT G1=ZER @ MAT G2=ZER @ MAT T=ZER @ MAT V1=ZER @ MAT V2=ZER @ MAT V3=ZEF

1681 MAT V4=ZER @ MAT C=ZER
1690 DISP @ PRINT
1700 DISP "INPUT DAMP WEIGHT: MEAN. C.VAR"
1710 PRINT "DAMP WEIGHT: MEAN. C.VAR"
1720 FOR I=1 TO N2
1730 DISP "LAYER";I;
1740 INPUT G1(I),V2(I)
1750 PRINT G1(I).V2(I)
1760 NEXT I
1770 DISP @ PRINT
1780 DISP "INPUT SUBM. WEIGHT:MEAN. C.VAR"
1790 PRINT "SUBMERGED WEIGHT: MEAN. C.VAR"
1800 FOR I=1 TO N2
```

```
1810 DISP "LAYER";I;
1820 INPUT G2(I),V3(I)
1830 PRINT G2(I),V3(I)
1840 NEXT I
1850 DISP @ PRINT
1860 DISP "TAN OF FRICT. ANGLE: MEAN. C.VAR"
1870 PRINT "TAN FR ANG: MEAN, C.VAR"
1880 FOR I=1 TO N2*2-1 STEP 2
1890 DISP "DRY LAYER";(I+1)/2:
1900 INPUT T(I),V4(I)
1910 PRINT "DRY:",T(I),V4(I)
1912 DISP "WET LAYER";(I+1)/2;
1914 INPUT T(I+1),V4(I+1)
1916 PRINT "WET:".T(I+1),V4(I+1)
1920 NEXT I
1930 DISP @ PRINT
1940 DISP "COHESION (F/L^2) : MEAN. C.VAR"
1950 PRINT "COHESION (F/L^2) : MEAN, C.VAR"
1960 FOR I=1 TO N2*2-1 STEP 2
1970 DISP "DRY LAYER";(I+1)/2;
1980 INPUT C(I).V1(I)
1990 PRINT "DRY:",C(I),V1(I)
1992 DISP "WET LAYER":(I+1)/2:
1994 INPUT C(I+1).V1(I+1)
1996 PRINT "WET:",C(I+1),V1(I+1)
2000 NEXT I
2010 DISP @ PRINT
2020 CLEAR
2030 REM STORE FILE
2040 N3=INT ((N3*8+9)/32)+1
2050 GOSUB 1460
2060 A$="SOIL PROP"
2070 ASSIGN# 1 TO  F$
2080 PRINT# 1 : A$
2090 PRINT# 1 : G1().V2(),G2().V3().T().V4().C().V1()
2095 PRINT " SOIL PROPERTIES SAVED UNDER THE NAME ":F$
2100 ASSIGN# 1 TO  *
2105 MASS STORAGE IS ":D700"
2110 GOTO 70
2120 END
2130 REM *******************
2200 REM *******************
2210 CHAIN "SEEK86E0X"
2220 REM *******************
```

```
10 ! *** SEEK86EQX: STREAMLINED SLIP CIRCLE SEARCH WITH END CORRECTIONS ***
20 PRINTER IS 401,132 @ PRINT CHR$ (15) @ PRINT @ PRINT @ PRINT @ PRINT
30 PRINT "SEEK86EQX: STREAMLINED VERSION 16-AUG-83: E.Q. CAPABILITY" @ PRINT @
RINT
40 ! SEE LIST OF MAIN VARIABLES IN LISTING OF OLD "STB86"
50 OPTION BASE 1
60 COM Y(5,400),W(5,400),Y6(400),Z(400),Z1(400) ,SHORT X6(400),Y9(400),H(400),F
(400)
70 COM SHORT G1(5),G2(5),T(10),C(10),V1(10),V2(5),V3(5),V4(10)
80 DIM S(9),X(9),TITLE$[80]
100 Z1$="NO EMBKMT INFO" @ F9$="0" @ Z3$="NO PHREAT INFO" @ Z2$="NO SOIL   INFC
 @ P$="0" @ Z4$="NO TITLE & DATE" @ Z5$="NO ACCELERATION"
105  ACCEL=0
110 ON KEY# 1,"1) EMBKMT" GOTO 2320
120 ON KEY# 2,"2) SOIL" GOTO 360
130 ON KEY# 3,"3) PHREAT" GOTO 2460
140 ON KEY# 4,"4) CHG PHR" GOTO 2770
145 ON KEY# 5,"5) SEEK-CR" GOTO 3220
150 ON KEY# 6,"6) ACCEL" GOTO 5100
155 ON KEY# 7,"7) DATE " GOTO 202
160 ON KEY# 8,"8) DISP " GOTO 1580
170 MASS STORAGE IS ":D700"
180 CLEAR @ KEY LABEL @ DISP "CONT 180" @ DISP
190 DISP Z1$ @ DISP Z2$ @ DISP Z3$ @ DISP Z4$ @ DISP Z5$ @ WAIT 5000
200 GOTO 170
202 CLEAR
204 DISP "ENTER TITLE AND TODAY'S DATE"
205 INPUT TITLE$
206 Z4$="OK TITLE & DATE"
207 GOTO 180
210 REM ********************************************
220 PRINT @ PRINT "SPECIFICATIONS FOR THIS RUN"
225 PRINT @ PRINT TITLE$ @ PRINT
230 PRINT "SOIL PROPERTIES: FILE ";F$
240 PRINT "EMBKMT GEOMETRY: FILE ";F9$
250 PRINT "PHREATIC SURFACE:  ";@ IF P$="0" THEN PRINT "NONE" ELSE PRINT "FILE
;P$;" SURF:";U9
260 RETURN
270 REM ********************************************
280 REM GENERATE A BASIC COORD. USED BY CONVEN. ELLIPS AND CYL.
290 FOR I=1 TO N2
300 Y6(I)=0
310 Y9(I)=0
320 NEXT I
330 H=40
340 RETURN
350 REM ************************************************
360 !    *** SOIL-2 ****
370 CLEAR @ MASS STORAGE IS ":D701"
380 A$="SOIL PROP"
390 DISP "Soil Property File Name";
400 INPUT F$
410 ASSIGN# 1 TO  F$
420 READ# 1 : B$
430 IF A$=B$ THEN 460
440 GOSUB 2150
450 GOTO 380
```

```
460 C7=1 ! CORRELATION COEFF. OF SOIL PROPERTIES IN VERTICAL DIRECTION
470 READ# 1 : G1(),V2(),G2(),V3(),T(),V4(),C(),V1()
480 ASSIGN# 1 TO  *
490 Z2$="OK SOIL INFO"
500 GOTO 170
510 REM ****************************************
520 !  *** ELLIPSE ****
530 REM ****************************************
540 REM : ANALYZE ONE SLICE
550 K=1 @ B2=B @ B3=B @ B4=B @ G5=1
560 L=0 @ N9=0 @ A2=0 @ A3=0 @ G=0 @ F9=0 ! ---> MDH,1/14/83
570 G3=62.4
580 IENTRY=-1
590 FOR I=1 TO N2
600 Z(I)=Z0
610 FOR D=1 TO N3
620 Z(I)=Z(I)+Y(D,I)+W(D,I)
630 NEXT D
640 F0(I)=0
650 Y6(I)=0
660 IF B2*B2<= (X0-X6(I))*(X0-X6(I)) THEN 680 ! 8/16/83
670 Y6(I)=Y0-SQR (B2*B2-(X0-X6(I))*(X0-X6(I))) ! 8/16/83
680 NEXT I
690 ! IF P$="0" THEN 890
700 FOR I=2 TO N2
710 P4=SQR ((X0-X6(I-1))*(X0-X6(I-1))+(Y0-Z(I-1))*(Y0-Z(I-1))) ! 8/16/83
720 P6=SQR ((X0-X6(I))*(X0-X6(I))+(Y0-Z(I))*(Y0-Z(I))) ! 8/16/83
730 IF P4<= B2 OR P6<= B2 THEN 750
740 GOTO 1020 ! --> SLIP CIRCLE DOES NOT INTERSECT iTH SLICE
750 IF P4>B2 OR P6>B2 THEN 800
760 ! CASE OF NORMAL LATERAL HYDRAULIC LOAD
770 O1=.5*(Z(I)+Z(I-1)) @ O2=.5*(Z(I)-Z(I-1))
780 F0(I)=-(.5*G3*(H(I)*H(I)-H(I-1)*H(I-1))*L7*(Y0-O1+O2/3)) ! 8/16/83
790 GOTO 1020
800 ! COMPUTE P5, THE X COORD OF THE POINT WHERE Z(X) INTERSECTS Y6(X)
810 MM=(Z(I)-Z(I-1))/L6 ! SLOPE m
820 BB=Z(I-1)-X6(I-1)*MM ! INTERCEPT b
830 BBB=(MM*BB-MM*Y0-X0)/(MM*MM+1) ! 8/16/83
840 CCC=(X0*X0+(Y0-BB)*(Y0-BB)-B2*B2)/(2*(MM*MM+1)) ! 8/16/83
850 ROOT1=-BBB+SQR (BBB*BBB-2*CCC) ! 8/16/83
860 ROOT2=-BBB-SQR (BBB*BBB-2*CCC) ! 8/16/83
863 ! PRINT "I,Z(I-1),Z(I),X6(I-1),X6(I),MM,BB,BBB,CCC,ROOT1,ROOT2,P5:";
864 MEAN=(X6(I)+X6(I-1))/2
865 IF (ROOT1-MEAN)*(ROOT1-MEAN)<(ROOT2-MEAN)*(ROOT2-MEAN) THEN P5=ROOT1 ELSE P
=ROOT2 ! 8/16/83
881 ! PRINT I;Z(I-1);Z(I);X6(I-1);X6(I);MM;BB;BBB;CCC;ROOT1;ROOT2;P5;@ PRINT
890 H6=Z(I-1)+(Z(I)-Z(I-1))/(X6(I)-X6(I-1))*(P5-X6(I-1))
900 IF P4<= B2 THEN 980
910 ! Y6(I-1) EXCEEDS Z(I-1)
920 O1=.5*(Z(I)+H6) @ O2=.5*(Z(I)-H6)
930 H7=H(I-1)+(H(I)-H(I-1))/(X6(I)-X6(I-1))*(P5-X6(I-1))
940 F0(I)=-(.5*G3*(H(I)*H(I)-H7*H7)*L7*(Y0-O1+O2/3)) ! 8/16/83
950 XAL=P5 @ YAL=H6
960 GOTO 1020
970 ! Y6(I) EXCEEDS Z(I)
980 O1=.5*(Z(I-1)+H6) @ O2=-(.5*(Z(I-1)-H6))
990 H8=H(I-1)+(H(I)-H(I-1))/(X6(I)-X6(I-1))*(P5-X6(I-1))
1000 F0(I)=-(.5*G3*(H8*H8-H(I-1)*H(I-1))*L7*(Y0-O1+O2/3)) ! 8/16/83
1010 XAR=P5 @ YAR=H6
1020 NEXT I
1030 FOR I=1 TO N2
1040 H1=H(I)+70 @ M=0
1050 MVW=H(I)*G3*L6*L7 ! WATER COLUMN IN RESERVE
1055 FEQ=0 ! E.Q. MOMENT SUMMAND
1060 FOR D=1 TO N3
1070 H1=H1+W(D,I) ! PRESSURE HEAD
```

```
1080 NEXT W
1090 ! PRINT H(I),H1
1100 D0=SQR ((X0-X6(I))*(X0-X6(I))+(Y0-Z(I))*(Y0-Z(I))) ! 8/16/83
1110 IF D0<B2 THEN 1130
1120 Y6(I)=0 @ GOTO 1520
1130 IF I=1 THEN 3580
1140 IF I=N2 THEN 3580
1150 H1=(H1-Y6(I))*(H1>Y6(I))
1160 W0=0
1170 Z1(I)=Z(I)-Y6(I) @ U1X=0
1180 FOR D=1 TO N3
1190 D1=D*2-1 ! MAKE DRY
1200 Z1(I)=Z1(I)-W0
1210 IF Y(D,I)=0 THEN 1290
1220 IF Y(D,I)<Z1(I) THEN 1260
1230 M1=G1(D)*Z1(I)*L6*L7 @ U1X=U1X+Z1(I)*L6
1235 FEQ=FEQ+M1*(Y0-Y6(I)-Z1(I)/2)
1240 M=M+M1
1250 GOTO 1410
1260 M1=G1(D)*Y(D,I)*L6*L7 @ U1X=U1X+Y(D,I)*L6
1265 FEQ=FEQ+M1*(Y0-Y6(I)-Z1(I)+Y(D,I)/2)
1270 M=M+M1
1280 Z1(I)=Z1(I)-Y(D,I)
1290 IF W(D,I)=0 THEN 1380
1300 IF W(D,I)<Z1(I) THEN 1350
1310 M1=(G2(D)+G3)*Z1(I)*L6*L7 @ U1X=U1X+Z1(I)*L6
1315 FEQ=FEQ+M1*(Y0-Y6(I)-Z1(I)/2)
1320 M=M+M1
1330 D1=D*2 ! WET
1340 GOTO 1410
1350 M1=(G2(D)+G3)*W(D,I)*L6*L7 @ U1X=U1X+W(D,I)*L6
1355 FEQ=FEQ+M1*(Y0-Y6(I)-Z1(I)+W(D,I)/2)
1360 M=M+M1
1370 D1=D*2 ! WET
1380 W0=W(D,I)
1390 NEXT D
1400 D=D-1
1410 GOSUB 3680
1420 DEF FNHYP(XA,XB,YA,YB) = SQR ((XA-XB)*(XA-XB)+(YA-YB)*(YA-YB)) ! 8/16/83
1430 DEF FNDETR(XA,XB,XC,YA,YB,YC) = .5*(XB*YC-XC*YB-XA*YC+XC*YA+XA*YB-XB*YA)
1440 FRICT1=(M*FACTF1+MVW*FACTFW)*(Y0-Y6(I))/G5*T(D1)
1450 FRICT2=-(H1*G3*B2*L9*G5*L7*T(D1)*FACTF2) @ A0=FRICT1+FRICT2
1460 IF A0<0 THEN A0=0
1470 A1=L9*L7*C(D1)*B2*G5*FACTCO
1480 A2=A2+A0
1490 A3=A3+A1
1500 G1=(M*FACTDM+MVW*FACTVH)*(X0-X6(I))+FEQ*ACCEL*FACTCA
1510 G=G+G1+F0(I) @ F9=F9+F0(I)
1512 ! PRINT "I,X6(I),Z(I),FEQ,FACTCA, FEQ*ACCEL*FACTCA";I;X6(I);Z(I);FEQ;FACTC
;FEQ*ACCEL*FACTCA @ PRINT
1520 NEXT I
1530 IF ABS (G)>.0001 THEN S=(A2+A3)/G*SGN (G) ELSE S=-1
1540 ! PRINT " X0,Y0,B,A2,A3,G, S ARE ";@ PRINT
1541 ! PRINT X0;Y0;B;A2;A3;G;S;@ PRINT
1550 RETURN
1560 REM ***************************************************************
1570 ! ****  DISP-4 ****
1580 CLEAR
1590 DISP
1600 DISP USING "2(K,3D,1X)/3(K,3D,1X)" ; "X0=",X0,"Y0=",Y0," B=",B,"L1=",L1,"
=",L0
1610 DISP USING "2(K,MD,4DE,1X)" ; " S= ",S," V=",V," P=",P
1620 DISP @ ! COPY   --->HP 86 WILL NOT ACCEPT COPY STMNT
1630 I3=0
1640 FOR K=1 TO 2
1650 CLEAR
```

```
1660 I1=(K-1)*INT ((N2-1)/2)+1
1670 I2=K*INT ((N2-1)/2)+1
1680 SCALE X6(I1),X6(I2),Z0,75+Z0
1690 XAXIS Z0,L6
1700 YAXIS X6(I1).10
1710 FOR I=I1 TO I2 STEP 5
1720 FOR J=INT (Z0/10)*10+10 TO Z0+70 STEP 10
1730 PLOT X6(I).J
1740 PEN UP
1750 NEXT J
1760 NEXT I
1770 I3=I2*5-5-I
1780 FOR I=1 TO N2
1790 Z(I)=Z0
1800 NEXT I
1810 FOR L=N3 TO 1 STEP -1
1820 MOVE X6(I1).Z0
1830 FOR I=I1 TO I2
1840 Z(I)=Z(I)+Y(L.I)+W(L.I)
1850 DRAW X6(I).Z(I)
1860 NEXT I
1870 PEN UP
1880 NEXT L
1890 FOR I=I1 TO I2
1900 IF X6(I)<X0-B THEN 1940
1910 IF X6(I)>X0+B THEN 1940
1920 Y9(I)=Y0-SQR (B*B-(X0-X6(I))*(X0-X6(I))) ! 8/16/83
1930 IF Y9(I)<= Z(I) THEN 1950
1940 Y9(I)=Z(I)
1950 NEXT I
1960 MOVE X6(I1).Z0
1970 FOR I=I1 TO I2
1980 Z(I)=Z0
1990 FOR M=N3 TO 1 STEP -1
2000 Z(I)=Z(I)+W(M.I)
2010 NEXT M
2020 DRAW X6(I).Z(I)
2030 NEXT I
2040 PEN UP
2050 MOVE X6(I1).Y9(I1)
2060 FOR I=I1 TO I2
2070 DRAW X6(I).Y9(I)
2080 NEXT I
2090 ! COPY
2100 NEXT K
2110 GOTO 170
2120 REM ***********
2130 BEEP 40,150 @ BEEP 200,300 @ GOTO 170
2140 REM ***************
2150 ! WARNING FOR WRONG DATA FILE
2160 DISP @ DISP
2170 DISP "MISMATCHED DATA FILES"
2180 DISP "DATA FILE IS ";B$
2190 DISP "FILE SHOULD BE ";A$
2200 DISP "TRY AGAIN"
2210 RETURN
2220 REM **********************
2230 REM FILE CREATOR
2240 DISP "I NEED";N3;" RECORDS TO STORE THIS"
2250 DISP "I NEED 0 RECORDS IF FILE EXISTS"
2260 DISP "INPUT FILE NAME. NUMBER OF RECORDS (NB)"
2270 INPUT F$.N3
2280 MASS STORAGE IS ":D701"
2290 IF N3#0 THEN CREATE F$,N3
2300 RETURN
2310 REM ***************************
```

```
2320 REM ENTRY FOR NEW EMBANKMENT INFOSMAUIOO
2330 CLEAR @ MASS STORAGE IS ":D701"
2340 DISP "INPUT FILE NAME WITH EMBK. PROCESSED GEOMETRY"
2350 INPUT F9$
2360 ASSIGN# 1 TO  F9$
2370 A$="PRO SEC GEO"
2380 READ# 1 : B$
2390 IF B$=A$ THEN 2420
2400 GOSUB 2140
2410 GOTO 2340
2420 Z1$="OK EMBKMT INFO"
2430 GOTO 170
2440 REM ****************************
2450 REM INPUT PHREATIC SURFACE
2460 CLEAR @ MASS STORAGE IS ":D701"
2470 IF F9$#"0" THEN 2500
2480 DISP "GIVE EMBKMT INFO FIRST"
2490 GOTO 2340
2500 ASSIGN# 1 TO  F9$
2510 READ# 1 : B$
2520 READ# 1 : X8,X9,Z0,N2,N3,L6
2530 FOR I=1 TO N2
2540 X6(I)=L6*(I-1)+X8
2550 NEXT I
2560 FOR L=1 TO N3
2570 FOR I=1 TO N2
2580 READ# 1 : Y(L,I)
2590 NEXT I
2600 NEXT L
2610 DISP "NAME FILE WITH PHREATIC SURFACE"
2620 DISP "INPUT 0 IN NO PHREATIC SURFACE"
2630 INPUT P$
2640 IF P$#"0" THEN 2790
2650 DISP "NO PHREATIC SURFACE"
2660 FOR I=1 TO N2
2670 H(I)=0
2680 FOR L=1 TO N3-1
2690 W(L,I)=0
2700 Y(L,I)=Y(L,I)-Y(L+1,I)
2710 NEXT L
2720 Y(L,I)=Y(L,I)-Z0
2730 W(L,I)=0
2740 NEXT I
2750 N5=0
2760 GOTO 3180
2770 REM ENTRY THROUGH SFK#4
2780 IF P$="0" THEN 2610
2790 ASSIGN# 2 TO  P$
2800 READ# 2 : B$
2810 A$="PRO SEC GEO"
2820 IF A$=B$ THEN 2840
2830 REM REM REM
2840 READ# 2 ; A,A,A,N4,N5,L7
2850 IF N4=N2 AND L6=L7 THEN 2880
2860 PRINT @ PRINT "PHREATIC SURFACE INCOMPATIBLE WITH EMBKMT."
2870 GOTO 2120
2880 DISP "CHOOSE SURFACE NUMBER, 0 TO ";N5
2890 INPUT L1
2900 U9=L1
2910 IF L1=0 THEN 2650
2920 FOR L=1 TO L1
2930 FOR I=1 TO N4
2940 READ# 2 : Z(I)
2950 NEXT I
2960 NEXT L
2970 ASSIGN# 2 TO  *
```

```
2980 FOR I=1 TO N2
2990 IF Z(I)>Y(1.I) THEN H(I)=Z(I)-Y(1.I) ELSE H(I)=0
3000 FOR L=2 TO N3
3010 IF Z(I)<Y(L,I) THEN 3060
3020 IF Z(I)>Y(L-1.I) THEN 3080
3030 W(L-1.I)=Z(I)-Y(L.I)
3040 Y(L-1.I)=Y(L-1.I)-Z(I)
3050 GOTO 3090
3060 W(L-1.I)=0 @ Y(L-1.I)=Y(L-1.I)-Y(L.I)
3070 GOTO 3090
3080 W(L-1.I)=Y(L-1,I)-Y(L.I) @ Y(L-1.I)=0
3090 NEXT L
3100 IF Z(I)<= ZO THEN 3140
3110 IF Z(I)>Y(L-1.I) THEN 3160
3120 W(L-1.I)=Z(I)-ZO @ Y(L-1.I)=Y(L-1.I)-Z(I)
3130 GOTO 3170
3140 W(L-1,I)=0 @ Y(L-1.I)=Y(L-1.I)-ZO
3150 GOTO 3170
3160 W(L-1.I)=Y(L-1.I)-ZO @ Y(L-1.I)=0
3170 NEXT I
3180 ASSIGN# 1 TO  *
3190 MASS STORAGE IS ":D700"
3200 Z3$="OK PHREAT INFO"
3210 GOTO 170
3220 REM **************************
3230 REM COMPUTE A NUMBER OF CIRCLES: DEDUCE CRITICAL CIRCLE FROM OUTPUT
3240 REM THE CODING BELOW IS THE IMPLEMENTATION OF THE O.M.S.
3250 PRINT @ PRINT "SC3BJ3: CONVENTIONAL SLIP CIRCLE." @ GOSUB 220 @ GOSUB 280
 L7=1
3260 CLEAR @ DISP "DESCRIBE SEARCH REGION" @ DISP
3270 DISP "XMIN.XMAX.STEP"
3280 INPUT X2.X3,M2
3290 DISP "YMIN.YMAX,STEP"
3300 INPUT Y2.Y3.M3
3310 DISP "NB OF CIRCL PER CENTER POINT. STEP OF RADIUS CHANGE";
3320 INPUT K2,M4
3326 IF ACCEL#0 THEN PRINT " ---------------->   HORIZONTAL E.Q. ACCELERATION OF
":ACCEL:" g'S";
3330 DISP "RADIUS SHIFT M5: B9 = YO-ZO-M5 INSTEAD OF THE USUAL B9=YO-ZO"
3340 INPUT M5
3350 IF M5#0 THEN PRINT "**NOTE: SEARCH BEGINS AT ZO + ":M5:
3360 S7=75 ! USE THIS TO CALC. MINIMUM FACTOR OF SAFETY S
3370 MAT S=ZER (9)@ MAT X=ZER
3380 I=0 @ FOR X=X2 TO X3 STEP M2 @ I=I+1 @ X(I)=X @ NEXT X
3390 FOR YO=Y2 TO Y3 STEP M3
3400 CLEAR
3410 B9=YO-ZO-M5 @ B8=B9-(K2-1)*M4
3420 PRINT @ PRINT USING 3430 ; YO.X(1).X(2),X(3).X(4).X(5),X(6).X(7).X(8).X(9)
3430 IMAGE 5X."YO".4X."RAD".4X."X01     X02      ..."/5D.D.7X.9(5D.D)
3440 FOR B=B9 TO B8 STEP -M4
3450 DISP
3460 K1=0
3470 FOR XO=X2 TO X3 STEP M2
3480 DISP XO:
3490 K1=K1+1
3500 GOSUB 540
3510 S(K1)=S
3520 IF S>S7 OR S<.00001 THEN 3590
3530 S7=S
3540 J1=XO
3550 J2=YO
3560 BSMIN=B
3570 GOTO 3590
3580 S(K1)=99.99
3590 NEXT XO
```

```
3610 IMAGE 7X.5D.D,9(4D.2D)
3620 NEXT B
3630 PRINT "---------------------------------------------------------------------------
-----" @ PRINT
3640 NEXT YO
3650 PRINT USING 3660 ; S7,J1.J2.BSMIN
3660 IMAGE 10X."MIN S=".4D.2D." AT XO,YO,B =".3(5D.D)
3670 BEEP 200,250 @ GOTO 170
3680 REM            **** END CORRECTION SUBROUTINE ****
3690 ! BEGIN SUB TO CORRECT FOR END EFFECTS
3700 ! DELTA=L6
3710 ! SET UP DEFAULT FACTORS FOR NOMINAL (NORMAL) CASE
3720 FACTF1=1 @ FACTF2=1
3730 FACTCO=1 @ FACTDM=1
3740 FACTVH=1 @ FACTFW=1 @ FACTCA=1
3750 AP=1 @ BP=1 @ CP=1 @ DP=1 @ EP=1 @ FFP=1 @ GGP=1
3760 ! COMPUTE THE NOMINAL ARC LENGTH
3770 XB=.5*(X6(I)+X6(I-1)) @ XC=.5*(X6(I)+X6(I+1))
3780 IF B2*B2>= (XO-XB)*(XO-XB) THEN YB=YO-SQR (B2*B2-(XO-XB)*(XO-XB)) ELSE YB=
AL !  8/16/83
3790 IF B2*B2>= (XO-XC)*(XO-XC) THEN YC=YO-SQR (B2*B2-(XO-XC)*(XO-XC)) ELSE YC=
AR ! 8/16/83
3800 XF=X6(I) @ YF=Y6(I)
3810 L9=FNHYP(XB,XF,YB.YF)+FNHYP(XF,XC,YF,YC)
3820 RXO=XO-X6(I)
3830 RYO=YO-Y6(I)
3840 ! CHECK FOR FIRST ENTRY:  IENTRY= -1 ---> 1st ENTRY
3850 !                              =  1 ---> NON-1st ENTRY
3860 IF IENTRY=1 THEN GOTO 3960
3870 IENTRY=1
3880 !                    *** FIRST ENTRY ***
3890 ! CHECK FOR CASE 1-L AT I-1
3900 IF X6(I-1)<XAL AND X6(I-1)+L6/2>XAL AND X6(I)-L6/2>XAL AND X6(I)+L6/2<XAR
HEN GOTO 4060
3910 ! CHECK FOR CASE 2-L AT I
3920 IF X6(I)>= XAL AND X6(I)-L6/2<= XAL THEN 4580
3930 ! PRINT "ERROR: 1st ENTRY AND NOT 1-L OR 2-L"
3940 ! PRINT "I,X6(I-1),X6(I).L6/2,XAL ARE:";I;X6(I-1);X6(I):L6/2:XAL:@ PRINT
3950 ! RETURN
3960 !                    *** NON-1st ENTRY ***
3970 ! CHECK FOR CASE 1-R AT I+1
3980 IF X6(I+1)>XAR AND X6(I+1)-L6/2<XAR AND X6(I)-L6/2>XAL AND X6(I)+L6/2<XAR
HEN GOTO 4320
3990 ! CHECK FOR CASE 2-R  AT I
4000 IF X6(I)<= XAR AND X6(I)+L6/2>= XAR THEN 4840
4010 ! CHECK TO SEE IF NOMINAL CASE OCCURS
4020 IF X6(I)-L6/2>XAL AND X6(I)+L6/2<XAR THEN RETURN
4030 PRINT "ERROR: DOES NOT FALL INTO ANY OF THE KNOWN CATEGORIES"
4040 PRINT "I,X6(I-1),X6(I).X6(I+1).L6/2.XAL,XAR ARE:";I;X6(I-1):X6(I);X6(I+1):
6/2:XAL:XAR:@ PRINT
4050 RETURN
4060 ! PRINT "---------------- CASE 1-L --------------"
4070 XA=XAL @ YA=YAL
4080 XB=X6(I)-L6/2 @ YB=YO-SQR (B2*B2-(XO-XB)*(XO-XB)) ! 8/16/83
4090 XD=X6(I)+L6/2 @ YD=YO-SQR (B2*B2-(XO-XD)*(XO-XD)) ! 8/16/83
4100 XG=XB @ YG=.5*(Z(I-1)+Z(I))
4110 AB=FNHYP(XA.XB,YA.YB)
4120 ABG=FNDETR(XA.XB.XG.YA.YB.YG)
4130 AP=ABG/U1X
4140 RX1=XO-(X6(I)-L6/2-(XB-XA)/3)
4150 IF RXO#0 THEN BP=RX1/RXO ELSE BP=0
4160 RY1=YO-(YA+YB+YG)/3
4170 IF RYO#0 THEN CP=RY1/RYO ELSE CP=0
4180 HS=H7+(H1-H7)/(X6(I)-XAL)*(XB-(XB-XA)/3-XAL)
4190 IF H1#0 THEN DP=HS/H1 ELSE DP=0
4200 EP=AP/1.8
```

```
4220 IF RX0#0 THEN FFP=RW1/RX0 ELSE FFP=0
4230 IF H(I)#0 THEN GGP=.5*(XB-XA)*(H7+.5*(H(I)+H(I-1)))/(H(I)*L6) ELSE GGP=0
4240 FACTF1=1+AP*CP
4250 FACTF2=1+DP*EP
4260 FACTCO=1+EP
4270 FACTDM=1+AP*BP
4280 FACTVH=1+FFP*GGP
4290 FACTFW=1+GGP
4300 FACTCA=1+AP
4310 RETURN
4320 ! PRINT "------------------ CASE 1-R ---------------"
4330 XA=XAR @ YA=YAR
4340 XB=X6(I)+L6/2 @ YB=Y0-SQR (B2*B2-(X0-XB)*(X0-XB)) ! 8/16/83
4350 XD=X6(I)-L6/2 @ YD=Y0-SQR (B2*B2-(X0-XD)*(X0-XD)) ! 8/16/83
4360 XG=XB @ YG=.5*(Z(I+1)+Z(I))
4370 AB=FNHYP(XA,XB,YA,YB)
4380 ABG=FNDETR(XA,XG,XB,YA,YG,YB)
4390 AP=ABG/U1X
4400 RX1=X0-(X6(I)+L6/2+(XB-XA)/3)
4410 IF RX0#0 THEN BP=RX1/RX0 ELSE BP=0
4420 RY1=Y0-(YA+YB+YG)/3
4430 IF RY0#0 THEN CP=RY1/RY0 ELSE CP=0
4440 HS=H1+(H8-H1)/(XAR-X6(I))*(XB-(XB-XA)/3-X6(I))
4450 IF H1#0 THEN DP=HS/H1 ELSE DP=0
4460 EP=AB/L9
4470 RW1=X0-(X6(I)+L6/2+(XB-XA)/2)
4480 IF RX0#0 THEN FFP=RW1/RX0 ELSE FFP=0
4490 IF H(I)#0 THEN GGP=.5*(XA-XB)*(H8+.5*(H(I)+H(I+1)))/(H(I)*L6) ELSE GGP=0
4500 FACTF1=1+AP*CP
4510 FACTF2=1+DP*EP
4520 FACTCO=1+EP
4530 FACTDM=1+AP*BP
4540 FACTVH=1+FFP*GGP
4550 FACTFW=1+GGP
4560 FACTCA=1+AP
4570 RETURN
4580 ! PRINT "------------------ CASE 2-L ---------------"
4590 XA=XAL @ YA=YAL
4600 XB=X6(I) @ YB=Y6(I)
4610 XC=XB+L6/2 @ YC=Y0-SQR (B2*B2-(X0-XC)*(X0-XC)) ! 8/16/83
4620 XD=XC @ YD=.5*(Z(I+1)+Z(I))
4630 ABCDE=FNDETR(XA,XB,XD,YA,YB,YD)+FNDETR(XD,XB,XC,YD,YB,YC)
4640 AP=ABCDE/U1X
4650 RX1=X0-(X6(I)+L6/2-(XD-XA)/3)
4660 IF RX0#0 THEN BP=RX1/RX0 ELSE BP=0
4670 RY1=Y0-(YA+YD+YC)/3
4680 IF RY0#0 THEN CP=RY1/RY0 ELSE CP=0
4690 HS=H7+(H1-H7)/(X6(I)-XAL)*(XC-(XD-XA)/3-XAL)
4700 IF H1#0 THEN DP=HS/H1 ELSE DP=0
4710 AB=FNHYP(XA,XB,YA,YB) @ BC=FNHYP(XB,XC,YB,YC)
4720 EP=(AB+BC)/L9
4730 RW1=X0-(XD+XA)/2
4740 IF RX0#0 THEN FFP=RW1/RX0 ELSE FFP=0
4750 IF H(I)#0 THEN GGP=.5*(XD-XA)*(H7+.5*(H(I)+H(I+1)))/(H(I)*L6) ELSE GGP=0
4760 FACTF1=AP*CP
4770 FACTF2=DP*EP
4780 FACTCO=EP
4790 FACTDM=AP*BP
4800 FACTVH=FFP*GGP
4810 FACTFW=GGP
4820 FACTCA=AP
4830 RETURN
4840 ! PRINT "------------------ CASE 2-R ---------------"
4850 XA=XAR @ YA=YAR
```

```
4880 XD=XC @ YD=.5*(Z(I-1)+Z(I))
4890 ABCDE=FNDETR(XA.XD,XB,YA.YD,YB)+FNDETR(XD,XC.XB,YD,YC,YB)
4900 AF=ABCDE/U1X
4910 RX1=X0-(X6(I)-L6/2+(XD-XA)/3)
4920 IF RX0#0 THEN BP=RX1/RX0 ELSE BP=0
4930 RY1=Y0-(YA+YD+YC)/3
4940 IF RY0#0 THEN CP=RY1/RY0 ELSE CP=0
4950 HS=H1+(H8-H1)/(XAR-X6(I))*(XC-(XD-XA)/3-X6(I))
4960 IF H1#0 THEN DP=HS/H1 ELSE DP=0
4970 AB=FNHYP(XA,XB.YA,YB) @ BC=FNHYP(XB,XC.YB,YC)
4980 EP=(AB+BC)/L9
4990 RW1=X0-(XD+XA)/2
5000 IF RX0#0 THEN FFP=RW1/RX0 ELSE FFP=0
5010 IF H(I)#0 THEN GGP=.5*(XA-XD)*(H8+.5*(H(I)+H(I-1)))/(H(I)*L6) ELSE GGP=0
5020 FACTF1=AP*CP
5030 FACTF2=DP*EP
5040 FACTCO=EP
5050 FACTDM=AP*BP
5060 FACTVH=FFP*GGP
5070 FACTFW=GGP
5080 FACTCA=AP
5090 RETURN
5100 ! INPUT HORIZONTAL ACCEL
5105 CLEAR
5110 DISP "ENTER EARTHQUAKE HORIZONTAL ACCELERATION IN g UNITS";@ INPUT ACCEL
5115 Z5$="OK ACCEL"
5120 GOTO 170
```

```
10 ! *** SUPERSTB : HAS BEEN STREAMLINED**** : RENUMBERED ON MAY 20
20 PRINTER IS 401,132 @ PRINT CHR$ (15) @ PRINT @ PRINT
30 PRINT "SUPERSTB: VERSION 30-AUG-83: E.Q. CAPABILITY, SLICE SIZING TIED TO RU
T LENGTH" @ PRINT @ PRINT
35 ! AUG30 83 CHANGE: U2 WAS SET TO ACCUMULATE IN TWO CASES
40 OPTION BASE 1
50 COM Y(5,400),W(5,400),Y6(400),Z(400),Z1(400) ,SHORT X6(400),Y9(400),H(400),F
(400)
60 COM SHORT G1(5),G2(5),T(10),C(10),V1(10),V2(5),V3(5),V4(10)
70 SHORT L(20)
80 DIM TITLE$[80]
90 Z1$="NO EMBKMT INFO" @ F9$="0" @ Z3$="NO PHREAT INFO" @ Z2$="NO SOIL   INFO'
@ P$="0" @ Z4$="NO TITLE" @ Z5$="ACCELERATION = 0"
100 ON KEY# 1,"1) EMBKMT" GOTO 4760
110 ON KEY# 2,"2) SOIL" GOTO 560
120 ON KEY# 3,"3) PHREAT" GOTO 4900
130 ON KEY# 4,"4) TITLE" GOTO 250
140 ON KEY# 5,"5) CONVEN " GOTO 4350
150 ON KEY# 6,"6) ELLIPS" GOTO 720
160 ON KEY# 7,"7) CYLIND " GOTO 5670
170 ON KEY# 8,"8) DISP" GOTO 3760
180 ON KEY# 9,"9) ACCEL  " GOTO 7500
190 ON KEY# 10,"10) DECAY" GOTO 6040
200 G3=62.4 @ ACCEL=0
210 MASS STORAGE IS ":D700"
220 CLEAR @ KEY LABEL @ DISP "CONT 220" @ DISP
230 DISP Z1$ @ DISP Z2$ @ DISP Z3$ @ DISP Z4$ @ DISP Z5$ @ WAIT 5000
240 GOTO 220
250 DISP "ENTER TITLE AND TODAYS'S DATE"
260 INPUT TITLE$
270 Z4$="TITLE IS IN"
280 GOTO 220
290 REM **********************************
300 PRINT @ PRINT "SPECIFICATIONS FOR THIS RUN"
310 PRINT @ PRINT TITLE$ @ PRINT
320 PRINT "SOIL PROPERTIES: FILE ";F$
330 PRINT "EMBKMT GEOMETRY: FILE ";F9$
340 PRINT "PHREATIC SURFACE: ";@ IF P$="0" THEN PRINT "NONE" ELSE PRINT "FILE '
P$;" SURFACE:";U9
350 RETURN
360 REM *****************
370 REM GENERATE BASIC COORDINATES USED BY CONVEN.,ELLIPSE AND CYLINDER
380 FOR I=1 TO N2
390 Y6(I)=0
400 Y9(I)=0
410 Z(I)=Z0
420 FOR D=1 TO N3
430 Z(I)=Z(I)+Y(D,I)+W(D,I)
440 NEXT D
450 NEXT I
460 H=40
470 DISP "ELLIP. COORD. X0=";
480 INPUT X0
490 DISP "ELLIP. COORD. Y0=";
500 INPUT Y0
510 DISP "SLIP RADIUS R =";
520 INPUT R
```

```
530 IF Y0-B<20 THEN 3650
540 RETURN
550 REM ************************
560 !    *** SOIL-2 ***
570 CLEAR @ MASS STORAGE IS ":D701"
580 A$="SOIL PROP"
590 DISP "Soil Property File Name";
600 INPUT F$
610 ASSIGN# 1 TO  F$
620 READ# 1 ; B$
630 IF A$=B$ THEN 660
640 GOSUB 4590
650 GOTO 590
660 C9=1 ! CORR. COEFF. OF SOIL PROPERTIES IN THE VERTICAL DIRECTION
670 READ# 1 ; G1(),V2(),G2(),V3(),T(),V4(),C(),V1()
680 ASSIGN# 1 TO  *
690 Z2$="OK SOIL INFOR"
700 GOTO 210
710 REM ******************************
720 !    *** ELLIPSE ***
730 A9$="ELP"
740 PRINT "ELLIPSOIDAL FAILURE SURFACE" @ PRINT
750 CLEAR @ PRINT "STB86: D0>B2" @ GOSUB 300
760 GOSUB 370
770 DISP "RUPTURE LENGTH:RLENGTH=";
780 INPUT RLENGTH
790 DISP "NB OF SLICES IN RLENGTH/2  N7=";
800 INPUT N7
810 IF ACCEL#0 THEN PRINT "------> HORIZONTAL ACCELERATION = ";ACCEL;" g's";@ PR
NT
820 RMIN=1000000 ! FIND RADIUS TANGENT TO SURFACE
830 FOR I=1 TO N2
840 ! RTEMP=SQR ((X0-X6(I))*(X0-X6(I))+(Y0-Y6(I))*(Y0-Y6(I)))  OLD
845 RTEMP=SQR ((X0-X6(I))*(X0-X6(I))+(Y0-Z(I))*(Y0-Z(I))) ! NEW    09 AUG 83
850 IF RTEMP>= RMIN THEN GOTO 870
860 RMIN=RTEMP
870 NEXT I
880 IF RMIN<B THEN GOTO 920
890 DISP "WARNING: RMIN >= B (ELLIPSE MINOR AXIS):  RECHECK DATA"
900 PAUSE
910 GOTO 220
920 L1=RLENGTH/SQR (1-RMIN*RMIN/(B*B))
930 A2=0 @ A3=0 @ Q4=0 @ Q5=0 @ G=0 @ G6=0 @ N8=0 @ L0=0 @ Q=0 @ SFEQ=0
940 L7=RLENGTH/2/N7 ! WAS  L7=L1/2/N7 IN THE OLD PROGRAM
950 DISP " OPTIMIZED LONGITUDINAL SLICE WIDTH =";L7;" RUPT LENGTH= ";RLENGTH;"
LLIPSE MAJOR AXIS L1=";L1
960 F9=0
970 PRINT USING 980 ; X0,Y0,B,L1
980 IMAGE /"ELLIPS.CENTER: X0=",4D.DD,10X,"Y0=",4D.DD/"MIN AXIS=",4D.DDD,10X,"M
J AXIS=",4D.DDD
990 PRINT @ PRINT "TRANSVERSE SEGMENT WIDTH =";L6 @ PRINT "LONGITUDINAL SLICE W
DTH =";L7
1000 GOSUB 3520
1010 FOR K=1 TO N7
1020 B2=B*SQR (1-L7*(K-.5)*(L7*(K-.5))/(L1/2)/(L1/2)) ! ^ 3/18/83
1030 B3=B*SQR (1-L7*(K-1)*(L7*(K-1))/(L1/2)/(L1/2)) ! ^ 3/18/83
1040 B4=B*SQR (1-L7*K*(L7*K)/(L1/2)/(L1/2)) ! ^ 3/18/83
1050 G5=SQR (L7*L7+(B3-B4)*(B3-B4))/L7 ! ^ 3/18/83
1060 GOSUB 1120
1070 NEXT K
1080 GOSUB 3040
1090 BEEP 200,250
1100 GOTO 210
1110 REM ****************************************
1120 REM :  ANALYZE ONE SLICE
1130 I=0 @ N8=0 @ A4=A2 @ A5=A3 @ G0=G @ Q6=Q4 @ Q7=Q5 @ Q0=Q @ U5=0 @ U7=0 @
```

```
=(
1140 IENTRY=-1 @ ! PRINT B3;B3;B4
1150 FOR I=1 TO N2
1160 IF B2*B2<(X0-X6(I))*(X0-X6(I)) THEN 1180 ! ^ 3/18/83
1170 Y6(I)=Y0-SQR (B2*B2-(X0-X6(I))*(X0-X6(I))) ! ^ 3/18/83
1180 F0(I)=0
1190 NEXT I
1200 ! IF P$="0" THEN 1750
1210 ROOTCHK=-1
1220 FOR I=2 TO N2
1230 P4=SQR ((X0-X6(I-1))*(X0-X6(I-1))+(Y0-Z(I-1))*(Y0-Z(I-1))) ! ^ 3/18/83
1240 P6=SQR ((X0-X6(I))*(X0-X6(I))+(Y0-Z(I))*(Y0-Z(I))) ! ^ 3/18/83
1250 IF P4<B2 OR P6<B2 THEN 1270
1260 GOTO 1550 !  SLIP CIRCLE IS ABOVE THE iTH SLICE
1270 IF P4>B2 OR P6>B2 THEN 1330
1280 !  CASE OF LATERAL HYDR LOAD FULLY BOUNDING THE iTH SLICE
1290 O1=.5*(Z(I)+Z(I-1)) @ O2=.5*(Z(I)-Z(I-1))
1300 F0(I)=-(.5*G3*(H(I)*H(I)-H(I-1)*H(I-1))*L7*(Y0-O1+O2/3)) ! ^3/18/83
1310 GOTO 1550
1320 ! THE FOLLOWING IS THE REFINED  INTERSECTION SCHEME:
1330 MM=(Z(I)-Z(I-1))/L6 ! SLOPE M
1340 BB=Z(I-1)-X6(I-1)*MM ! INTERCEPT b
1350 BBB=(MM*BB-MM*Y0-X0)/(MM*MM+1) ! ^ 3/18/83
1360 CCC=(X0*X0+(Y0-BB)*(Y0-BB)-B2*B2)/(2*(MM*MM+1)) ! ^ 3/18/83
1370 ROOT1=-BBB+SQR (BBB*BBB-2*CCC) ! ^ 3/18/83
1380 ROOT2=-BBB-SQR (BBB*BBB-2*CCC) ! ^ 3/18/83
1390 MEAN=(X6(I)+X6(I-1))/2
1400 IF (MEAN-ROOT1)*(MEAN-ROOT1)<(MEAN-ROOT2)*(MEAN-ROOT2) THEN P5=ROOT1 ELSE 
5=ROOT2 ! ^ 3/18/83
1410 H6=Z(I-1)+(Z(I)-Z(I-1))/(X6(I)-X6(I-1))*(P5-X6(I-1))
1420 IF ROOTCHK=1 THEN GOTO 1510 @ ! IF P4<= B2 OR ROOTCHK=1 THEN 1730
1430 ! Y6(I-1) EXCEEDS Z(I-1)
1440 O1=.5*(Z(I)+H6) @ O2=.5*(Z(I)-H6)
1450 H7=H(I-1)+(H(I)-H(I-1))/(X6(I)-X6(I-1))*(P5-X6(I-1))
1460 F0(I)=-(.5*G3*(H(I)*H(I)-H7*H7)*L7*(Y0-O1+O2/3)) ! ^ 3/18/83
1470 XAL=P5 @ YAL=H6 ! MDH 2/28/83 -->NEED THESE FOR END CORRECTIONS
1480 ROOTCHK=1
1490 GOTO 1550
1500 ! Y6(I) EXCEEDS Z(I)
1510 O1=.5*(Z(I-1)+H6) @ O2=.5*(H6-Z(I-1))
1520 H8=H(I-1)+(H(I)-H(I-1))/(X6(I)-X6(I-1))*(P5-X6(I-1))
1530 F0(I)=-(.5*G3*(H8*H8-H(I-1)*H(I-1))*L7*(Y0-O1+O2/3)) ! MDH     ! ^ 3/18/83
1540 XAR=P5 @ YAR=H6 ! MDH 2/28/83 -->USE FOR END CORRECTIONS
1550 NEXT I
1560 FOR I=1 TO N2
1570 R=0 @ R9=0
1580 H1=H(I)+Z0 @ MVW=H(I)*G3*L6*L7 @ M=0 ! MDH 2/28/83
1590 FEQ=0 ! E.Q. MOMENT SUMMAND
1600 FOR D=1 TO N3
1610 H1=H1+W(D,I)
1620 NEXT D
1630 D0=SQR ((X0-X6(I))*(X0-X6(I))+(Y0-Z(I))*(Y0-Z(I))) ! ^ 3/18/83
1640 IF D0<B2 THEN 1660
1650 Y6(I)=0 @ GOTO 2860
1660 IF I=1 THEN 3630
1670 IF I=N2 THEN 3630
1680 H1=(H1-Y6(I))*(H1>Y6(I))
1690 W0=0
1700 Z1(I)=Z(I)-Y6(I) @ U1X=0
1710 IF A9$#"CYL" THEN 2190
1720 U=0 @ U2=0 @ X5=(X6(I)-X0)*(X6(I)-X0) ! MDH 2/28/83      ! ^ 3/18/83
1730 FOR D=1 TO N3
1740 Z1(I)=Z1(I)-W0
1750 ! BELOW:D0->DRY; D2->WET
1760 D0=2*D-1 @ D2=D*2 @ D1=D0
1770 IF Y(D,I)=0 THEN 1840
```

```
1780 IF Y(D,I)<Z1(I) THEN 1870
1790 M1=G1(D)*Z1(I)*L6*L7 @ U1=Z1(I)*L6 @ U1X=U1X+U1
1800 R1=V2(D)*M1
1810 EQT=M1*(Y0-Y6(I)-Z1(I)/2) @ FEQ=FEQ+EQT @ REQ=V2(D)*EQT*V2(D)*EQT ! ^3/18/
3
1820 R9=R9+REQ
1830 X6=SQR (X5+(Y0-Z(I)+Z1(I)/2)*(Y0-Z(I)+Z1(I)/2)) ! ^3/18/83
1840 M=M+M1 @ U=U+U1*C(D0)*X6
1850 R=R+R1*R1 @ U2=U2+V1(D0)*U1*C(D0)*X6 ! MDH, FEB09 83 !^3/18/83  ! AUG31 8
1851 ! OLD 1850 R=R+R1*R1 @ U2=V1(D0)*U1*C(D0)*X6 ! MDH, FEB09 83 !^3/18/83
1860 GOTO 2580
1870 M1=G1(D)*Y(D,I)*L6*L7 @ U1=Y(D,I)*L6 @ U1X=U1X+U1
1880 R1=V2(D)*M1
1890 EQT=M1*(Y0-Y6(I)-Z1(I)+Y(D,I)/2) @ FEQ=FEQ+EQT @ REQ=V2(D)*EQT*V2(D)*EQT !
^3/18/83
1900 R9=R9+REQ
1910 X6=SQR (X5+(Y0-Z(I)+Y(D,I)/2)*(Y0-Z(I)+Y(D,I)/2)) ! ^3/18/83
1920 M=M+M1 @ U=U+U1*C(D0)*X6
1930 R=R+R1*R1 @ U2=U2+V1(D0)*U1*C(D0)*X6 ! MDH, FEB09 83  ! ^3/18/83 ! AUG31 8

1931 ! OLD 1930 R=R+R1*R1 @ U2=V1(D0)*U1*C(D0)*X6 ! MDH, FEB09 83      ! ^3/18/8

1940 Z1(I)=Z1(I)-Y(D,I)
1950 IF W(D,I)=0 THEN 2140
1960 IF W(D,I)<Z1(I) THEN 2060
1970 M1=(G2(D)+G3)*Z1(I)*L6*L7 @ U1=Z1(I)*L6 @ U1X=U1X+U1
1980 R1=V3(D)*M1
1990 EQT=M1*(Y0-Y6(I)-Z1(I)/2) @ FEQ=FEQ+EQT @ REQ=V3(D)*EQT*V3(D)*EQT ! ^3/18/
3
2000 R9=R9+REQ
2010 X6=SQR (X5+(Y0-Z(I)+Y(D,I)+Z1(I)/2)*(Y0-Z(I)+Y(D,I)+Z1(I)/2)) ! ^ 3/18/83
2020 M=M+M1 @ U=U+U1*C(D2)*X6
2030 R=R+R1*R1+2*R1*SQR (R)*C9 @ U2=U2+V1(D2)*U1*C(D2)*X6 ! MDH FEB09 83 !^3/18
2040 D1=D2 ! WET
2050 GOTO 2580
2060 M1=(G2(D)+G3)*W(D,I)*L6*L7 @ U1=W(D,I)*L6 @ U1X=U1X+U1
2070 R1=V3(D)*M1
2080 EQT=M1*(Y0-Y6(I)-Z1(I)+W(D,I)/2) @ FEQ=FEQ+EQT @ REQ=V3(D)*EQT*V3(D)*EQT !
^3/18/83
2090 R9=R9+REQ
2100 X6=SQR (X5+(Y0-Z(I)+Y(D,I)+W(D,I)/2)*(Y0-Z(I)+Y(D,I)+W(D,I)/2)) ! ^3/18/8
2110 M=M+M1 @ U=U+U1*C(D2)*X6
2120 R=R+R1*R1+2*R1*SQR (R)*C9 @ U2=U2+V1(D2)*U1*C(D2)*X6 ! MDH FEB09 !^3/18
2130 D1=D2 ! WET
2140 W0=W(D,I)
2150 NEXT D
2160 D=D-1
2170 GOTO 2580
2180 UX1=0
2190 FOR D=1 TO N3
2200 D1=2*D-1 ! MAKE DRY
2210 Z1(I)=Z1(I)-W0
2220 IF Y(D,I)=0 THEN 2370
2230 IF Y(D,I)<Z1(I) THEN 2310
2240 M1=G1(D)*Z1(I)*L6*L7 @ U1X=U1X+Z1(I)*L6 ! MDH, 2/28/83
2250 R1=V2(D)*M1
2260 M=M+M1
2270 R=R+R1*R1+2*R1*SQR (R)*C9 ! ^3/18/83
2280 EQT=M1*(Y0-Y6(I)-Z1(I)/2) @ FEQ=FEQ+EQT @ REQ=V2(D)*EQT*V2(D)*EQT ! ^3/18/
3
2290 R9=R9+REQ
2300 GOTO 2580
2310 M1=G1(D)*Y(D,I)*L6*L7 @ U1X=U1X+Y(D,I)*L6 ! MDH, 2/28/83
2320 R1=V2(D)*M1
2330 M=M+M1
2340 R=R+R1*R1+2*R1*SQR (R)*C9 ! ^3/18/83
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```
2350 EQT=M1*(Y0-Y6(I)-Z1(I)+Y(D.I)/2) @ FEQ=FEQ+EQT @ REQ=V2(D)*EQT*V2(D)*EQT !
^3/18/83
2360 R9=R9+REQ
2370 Z1(I)=Z1(I)-Y(D.I)
2380 IF W(D.I)=0 THEN 2550
2390 IF W(D.I)<Z1(I) THEN 2480
2400 M1=(G2(D)+G3)*Z1(I)*L6*L7 @ U1X=U1X+Z1(I)*L6 ! MDH, 2/28/83
2410 R1=V3(D)*M1
2420 M=M+M1
2430 R=R+R1*R1+2*R1*SQR (R)*C9 ! ^3/18/83
2440 EQT=M1*(Y0-Y6(I)-Z1(I)/2) @ FEQ=FEQ+EQT @ REQ=V3(D)*EQT*V3(D)*EQT ! ^3/18/
3
2450 R9=R9+REQ
2460 D1=D*2 ! WET
2470 GOTO 2580
2480 M1=(G2(D)+G3)*W(D,I)*L6*L7 @ U1X=U1X+W(D,I)*L6 ! MDH, 2/28/83
2490 R1=V3(D)*M1
2500 M=M+M1
2510 R=R+R1*R1+2*R1*SQR (R)*C9 ! ^3/18/83
2520 EQT=M1*(Y0-Y6(I)-Z1(I)+W(D,I)/2) @ FEQ=FEQ+EQT @ REQ=V3(D)*EQT*V3(D)*EQT
^3/18/83
2530 R9=R9+REQ
2540 D1=D*2 ! WET
2550 W0=W(D.I)
2560 NEXT D
2570 D=D-1
2580 GOSUB 6090
2590 DEF FNHYP(XA.XB.YA.YB) = SQR ((XA-XB)*(XA-XB)+(YA-YB)*(YA-YB)) ! ^3/18/83
2600 DEF FNDETR(XA.XB.XC.YA.YB.YC) = .5*(XB*YC-XC*YB-(XA*YC-XC*YA)+XA*YB-XB*YA)
2610  FRICT1=(M*FACTF1+MVW*FACTFW)*(Y0-Y6(I))/G5*T(D1)
2620  FRICT2=-(H1*G3*B2*L9*G5*L7*T(D1)*FACTF2) @ A0=FRICT1+FRICT2
2630 ! PRINT "FACTF1.FACTFW.FACTF2 ARE":FACTF1;FACTFW:FACTF2;" FRICT1, FRICT2 A
E:";FRICT1:FRICT2
2640 IF A0<0 THEN A0=0
2650 Q0=SQR (R/(M*FACTF1+MVW*FACTFW)/(M*FACTF1+MVW*FACTFW)+V4(D1)*V4(D1)) ! ^3/
8
2660 A1=L9*L7*C(D1)*B2*G5*FACTCO
2670 Q1=V1(D1)
2680 DEN=M*FACTDM+MVW*FACTVH
2690 G1=DEN*(X0-X6(I))+FEQ*ACCEL*FACTCA @ IF ABS (G1)>.0001 THEN GOTO 2710
2700 Q9=0 @ GOTO 2720 ! MAY 19 12:01 PM
2710 Q9=SQR (R*(X0-X6(I))*(X0-X6(I))+R9*ACCEL*ACCEL)/ABS (G1) ! CHNGD ON 3/12/8
 ! ^3/18/83
2720 IF ACCEL=0 THEN GOTO 2750
2730 TQ9=SQR (R)/ABS (DEN)
2740 IF Q9>2*TQ9 THEN Q9=2*TQ9 ! BOGUS, BUT WHAT CAN WE DO?
2750 L=L+L9*FACTCO
2760 ! PRINT "L9, FACTCO, L9*FACTCO, L ARE:":L9:FACTCO;L9*FACTCO:L
2770 N9=N9+1
2780 SFEQ=SFEQ+FEQ*FACTCA ! USE TO COMPUTE g LEVEL AT WHICH FS=1
2790 IF A9$#"CYL" THEN 2810
2800 U3=U3+U*FACTCA @ U5=U5+U2/U @ U0=U0+U1X*FACTCA
2810 A2=A2+A0 @ A3=A3+A1
2820 Q4=Q4+Q0 @ Q5=Q5+Q1
2830 REM NOTE CHANGES IN Q9 AND G!
2840 G=G+G1+F0(I) @ Q=Q+Q9 @ F9=F9+F0(I) ! @ PRINT "**I,Q9,Q: ";I;Q9:Q @ PRINT
2850 !
2860 NEXT I
2870 IF K#1 THEN 2910
2880 N=IP (L/10)
2890 IF N<1 THEN 3590
2900 DISP "N=";N
2910 IF L=0 THEN 1080
2920 G6=G6+L7*G5*L
2925 ! PRINT " K=";K;" G5=":G5:" L=":L:"  SURFACE AREA =",L7*G5*L @ PRINT
```

```
2940 LO=LO+L7*2
2950 A4=A2-A4 @ O6=(O4-O6)/N9 @ A5=A3-A5 @ O7=(O5-O7)/N9 @ G0=G-G0 @ O8=(O-O8)
9
2960 ! PRINT "***O.O8,N9:";O;O8;N9 @ PRINT
2970 PRINT USING 2980 ; K,B2,L,1/G5,A4,O6,A5,O7,G0,O8,(A4+A5)/G0
2980 IMAGE 3D,1X,DDDD.D,4D.D,DD.2D,3(1X,MD.2DE,DD.DD),4D.2D
2990 PRINT
3000 RETURN
3010 REM ******************************************
3020 REM : GET RESULTS FOR THE ENTIRE SURFACE. USED BY ELLIPSE, CYLINDER AND C
VENTIONAL PLANE STRAIN ANALYSES.
3030 REM ENTRY FOR ELLIPSE & CYLINDER
3040 IF N<1 THEN N=1
3050 N1=IP (2*G6/(100*N))
3060 IMAGE //"RUPTURE LENGTH=",5D/"RUPTURED SURFACE=",MD.3DE/
3070 IMAGE /"TOTAL-HALF RUPTURE   ",3(1X,MD.2DE,DD.2D)
3080 D=.015
3090 C7=1-.0048*(N+N1-2)
3100 C7=C7*(C7>0)
3110 GOTO 3140
3120 REM ENTRY FOR CONVENTIONAL PLANE STRAIN CASE
3130 C7=0
3140 O4=O4/N8
3150 O5=O5/N8
3160 O=O/N8*(G/(G+SFEO*ACCEL)) ! CHNGD ON 3/12/83
3170 S=(A2+A3)/G*SGN (G)*(1+O*C7*(O*C7)) ! ^3/18/83
3180 V=(O4*A2*(O4*A2)+O5*A3*(O5*A3))/((A2+A3)*(A2+A3)) ! ^3/18/83
3190 V=SQR (V+O*O/(1+2*O*O)*(1+V)) ! ^3/18/83
3200 PRINT USING 3070 ; A2,O4,A3,O5,G,O
3210 IF C7#0 OR ACCEL=0 OR ABS (S-1)<.001 THEN GOTO 3260
3220 IF G>= 0 THEN ACRIT=(A2+A3-(G-SFEO*ACCEL))/SFEO
3230 IF G<0 THEN ACRIT=-((A2+A3+(G-SFEO*ACCEL))/SFEO)
3240 PRINT USING 3250 : ACRIT @ PRINT
3250 IMAGE "***** S WILL BECOME UNITY AT A HORIZONTAL ACCEL =",DD.DDD," o'S"//
3260 PRINT USING 3580
3270 PRINT @ PRINT "RUPTURED LENGTH =":LO @ PRINT "RUPTURED AREA =":2*G6
3280 I$="SAFETY FACTOR" @ I1$="POINT EST COV " @ I2$="DECAY FACTOR "
3290 IMAGE ///K,3X,MD.3DE/K, 4D.3D/K,4D.3D/"COV",12X,4D.3D
3300 REM LOGNORMAL DISTRIBUTION
3310 IF C7=0 THEN 3360
3320 S3=SQR (LOG ((V*C7)^2+1))
3330 M9=S*EXP (-(.5*S3^2))
3340 P1=LOG (M9)/S3
3350 GOTO 3370
3360 P1=SGN (S-1)*10
3370 T8=1-(P1<0)
3380 Z=ABS (P1)
3390 Y=FNF(Z)
3400 P=Y*T8+(1-Y)*(T8=0)
3410 PRINT USING 3290 : I$.S.I1$,V,I2$.C7.V*C7
3420 PRINT USING 3440 : -P1.P
3430 PRINT
3440 IMAGE "LOGNORMAL MODEL"/"BETA ST.DEV  ", 4D.3D/"PROB OF FAIL. ",2D.6D
3450 IF SGN (G)<0 THEN PRINT USING 3470 ELSE PRINT USING 3480
3460 PRINT @ PRINT USING 3580
3470 IMAGE "RIVERSIDE FAILURE"
3480 IMAGE "LANDSIDE FAILURE"
3490 PRINT
3500 RETURN
3510 REM *******************************************************************
3520 PRINT USING 3580 @ PRINT USING 3550 @ PRINT USING 3560 @ PRINT USING 3570
3530 PRINT USING 3580
3540 RETURN
3550 IMAGE //"K=SLICE NUMBER"/"L=ARC LENGTH"/"B2=SLICE RADIUS"/"C=COS LONGIT.SI
PE"
3560 IMAGE "S=SAFETY FACTOR"
```

```
3570 IMAGE /"  K     B2      L",4X,"C",09X,"FRICTION",08X,"COHESION",05X,"FORCIN
MOM",5X,"S"
3580 IMAGE 39("--")
3590 REM IF K=1 AND L<10
3600 PRINT "CIRCLE DOES NOT INTERSECT EMBANKMENT"
3610 PRINT
3620 GOTO 4570
3630 REM BAD CIRCLE
3640 PRINT @ PRINT "CIRCLE GOES BEYOND DEFINED LIMITS"
3650 GOTO 4570
3660 REM NORMAL DISTRIBUTION *********************************************
3670 DEF FNF(X)
3680 T=1/(1+.2316419*X)
3690 P3=T*(.31938153+(T*(-.356563782+1.781477937*T)))
3700 P3=P3+(T^4*(-1.821255978+1.330274429*T))
3710 P3=1/SQR (2*PI )*EXP (-(X^2/2))*P3
3720 FNF=P3
3730 FN END
3740 REM **************************************************
3750 ! *** DISP-4 *********
3760 CLEAR
3770 DISP "INPUT M4.M5: M4=75 (75+Z0). M5=10 (YAXIS) IN HM VERSION":
3780 INPUT M4.M5
3790 DISP @ CLEAR
3800 DISP USING "2(K.5D.D.1X)/3(K.5D.D.1X)" : "X0=",X0."Y0=".Y0." B=".B."L1".L
"L0=",L0
3810 DISP USING "2(K,MD.4DE.1X)" : " S=".S," V=".V," P=",P
3820 DISP " M4=":M4:"  M5=":M5:
3830 ! DISP @ COPY
3840 I3=0
3850 FOR K=1 TO 2
3860 GCLEAR
3870 I1=(K-1)*INT ((N2-1)/2)+1
3880 I2=K*INT ((N2-1)/2)+1
3890 ! SCALE X6(I1).X6(I2).Z0.75+Z0
3900 SCALE X6(I1),X6(I2),Z0.M4+Z0
3910 XAXIS Z0.L6
3920 ! YAXIS X6(I1).10
3930 YAXIS X6(I1),M5
3940 FOR I=I1 TO I2 STEP 5
3950 FOR J=INT (Z0/10)*10+10 TO Z0+70 STEP 10
3960 PLOT X6(I).J
3970 PEN UP
3980 NEXT J
3990 NEXT I
4000 I3=I2*5-I-5
4010 FOR I=1 TO N2
4020 Z(I)=Z0
4030 NEXT I
4040 FOR L=N3 TO 1 STEP -1
4050 MOVE X6(I1).Z0
4060 FOR I=I1 TO I2
4070 Z(I)=Z(I)+Y(L.I)+W(L.I)
4080 DRAW X6(I).Z(I)
4090 NEXT I
4100 PEN UP
4110 NEXT L
4120 FOR I=I1 TO I2
4130 IF X6(I)<X0-B THEN 4170
4140 IF X6(I)>X0+B THEN 4170
4150 Y9(I)=Y0-SQR (B^2-(X0-X6(I))^2)
4160 IF Y9(I)<= Z(I) THEN 4180
4170 Y9(I)=Z(I)
4180 NEXT I
4190 MOVE X6(I1).Z0
4200 FOR I=I1 TO I2
```

```
4210 Z(I)=Z0
4220 FOR M=N3 TO 1 STEP -1
4230 Z(I)=Z(I)+W(M,I)
4240 NEXT M
4250 DRAW X6(I),Z(I)
4260 NEXT I
4270 PEN UP
4280 MOVE X6(I1),Y9(I1)
4290 FOR I=I1 TO I2
4300 DRAW X6(I),Y9(I)
4310 NEXT I
4320 ! COPY
4330 NEXT K
4340 GOTO 210
4350 REM ********************************************************************
4360 !     *** CONVENTIONAL PLANE STRAIN ANALYSIS ***
4370 A9$="CIR"
4380 CLEAR @ PRINT " CONVENTIONAL PLANE STRAIN SLIP CIRCLE " @ GOSUB 300
4390 GOSUB 370
4400 L1=1
4410 A2=0 @ A3=0 @ Q4=0 @ Q5=0 @ G=0 @ G6=0 @ N8=0 @ L0=0 @ Q=0
4420 L7=L1/2 @ SFEQ=0 ! MAY 25 83
4430 F9=0 ! MDH JAN 14 83
4440 PRINT "CIRCLE CENTER: X0=";X0;"      Y0=";Y0
4450 PRINT "CIRCLE RADIUS: B =";B
4460 PRINT @ PRINT "TRANSVERSE SEGMENT WIDTH =";L6 @ PRINT "WORKING LONGITUD. S
ICE WIDTH =";L7
4470 IF ACCEL#0 THEN PRINT "------> HORIZONTAL ACCELERATION = ";ACCEL;" g'S";@ P
INT
4480 GOSUB 3520
4490 K=1
4500 B2=B @ B3=B @ B4=B
4510 G5=1
4520 GOSUB 1120
4530 GOSUB 3120
4540 BEEP 200,250
4550 GOTO 210
4560 REM ******************************
4570 BEEP 40,150 @ BEEP 200,300 @ GOTO 210
4580 REM ******************************
4590 ! WARNING FOR WRONG DATA FILE
4600 DISP @ DISP
4610 DISP "MISMATCHED DATA FILES"
4620 DISP "DATA FILE IS ";B$
4630 DISP "DATA FILE SHOULD BE ";A$
4640 DISP "TRY AGAIN"
4650 RETURN
4660 REM ************************************
4670 REM FILE CREATOR
4680 DISP "I NEED";N3;" RECORDS TO STORE THIS"
4690 DISP "I NEED 0 RECORDS IF FILE EXISTS"
4700 DISP "INPUT FILE NAME, NB OF RECORDS"
4710 INPUT F$,N3
4720 MASS STORAGE IS ":D701"
4730 IF N3#0 THEN CREATE F$,N3
4740 RETURN
4750 REM ***************************************
4760 REM ENTRY FOR NEW EMBANKMENT SECTION
4770 CLEAR @ MASS STORAGE IS ":D701"
4780 DISP "INPUT FILE NAME WITH EMBK.PROCESSED GEOMETRY"
4790 INPUT F9$
4800 ASSIGN# 1 TO  F9$
4810 A$="PRO SEC GEO"
4820 READ# 1 ; B$
4830 IF B$=A$ THEN 4860
4840 GOSUB 4590
```

```
4850 GOTO 4780
4860 Z1$="OK EMBKMT INFO"
4870 GOTO 210
4880 REM ****************************************
4890 REM INPUT PHREATIC SURFACE
4900 CLEAR @ MASS STORAGE IS ":D701"
4910 IF F9$#"0" THEN 4940
4920 DISP "GIVE EMBKMT INFO FIRST"
4930 GOTO 4780
4940 ASSIGN# 1 TO  F9$
4950 READ# 1 ; B$
4960 READ# 1 : X8,X9,Z0,N2,N3,L6
4970 FOR I=1 TO N2
4980 X6(I)=L6*(I-1)+X8
4990 NEXT I
5000 FOR L=1 TO N3
5010 FOR I=1 TO N2
5020 READ# 1 : Y(L,I)
5030 NEXT I
5040 NEXT L
5050 DISP "NAME FILE WITH PHREATIC SURFACE"
5060 DISP "INPUT  0 IF NO PHR.SURF."
5070 INPUT P$
5080 IF P$#"0" THEN 5240
5090 DISP "NO PHREATIC SURFACE"
5100 FOR I=1 TO N2
5110 H(I)=0
5120 FOR L=1 TO N3-1
5130 W(L,I)=0
5140 Y(L,I)=Y(L,I)-Y(L+1,I)
5150 NEXT L
5160 Y(L,I)=Y(L,I)-Z0
5170 W(L,I)=0
5180 NEXT I
5190 N5=0
5200 GOTO 5630
5210 REM ENTRY THRU SFK#4
5220 MASS STORAGE IS ":D701"
5230 IF P$="0" THEN 5050
5240 ASSIGN# 2 TO  P$
5250 READ# 2 ; B$
5260 A$="PRO SEC GEO"
5270 IF A$=B$ THEN 5290
5280 REM REM REM
5290 READ# 2 : A.A.A.N4.N5.L7
5300 IF N4=N2 AND L6=L7 THEN 5330
5310 PRINT "PHREATIC SURFACE INCOMPATIBLE WITH EMBKMT"
5320 GOTO 4560
5330 DISP "CHOOSE SURFACE NUMBER   0 TO":N5
5340 INPUT L1
5350 U9=L1
5360 IF L1=0 THEN 5090
5370 FOR L=1 TO L1
5380 FOR I=1 TO N4
5390 READ# 2 ; Z(I)
5400 NEXT I
5410 NEXT L
5420 ASSIGN# 2 TO  *
5430 FOR I=1 TO N2
5440 IF Z(I)>Y(1.I) THEN H(I)=Z(I)-Y(1.I) ELSE H(I)=0
5450 FOR L=2 TO N3
5460 IF Z(I)<Y(L.I) THEN 5510
5470 IF Z(I)>Y(L-1.I) THEN 5530
5480 W(L-1.I)=Z(I)-Y(L.I)
5490 Y(L-1.I)=Y(L-1.I)-Z(I)
5500 GOTO 5540
```

```
5510 W(L-1,I)=0 @ Y(L-1,I)=Y(L-1,I)-Y(L,I)
5520 GOTO 5540
5530 W(L-1,I)=Y(L-1,I)-Y(L,I) @ Y(L-1,I)=0
5540 NEXT L
5550 IF Z(I)<= Z0 THEN 5590
5560 IF Z(I)>Y(L-1,I) THEN 5610
5570 W(L-1,I)=Z(I)-Z0 @ Y(L-1,I)=Y(L-1,I)-Z(I)
5580 GOTO 5620
5590 W(L-1,I)=0 @ Y(L-1,I)=Y(L-1,I)-Z0
5600 GOTO 5620
5610 W(L-1,I)=Y(L-1,I)-Z0 @ Y(L-1,I)=0
5620 NEXT I
5630 ASSIGN# 1 TO  *
5640 MASS STORAGE IS ":D700"
5650 Z3$="OK PHREAT INFO"
5660 GOTO 210
5670 REM ********************************************
5680 !  *** 3-D FINITE CYLINDRICAL FAILURE ***
5690 A9$="CYL"
5700 CLEAR @ GOSUB 370
5710 K1=0
5720 DISP "INPUT CYLINDER LENGTHS. END WITH 999"
5730 K1=K1+1
5740 INPUT L(K1)
5750 IF L(K1)#999 THEN 5730
5760 FOR K2=1 TO K1-1
5770 L1=L(K2)
5780 A2=0 @ A3=0 @ Q4=0 @ Q5=0 @ G=0 @ G6=0 @ N8=0 @ L0=0 @ Q=0 @ SFEQ=0
5790 F9=0 ! MDH, 1/14/83
5800 L7=L1/2
5810 PRINT "SC3AJ3: CYLINDRICAL SLIP SURFACE" @ GOSUB 300
5820 PRINT "CYLINDER CENTER: X0=";X0;"      Y0=";Y0
5830 PRINT "CYLINDER RADIUS: B =";B
5840 PRINT @ PRINT "CYLINDER LENGTH =";L7*2
5850 PRINT @ PRINT "TRANSVERSE SEGMENT WIDTH =";L6
5860 IF ACCEL#0 THEN PRINT "------> HORIZONTAL ACCELERATION = ";ACCEL;" g'S";@ P
INT
5870 GOSUB 3520
5880 K=1
5890 B2=B @ B3=B @ B4=B
5900 G5=1
5910 GOSUB 1120
5920 G6=G6+U0
5930 K=U0/G6
5940 A3=A3+U3
5950 Q5=Q5*(1-K)+U5*K
5960 ! Q5=(Q5/N8*(1-K)+U5*K)*N8 (OLD 5780)
5970 PRINT USING 5990 ; U0,U3,U5/N8
5980 GOSUB 3040
5990 IMAGE "END AREA(",MD.3DE,")",16X,MD.2DE,DD.DD
6000 PRINT @ PRINT @ PRINT @ PRINT
6010 NEXT K2
6020 BEEP 200,250
6030 GOTO 210
6040 REM ****************************
6050 REM DECAY FUNCTION
6060 CLEAR @ DISP "TRY ME SOME OTHER DAY"
6070 WAIT 5000
6080 GOTO 210
6090 ! BEGIN SUB TO CORRECT EFFECTS
6100 ! DELTA=L6
6110 ! SET UP DEFAULT FACTORS FOR NOMINAL (NORMAL) CASE
6120 FACTF1=1 @ FACTF2=1
6130 FACTC0=1 @ FACTDM=1
6140 FACTVH=1 @ FACTFW=1 @ FACTCA=1
6150 AB=1 @ BB=1 @ CB=1 @ DB=1 @ EB=1 @ EEB=1 @ GGB=1
```

```
6160 ! COMPUTE THE NOMINAL ARC LENGTH
6170 XB=.5*(X6(I)+X6(I-1)) @ IF B2*B2>= (X0-XB)*(X0-XB) THEN YB=Y0-SQR (B2*B2-(
0-XB)*(X0-XB)) ELSE YB=YAL ! ^3/18/83
6180 XC=.5*(X6(I)+X6(I+1)) @ IF B2*B2>= (X0-XC)*(X0-XC) THEN YC=Y0-SQR (B2*B2-(
0-XC)*(X0-XC)) ELSE YC=YAR ! ^3/18/83
6190 XF=X6(I) @ YF=Y6(I)
6200 L9=FNHYP(XB.XF.YB.YF)+FNHYP(XF,XC,YF.YC)
6210 RX0=X0-X6(I)
6220 RY0=Y0-Y6(I)
6230 ! CHECK FOR FIRST ENTRY:  IENTRY=-1 ---> 1st ENTRY
6240 !                               = 1 ---> NON-1st ENTRY
6250 IF IENTRY=1 THEN GOTO 6320
6260 IENTRY=1
6270 !                        *** FIRST ENTRY ***
6280 ! CHECK FOR CASE 1-L AT I-1
6290 IF X6(I-1)<XAL AND X6(I-1)+L6/2>XAL AND X6(I)-L6/2>XAL AND X6(I)+L6/2<XAR
HEN 6420
6300 ! CHECK FOR CASE 2-L AT I
6310 IF X6(I)>= XAL AND X6(I)-L6/2<= XAL THEN 6960
6320 !                        *** NON-1st ENTRY ***
6330 ! CHECK FOR CASE 1-R  AT I+1
6340 IF X6(I+1)>XAR AND X6(I+1)-L6/2<XAR AND X6(I)-L6/2>XAL AND X6(I)+L6/2<XAR
HEN 6690
6350 ! CHECK FOR CASE 2-R AT I
6360 IF X6(I)<= XAR AND X6(I)+L6/2>= XAR THEN 7230
6370 ! CHECK TO SEE IF NOMINAL CASE OCCURS
6380 IF X6(I)-L6/2>XAL AND X6(I)+L6/2<XAR THEN RETURN
6390 PRINT "ERROR: NOT ANY OF THE KNOWN CASES";@ PRINT
6400 PRINT "I.X6(I-1).X6(I).X6(I+1).L6/2,XAL.XAR ARE:";I:X6(I-1):X6(I):X6(I+1):
6/2;XAL:XAR;@ PRINT
6410 RETURN
6420 !                  *** CASE 1-L ***
6430 XA=XAL @ YA=YAL
6440 ! PRINT "---------- CASE 1-L----------- :I.L6.X6(I),XAL=";I;L6;X6(I):XAL;@ F
INT
6450 XB=X6(I)-L6/2 @ YB=Y0-SQR (B2*B2-(X0-XB)*(X0-XB)) ! ^3/18/83
6460 XD=X6(I)+L6/2 @ YD=Y0-SQR (B2*B2-(X0-XD)*(X0-XD)) ! ^3/18/83
6470 XG=XB @ YG=.5*(Z(I-1)+Z(I))
6480 AB=FNHYP(XA.XB.YA.YB)
6490 ABG=FNDETR(XA.XB.XG.YA.YB.YG)
6500 AP=ABG/U1X
6510 RX1=X0-(X6(I)-L6/2-(XB-XA)/3)
6520 IF RX0#0 THEN BP=RX1/RX0 ELSE BP=0
6530 RY1=Y0-(YA+YB+YG)/3
6540 IF RY0#0 THEN CP=RY1/RY0 ELSE CP=0
6550 ! HS=H1-((YA+YB)/2-Y6(I))
6560 HS=H7+(H1-H7)/(X6(I)-XAL)*(XB-(XB-XA)/3-XAL) ! 04 MAR 03
6570 IF H1#0 THEN DP=HS/H1 ELSE DP=0
6580 EP=AB/L9
6590 RW1=X0-(X6(I)-L6/2-(XB-XA)/2)
6600 IF RX0#0 THEN FFP=RW1/RX0 ELSE FFP=0
6610 IF H(I)#0 THEN GGP=.5*(XB-XA)*(H7+.5*(H(I)+H(I-1)))/(H(I)*L6) ELSE GGP=0
6620 FACTF1=1+AP*CP
6630 FACTF2=1+DP*EP
6640 FACTCO=1+EP
6650 FACTDM=1+AP*BP
6660 FACTVH=1+FFP*GGP
6670 FACTFW=1+GGP @ FACTCA=1+AP
6680 RETURN
6690 !                  *** CASE 1-R ***
6700 XA=XAR @ YA=YAR
6710 ! PRINT "---------- CASE 1-R----------- :I.L6,X6(I),XAR=";I;L6:X6(I):XAR;@ F
INT
6720 XB=X6(I)+L6/2 @ YB=Y0-SQR (B2*B2-(X0-XB)*(X0-XB)) ! ^3/18/83
6730 XD=X6(I)-L6/2 @ YD=Y0-SQR (B2*B2-(X0-XD)*(X0-XD)) ! ^3/18/83
6740 XG=XB @ YG=.5*(Z(I+1)+Z(I))
```

```
6750 AB=FNHYP(XA.XB,YA.YB)
6760 ABG=FNDETR(XA,XG,XB,YA,YG,YB)
6770 AP=ABG/U1X
6780 RX1=XO-(X6(I)+L6/2-(XA-XB)/3)
6790 IF RXO#0 THEN BP=RX1/RXO ELSE BP=0
6800 RY1=YO-(YA+YB+YG)/3
6810 IF RYO#0 THEN CP=RY1/RYO ELSE CP=0
6820 ! HS=H1-((YA+YB)/2-Y6(I))
6830 HS=H1+(H8-H1)/(XAR-X6(I))*(XB+(XA-XB)/3-X6(I)) ! 04 MAR 03
6840 IF H1#0 THEN DP=HS/H1 ELSE DP=0
6850 EP=AB/L9
6860 RW1=XO-(X6(I)+L6/2-(XA-XB)/2)
6870 IF RXO#0 THEN FFP=RW1/RXO ELSE FFP=0
6880 IF H(I)#0 THEN GGP=.5*(XA-XB)*(H8+.5*(H(I)+H(I+1)))/(H(I)*L6) ELSE GGP=0
6890 FACTF1=1+AP*CP
6900 FACTF2=1+DP*EP
6910 FACTCO=1+EP
6920 FACTDM=1+AP*BP
6930 FACTVH=1+FFP*GGP
6940 FACTFW=1+GGP @ FACTCA=1+AP
6950 RETURN
6960 !                    *** CASE 2-L ***
6970 XA=XAL @ YA=YAL
6980 ! PRINT "---------- CASE 2-L---------- :I.L6,X6(I).XAL=";I;L6;X6(I):XAL:@ F
INT
6990 XB=X6(I) @ YB=Y6(I)
7000 XC=XB+L6/2 @ YC=YO-SQR (B2*B2-(XO-XC)*(XO-XC)) ! ^3/18/83
7010 XD=XC @ YD=.5*(Z(I+1)+Z(I))
7020 ABCDE=FNDETR(XA,XB,XD.YA,YB,YD)+FNDETR(XD,XB,XC,YD,YB,YC)
7030 AP=ABCDE/U1X
7040 RX1=XO-(X6(I)+L6/2-(XD-XA)/3)
7050 IF RXO#0 THEN BP=RX1/RXO ELSE BP=0
7060 RY1=YO-(YA+YD+YC)/3
7070 IF RYO#0 THEN CP=RY1/RYO ELSE CP=0
7080 ! HS=H1-((YA+YC)/2-Y6(I))
7090 HS=H7+(H1-H7)/(X6(I)-XAL)*(XC-(XD-XA)/3-XAL) ! 04 MAR 03
7100 IF H1#0 THEN DP=HS/H1 ELSE DP=0
7110 AB=FNHYP(XA,XB,YA,YB)
7120 BC=FNHYP(XB,XC,YB,YC) @ EP=(AB+BC)/L9
7130 RW1=XO-(XD+XA)/2
7140 IF RXO#0 THEN FFP=RW1/RXO ELSE FFP=0
7150 IF H(I)#0 THEN GGP=.5*(XD-XA)*(H7+.5*(H(I)+H(I+1)))/(H(I)*L6) ELSE GGP=0
7160 FACTF1=AP*CP
7170 FACTF2=DP*EP
7180 FACTCO=EP
7190 FACTDM=AP*BP
7200 FACTVH=FFP*GGP
7210 FACTFW=GGP @ FACTCA=AP
7220 RETURN
7230 !                    *** CASE 2-R ***
7240 XA=XAR @ YA=YAR
7250 ! PRINT "---------- CASE 2-R---------- :I.L6.X6(I),XAR=";I;L6;X6(I):XAR:@ F
INT
7260 XB=X6(I) @ YB=Y6(I)
7270 XC=XB-L6/2 @ YC=YO-SQR (B2*B2-(XO-XC)*(XO-XC)) ! ^3/18/83
7280 XD=XC @ YD=.5*(Z(I-1)+Z(I))
7290 ABCDE=FNDETR(XA.XD,XB,YA,YD,YB)+FNDETR(XD,XC.XB,YD,YC,YB)
7300 AP=ABCDE/U1X
7310 RX1=XO-(X6(I)-L6/2-(XA-XD)/3)
7320 IF RXO#0 THEN BP=RX1/RXO ELSE BP=0
7330 RY1=YO-(YA+YD+YC)/3
7340 IF RYO#0 THEN CP=RY1/RYO ELSE CP=0
7350 ! HS=H1-((YA+YC)/2-Y6(I))
7360 HS=H1+(H8-H1)/(XAR-X6(I))*(XC+(XA-XD)/3-X6(I)) ! 04 MAR 03
7370 IF H1#0 THEN DP=HS/H1 ELSE DP=0
7380 AB=FNHYP(XA,XB,YA,YB)
```

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7390 BC=FNHYP(XB,XC,YB,YC) @ EP=(AB+BC)/L9
7400 RW1=XO-(XD+XA)/2
7410 IF RXO#0 THEN FFP=RW1/RXO ELSE FFP=0
7420 IF H(I)#0 THEN GGP=.5*(XA-XD)*(H8+.5*(H(I)+H(I-1)))/(H(I)*L6) ELSE GGP=0
7430 FACTF1=AP*CP
7440 FACTF2=DP*EP
7450 FACTCO=EP
7460 FACTDM=AP*BP
7470 FACTVH=FFP*GGP
7480 FACTFW=GGP @ FACTCA=AP
7490 RETURN
7500 ! INPUT GROUND ACCELERATION. g UNITS.
7510 CLEAR
7520 DISP " INPUT HORIZONTAL ACCELERATION IN g UNITS";
7530 INPUT ACCEL
7540 Z5$="OK ACCEL"
7550 GOTO 210
```