PROBABILISTIC SEISMIC STABILITY

ANALYSIS - A CASE STUDY

by

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The present study provides an application of a probabilistic seismic stability analysis to a natural slope located near Slingerlands, New York. A detailed description of the model used can be found in a previous report of this series. The safety of the slope is measured in terms of its probability of failure rather than the customary factor of safety. Three types of earthquake sources are investigated, namely, a point, a line and an area source, and the dependence on significant seismic parameters of the probability of failure of the slope is examined. On the basis of the results obtained in this study, it is concluded that the present model is useful in assessing the reliability of soil slopes under both static and seismic conditions and the probability of failure of a soil slope is greatly affected by the type of the earthquake source involved and by the values of seismic parameters that are associated with it.

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ABSTRACT

The present study provides an application of a probabilistic seismic stability analysis to a natural slope located near Slingerlands, New York. A detailed description of the model used can be found in a previous report of this series [2]. The safety of the slope is measured in terms of its probability of failure rather than the customary factor of safety.

Three types of earthquake sources are investigated, namely, a point, a line and an area source, and the dependence on significant seismic parameters of the probability of failure of the slope is examined.

On the basis of the results obtained in this study, it is concluded that (a) the present model is useful in assessing the reliability of soil slopes under both static and seismic conditions, and (b) the probability of failure of a soil slope is greatly affected by the type of the earthquake source involved and by the values of seismic parameters that are associated with it.

1. INTRODUCTION

The possibility of an earthquake is an important design factor in New York State. Nuclear power plants, dams and other important structures have to be designed to successfully withstand ground shaking which, in some regions of the State, is of the highest intensity. Seismic activity near the New York Metropolitan area has been concentrated along several fault systems of which Ramapo is the most active. It has been estimated [1] that the probability with which the nearby Indian Point nuclear power plants will experience, during their 40 year lifetime, an intensity equal to or greater than the design earthquake is 5-11%. Other areas of the State, like the Attica-Buffalo and St. Lawrence regions, have also been subjected to a seismic activity of high frequency and intensity, and moreover, the entire State has been affected, at some point in its relatively long history, by a large earthquake [7].

A seismic risk analysis for the State of New York was performed and the obtained results were presented in the third report of this series [4]. A total of 1242 seismic events with a range of magnitude between 2.0 and 7.0 have affected New York in the period between 1562 and 1975. A regression analysis on the collected seismic data provided a log-quadratic relationship between the frequency and magnitude of earthquakes. Finally, as the present case study involves the stability analysis of a slope located in the seismic environment of New York, local conditions are introduced with a number of parameters receiving values that are pertinent to this part of the country.

2. CASE STUDY

2.1 Geologic Description of the Site

The location of the site of the examined slope, reported in the literature to have failed [6], is shown in Figure 1. A large portion of the surrounding area consists of sloping ground, and a number of landslides have occurred at various times causing several deaths and extensive property damage. A detailed geologic history of the area has been performed by Woodward-Clyde Consultants [10] in connection with the construction of a nearby Blue Cross Building for the town of Bethlehem (also shown in Figure 1). A brief geologic description of the site follows.

The slope is located in the Hudson-Champlain Lowland physiographic province of New York State. The bedrock underlying the site belongs to the Snake Hill Formation of the Upper Middle Ordovician age and consists of strongly folded beds of shale and sandstone. Its elevation is estimated to be almost zero. Overlying the bedrock is a 20 ft. thick layer of sand and gravel, an outwash deposit from the meltwater streams of the retreating glacial ice sheet. Overlying this layer is a 100-200 ft. thick deposit of fine-grained silt and clay, a material known as "Albany Clay". The deposition of the Albany Clay is believed to be related to the formation of a large lake (or, a number of lakes) called the Albany Lake, which occupied an approximately 3,000 square mile area amidst the Hudson-Mohawk-Champlain Valleys. During the later age of the Albany Lake, sand dunes with an average height of 35-40 ft. were formed mainly through stream and wind erosion of the surrounding land. In Figure 2, is shown a glacial geologic picture of the area.

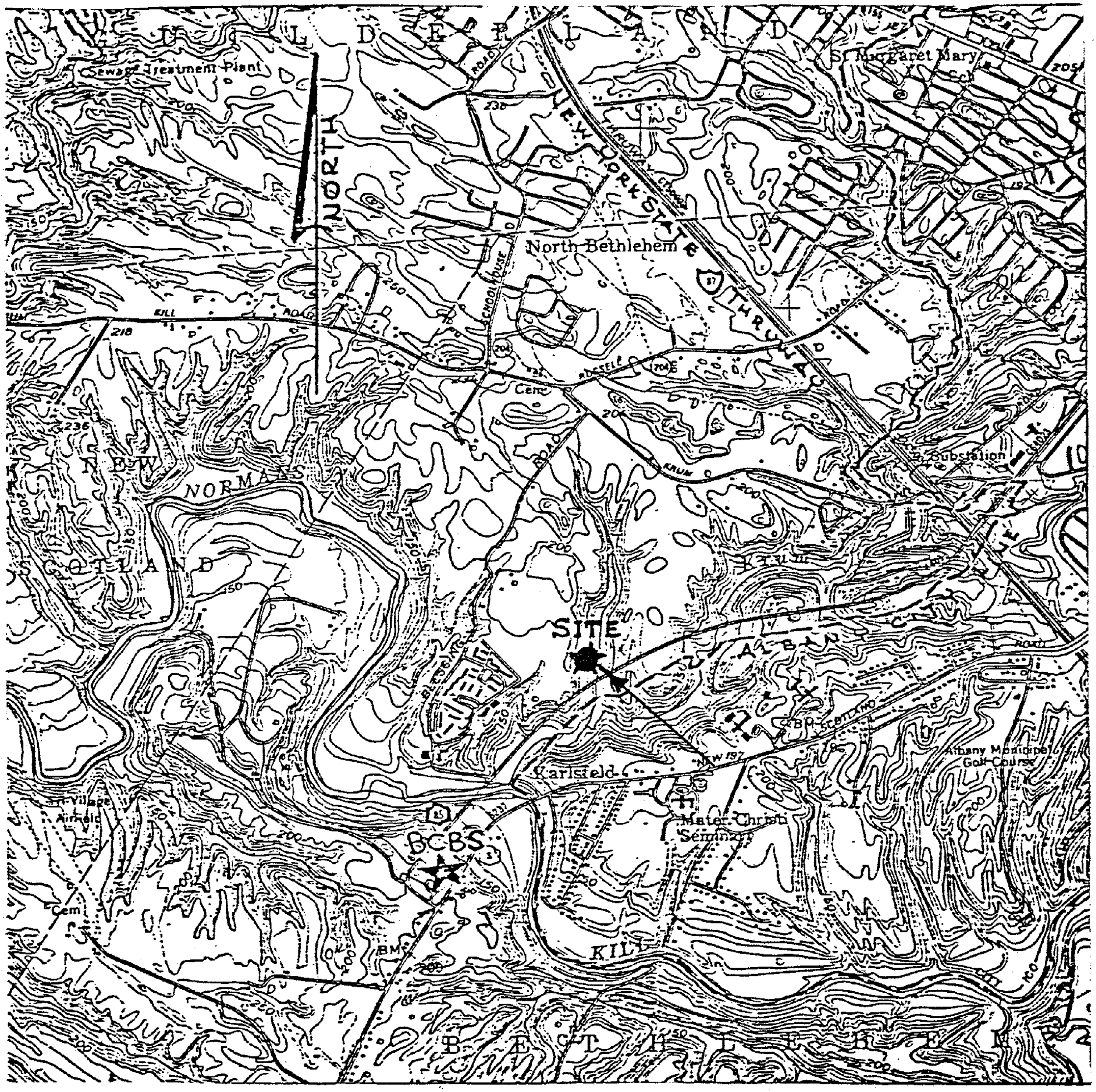


FIGURE 1. MAP INDICATING THE LOCATION OF THE SITE OF THE SLOPE IN SLINGERLANDS (NEAR ALBANY), NEW YORK

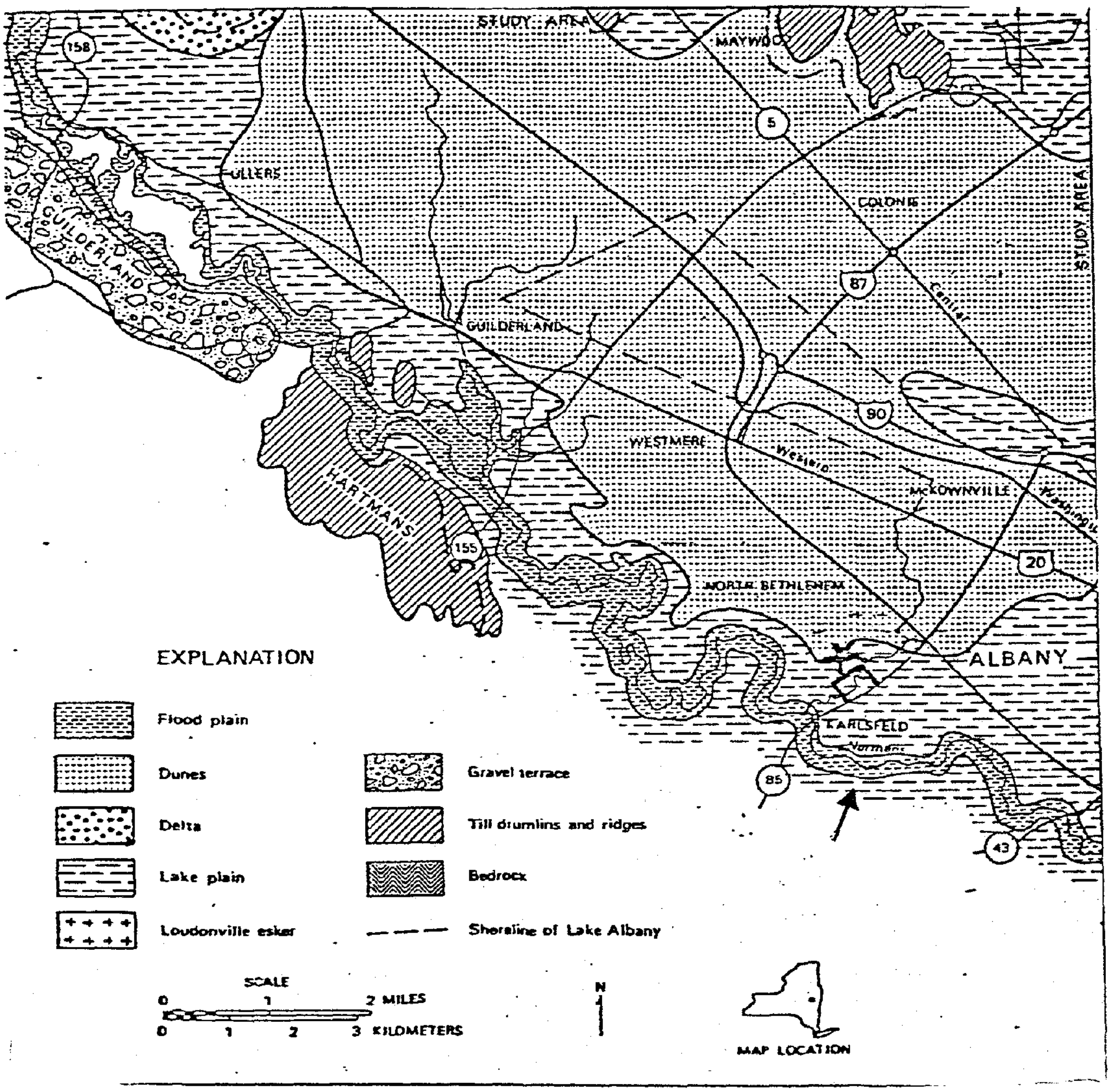


FIGURE 2. GEOLOGICAL MAP OF THE REGION SURROUNDING THE SITE OF THE SLOPE

2.2 Slope Profile and Material Parameters

The actual slope profile consists of three layers. The top layer involves a clay fill waste material that was dumped at the site from a nearby road construction and is essentially a mixture of the two underlying materials. The original top layer, of about 7-10 ft. thickness, is a rather sensitive brown clay. The bottom layer consists of varved clay and silt. For the purposes of this analysis, the slope is represented by an idealized slope profile shown schematically in Figure 3. The height h of the slope is 40.5 ft. (h = 40.5 ft) and its angle β is 15.52° (β = 15.52°). The moist unit weight γ_m of the material is 110 pcf (γ_m = 110 pcf), the saturated unit weight is 125 pcf (γ_s = 125 pcf) and the pore pressure parameter r_u is estimated to be 0.32 (r_u = 0.32).

A series of laboratory tests (mainly unconsolidated and consolidated undrained traixial tests) were performed in order to determine the soil strength parameters [6]. In Table 1 is given a summary of the statistical values of the parameters used in the case study.

FIGURE 3. GEOMETRY OF THE SLOPE USED IN CASE STUDY

TABLE 1. STATISTICAL VALUES OF PARAMETERS USED IN CASE STUDY

STATISTICAL VALUE	PARAMETER			
	STRENGTH		GEOMETRIC	
	c [psf]	t (= tan ϕ)	h_o [ft]	θ_o [deg.]
Minimum	0	0.39 (19°)	0.00	14.48
Mean	350	0.49 (26.3°)	60.75	44.48
Maximum	950	0.87 (41°)	121.50	74.48
Coef. of Var.	0.3	0.2	0.35	0.35

2.3 Stability Analysis of Slope under Static Conditions

(a) Conventional Analysis

A thorough stability analysis has been performed for the slope under investigation and the results are presented in [6]. Four limiting equilibrium stability analysis methods were used, namely, (a) ordinary method of slices, (b) Bishop's Modified method, (c) Spencer's method, and (d) Huang's stability charts. For the conditions used in this study, the values of the conventional factor of safety FS that correspond to each method are as follows:

NO.	Method of Analysis	Factor of Safety
1	Ordinary Method of Slices	1.55
2	Bishop's Modified Method	1.63
3	Spencer's Method	1.48
4	Huang's Method	1.52

(b) Probabilistic Analysis

The computer program RASSUEL was used to determine the probability of failure of the slope under static conditions [3]. One thousand iterations were specified in the Monte Carlo simulation of failure and it was found that the probability of failure was equal to 0.147; or,

$$p_f = 0.147 \simeq 0.15 \quad (1)$$

In Figure 4 are shown corresponding values between p_f and FS that have been obtained in a series of case studies involving conventional and probabilistic stability analyses under static conditions [5]. In the same figure are also shown the points (p_f, FS) obtained in the present study.

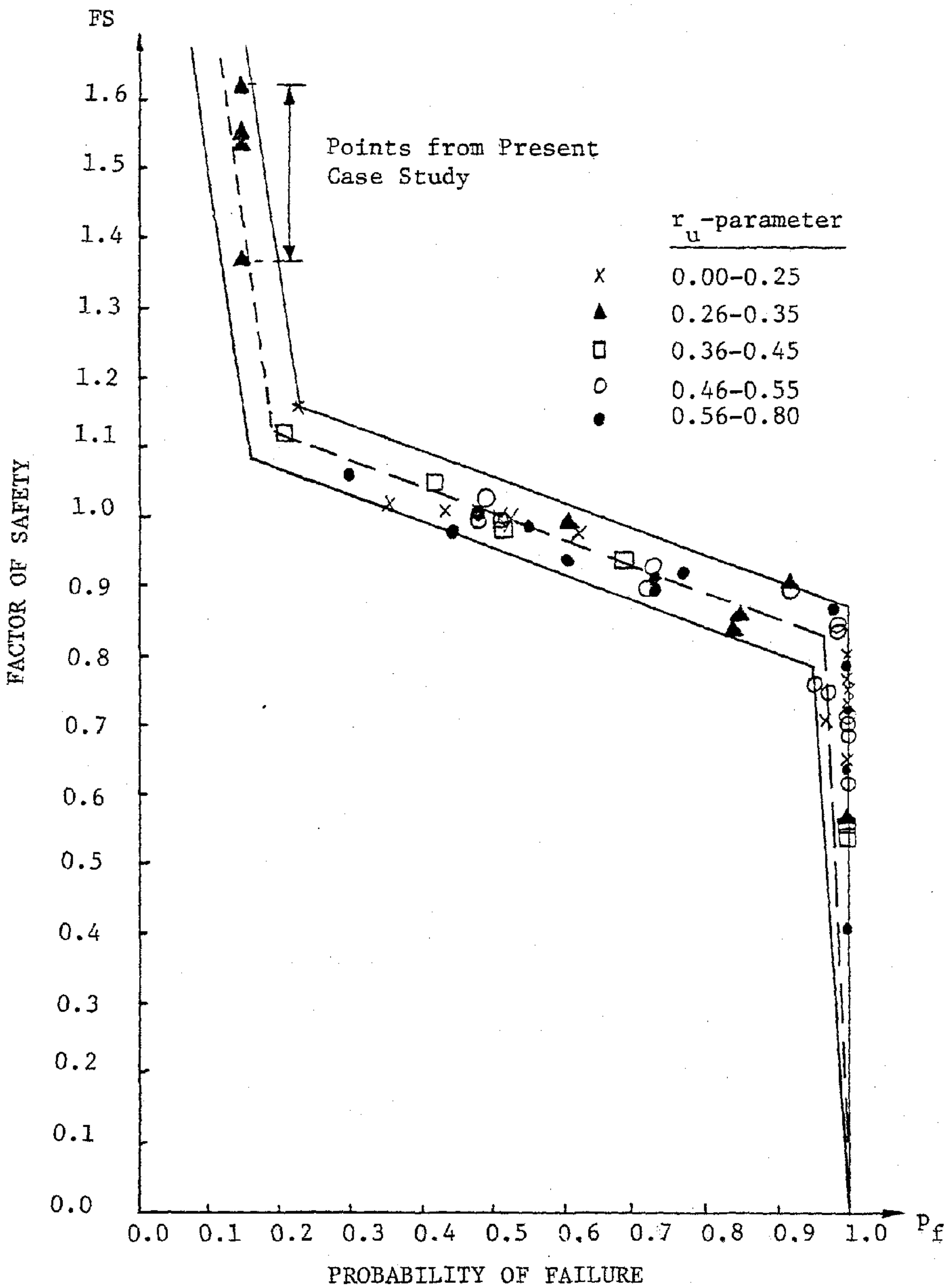


FIGURE 4. RELATIONSHIP BETWEEN p_f AND FS (After [5]).

2.4 Seismic Load at the Site of the Slope

A regression analysis performed on available seismic data for New York State provided the following relationship between earthquake frequency and magnitude [4]:

$$\ell n\ n_m = 1.6 + 0.203\ m - 0.132\ m^2, \qquad 2.0 < m < 7.0 \qquad (2)$$

where m = earthquake magnitude, and

n_m = annual number of earthquakes exceeding magnitude m.

Equation (2) was found using records of 1242 seismic events that affected New York State in the time period between 1568 and 1975.

The average number of earthquakes per year with a magnitude larger than the assumed lower limit $m_o = 2.0$ is found from Equation (2) to be equal to

$$n_{m_o} = \exp[1.6 + (0.203)(2.0) - (0.182)(2.0)^2]$$

or

$$n_{m_o} = 3.59$$

The probability with which an earthquake can occur with magnitude greater than m is given as the ratio of n_m over n_{m_o} [2]; i.e.,

$$P[M > m] = \frac{n_m}{n_{m_o}}$$

Introducing into the above expression the value of n_m obtained from Equation (2) and substituting 3.59 for n_m, it is found that

$$P[M > m] = 0.279 \exp(1.6 + 0.203\ m - 0.182\ m^2),\ 2.0 \lesssim m \lesssim 7.0 \qquad (3)$$

The cumulative distribution F(m) of magnitude m is equal to

$$F(m) = P[M \lesssim m] = 1 - P[M > m]$$

Introducing Equation (3) into the above expression, one has

$$F(m) = 1 - 0.279 \exp(1.6 + 0.203\ m - 0.182\ m^2),\ 2.0 \lesssim m \lesssim 7.0 \qquad (4)$$

For F(m) to be a cumulative distribution, it has to be multiplied by a constant k, so that when F(m) is evaluated at the upper bound of m (m_1 = 7.0) it becomes equal to unity; i.e.,

$$F(m_1) = k[1 - 0.279 \exp(1.6 + 2.03\, m_1 - 0.182\ m_1^2)] = 1$$

from which, after substituting for m_1 = 7.0, it is found that

$$k = 0.99923 \simeq 1.0$$

Therefore, one has that Equation (4) is a very good approximation of the cumulative distribution of m.

The probability density function of the earthquake magnitude can be determined from Equation (4) by taking the derivative of F(m) with respect to m. Thus,

$$f(m) = -\ 0.057 + 0.102\ m \exp(1.6 + 0.203\ m - 0.182\ m^2),\ 2.0 \lesssim m \lesssim 7.0 \qquad (5)$$

In Figure 5 are shown the frequency and cumulative distributions of the magnitude m, given by Equations (4) and (5), respectively.

The maximum horizontal ground acceleration at the site of the slope is determined with the aid of two attenuation relationships that have been previously proposed for this region [2]. These are the following:

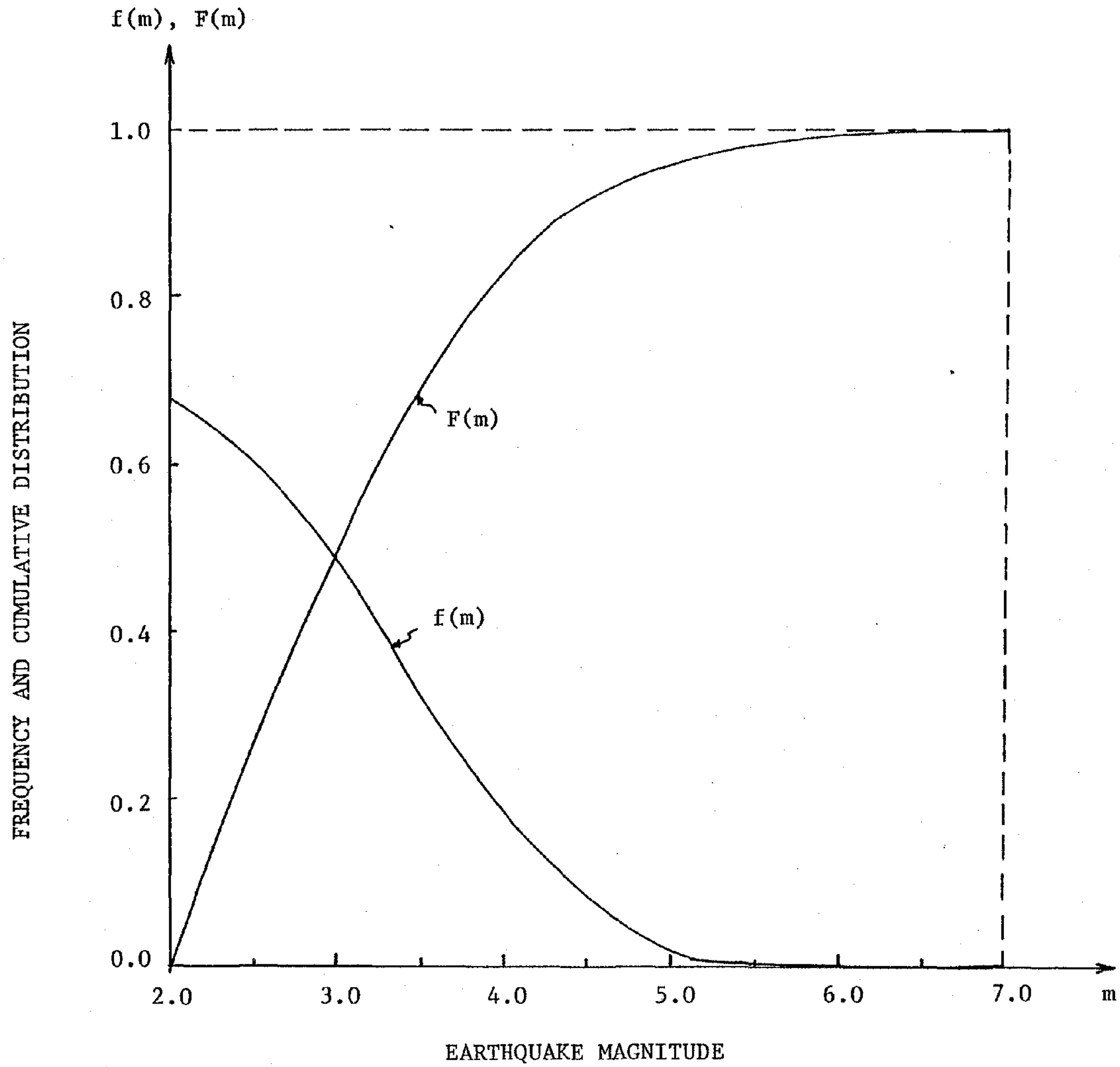


FIGURE 5. FREQUENCY AND CUMULATIVE DISTRIBUTION OF THE EARTHQUAKE MAGNITUDE FOR THE STATE OF NEW YORK

$$a_{max} = 1100\ e^{0.5m}\ (R + 25)^{-1.32} \qquad \text{(Case 1)} \qquad (6a)$$

$$a_{max} = 1.183\ e^{1.15m}\ R^{-1.0} \qquad \text{(Case 2)} \qquad (6b)$$

where m is the earthquake magnitude and R is the distance between earthquake source and site of slope.

When the log-normally distributed "error term" ε [2] is included in the attenuation relationships, the latter become

$$a_{max} = 1100\ e^{0.5m}\ (R + 25)^{-1.32}\ \varepsilon \qquad \text{(Case 1)} \qquad (7a)$$

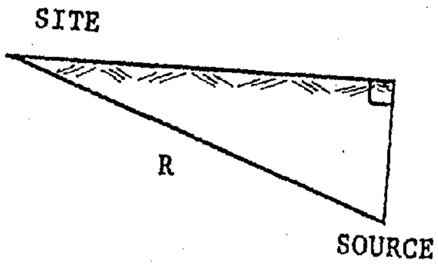
$$a_{max} = 1.183\ e^{0.5m}\ R^{-1.0}\ \varepsilon \qquad \text{(Case 2)} \qquad (7b)$$

2.5 Probabilistic Seismic Stability Analysis

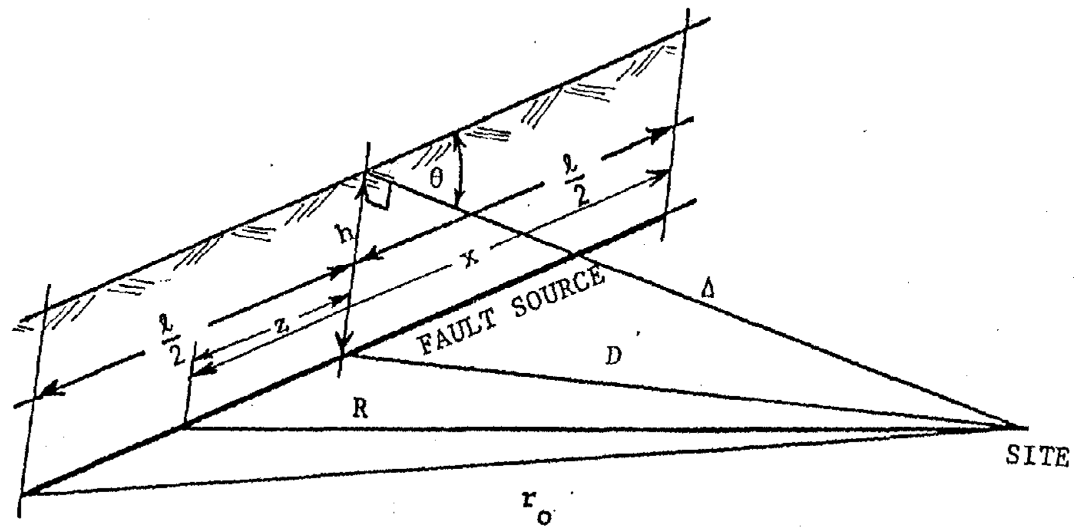
Using computer program RASSUEL, a probabilistic, pseudo-static seismic stability analysis is conducted for the slope shown schematically in Figure 3. The regional parameters that are necessary for the description of the seismic load [2] are selected from among those applicable to the Northeastern United States and, in particular, to New York State. Three types of earthquake source, shown schematically in Figure 6, are considered; namely, (a) a point source, (b) a line source, and (c) an area source. As it was reported in [4], the earthquake magnitude (m) for the State of New York varies between 2.0 and 7.0 ($2.0 \leq m \leq 7.0$). The log-quadratic frequency-magnitude relationship, given by Equation (2), is used herein. Also, the attenuation relationships, given by Equations (6), are employed to yield the values of the maximum acceleration as a function of the earthquake magnitude, the distance between the site of the slope and the earthquake source and a number of regional parameters. Finally, using Equations (7), the effect of the "error term (ε)" on the probability of failure p_f is examined for each type of earthquake source.

(a) Point Source

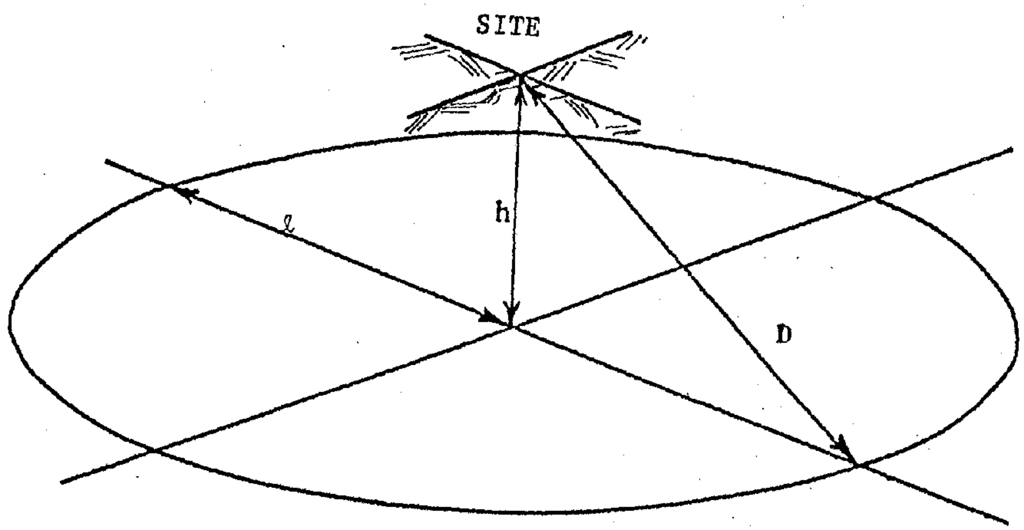
In the case of a point source, the probability of failure p_f of the soil slope was obtained as a function of the distance R between the source and the site of the slope. In Figure 7 is shown the variation of p_f with R and in Figure 8 is shown the same relationship but for the case where an error term ε is used in the attenuation relationship. Here, it is assumed that the median of ε is equal to unity, while two values are examined for its standard deviation σ_ε, namely, (a) $\sigma_\varepsilon = 0.5$, and (b) $\sigma_\varepsilon = 1.0$.



(a) Point Source (cross-section)



(b) Line Source (perspective)



(c) Area Source (perspective)

FIGURE 6. SCHEMATIC REPRESENTATION OF THE THREE EARTHQUAKE SOURCES

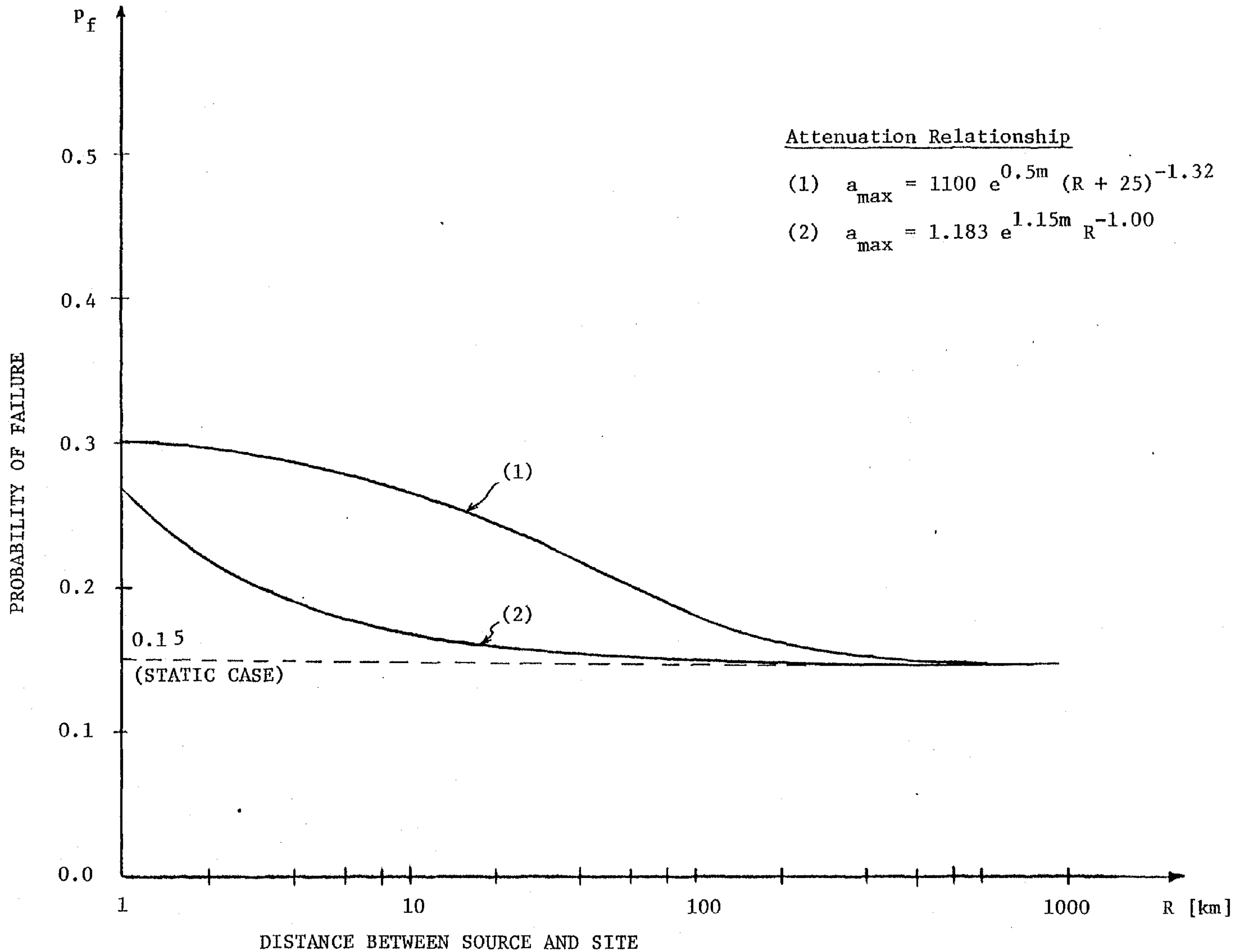


FIGURE 7. PROBABILITY OF FAILURE VS. DISTANCE FROM POINT SOURCE

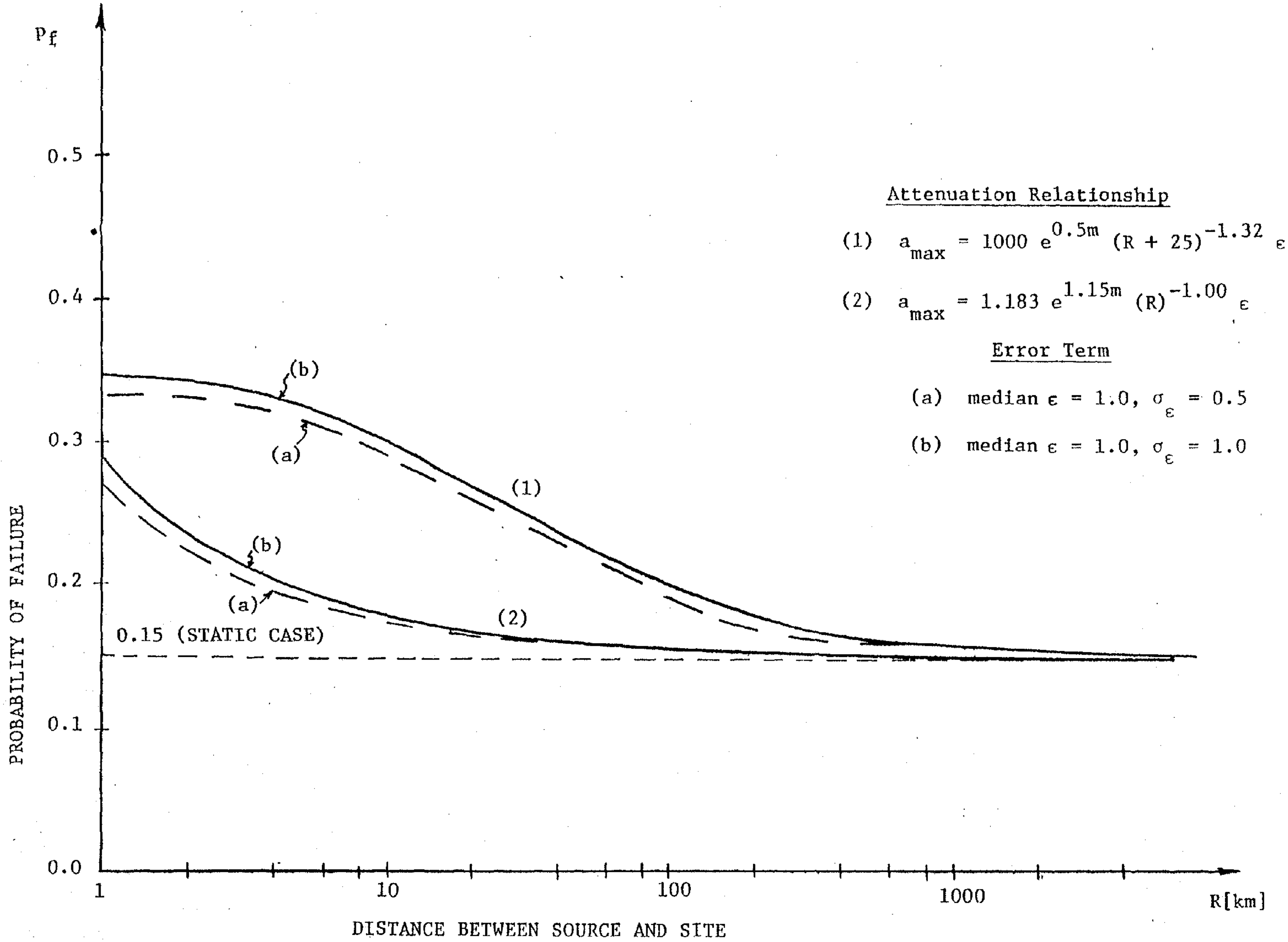


FIGURE 8. PROBABILITY OF FAILURE VS. DISTANCE FROM POINT SOURCE (WITH ERROR TERM)

(b) Line (or, Fault) Source

In the case of the line source, the probability of failure, p_f of the slope is found as a function of the distance D between the center of the fault and the slope's site. Two different orientations of the fault relative to the site were considered (Figure 6b); one, for $\theta = 45°$ and, another, for $\theta = 90°$. In addition, two values for the length (ℓ) of the fault were investigated, namely: $\ell = 100$ km and $\ell = 250$ km.

In Figures 9 and 10 are shown the relationship between p_f and D for the case where the angle of orientation θ is equal to 45° and 90°, respectively. The same relationships are also shown in Figures 11 and 12, but for the case where an "error term" is used in the two attenuation relationships. Figure 11 corresponds to Equation (7a) and Figure 12 to Equation (7b). Both figures were obtained for an orientation between fault and slope equal to 45° ($\theta = 45°$). Finally, Figures 13 and 14 are the equivalent of Figures 11 and 12 but for the case where $\theta = 90°$.

(c) Area Source

In the case of the area source, the probability of failure p_f of the slope was found as a function of the radius R of the source. Two different depths for the area source were considered: (a) zero depth, and (b) a depth equal to 20 km.

In Figure 15 is shown the variation of the probability of failure p_f with the radius R of the area source for the two values of the depth examined. In Figures 16 and 17 is shown the same relationship for the case where an "error term" is considered in the attenuation relationships. Figure 16 corresponds to the first attenuation relationship (Case 1) and Figure 17 to the second (Case 2).

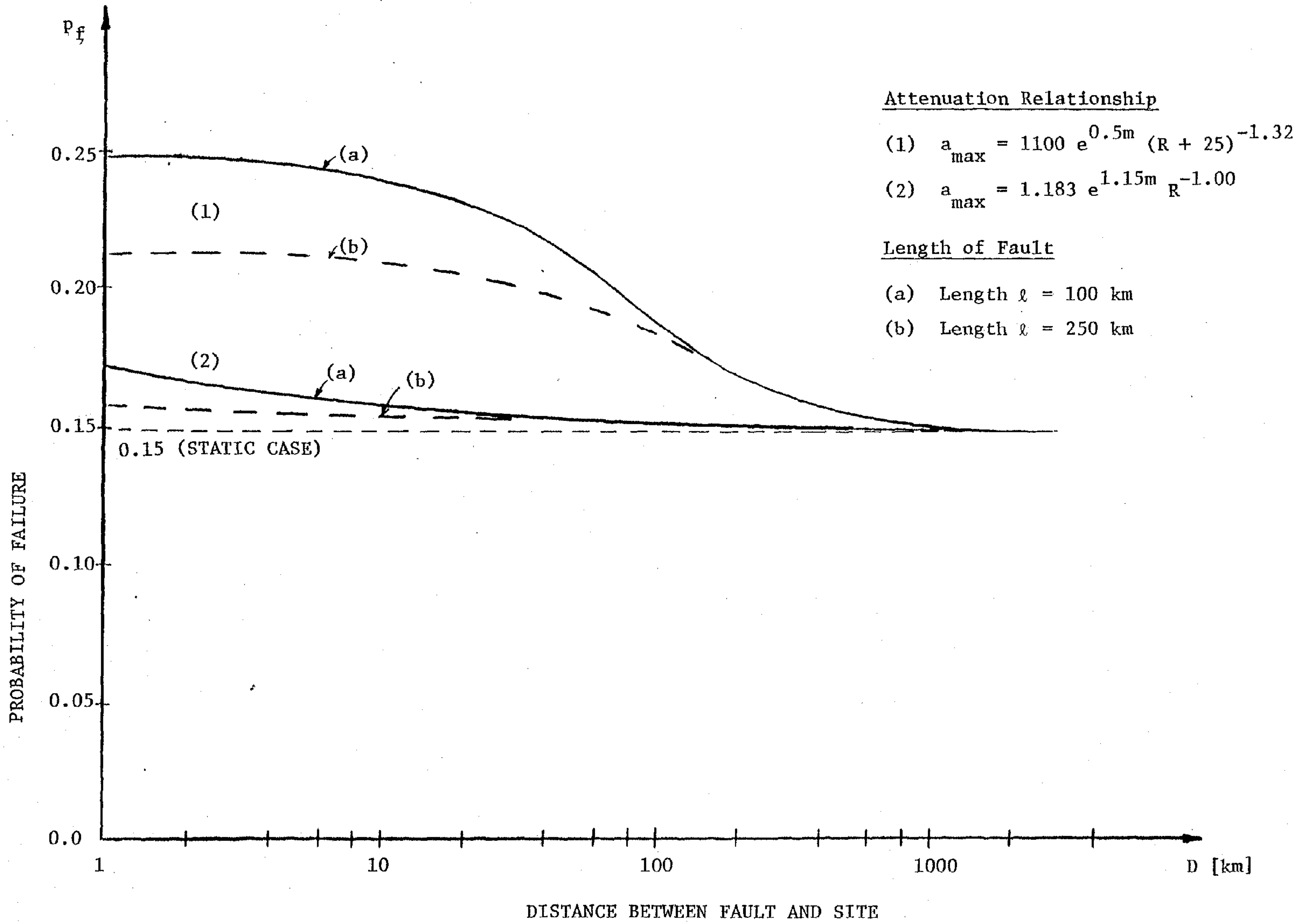


FIGURE 9. PROBABILITY OF FAILURE VS. DISTANCE BETWEEN FAULT AND SLOPE (θ = 45°)

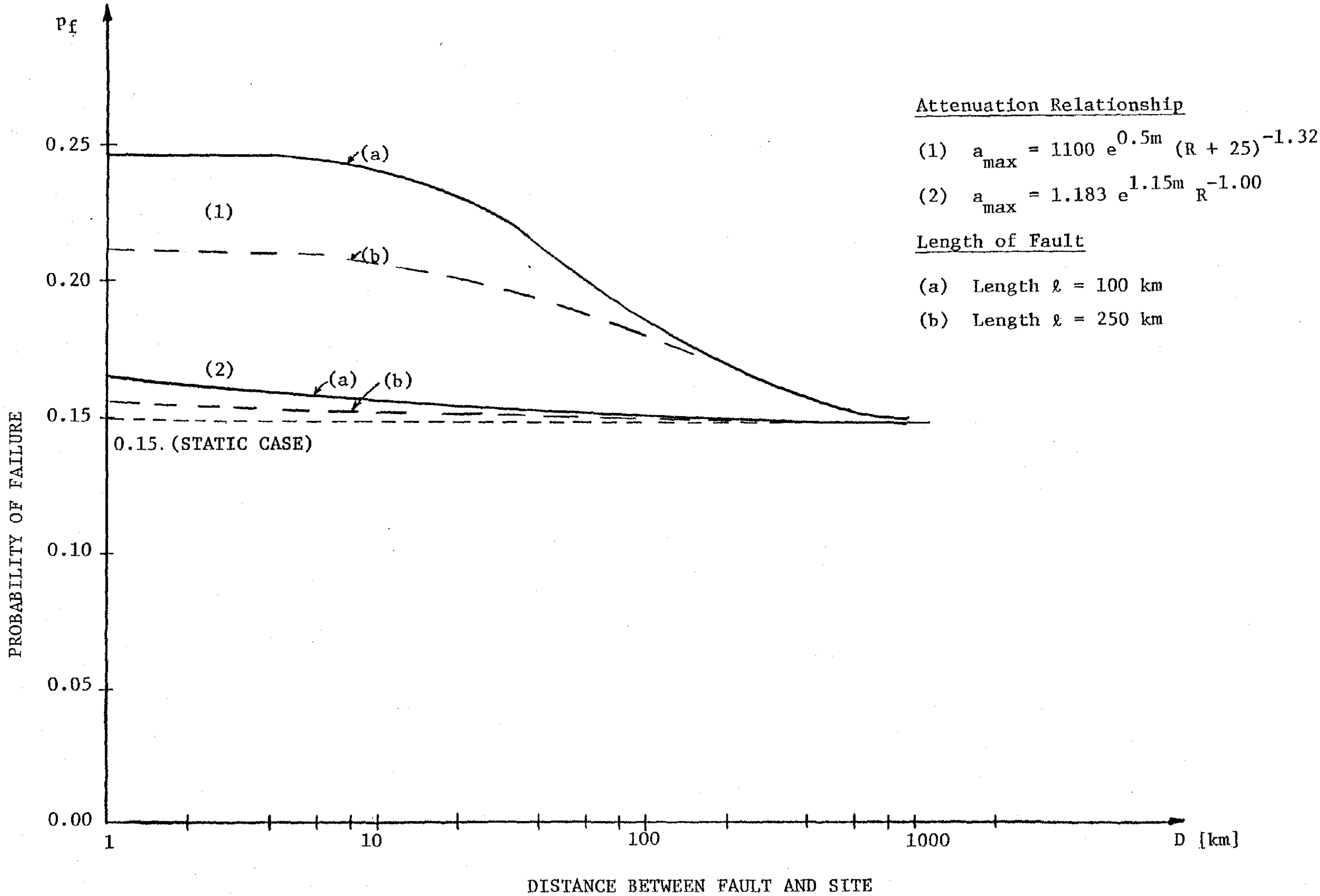


FIGURE 10. PROBABILITY OF FAILURE VS. DISTANCE BETWEEN FAULT AND SLOPE ($\theta = 90°$)

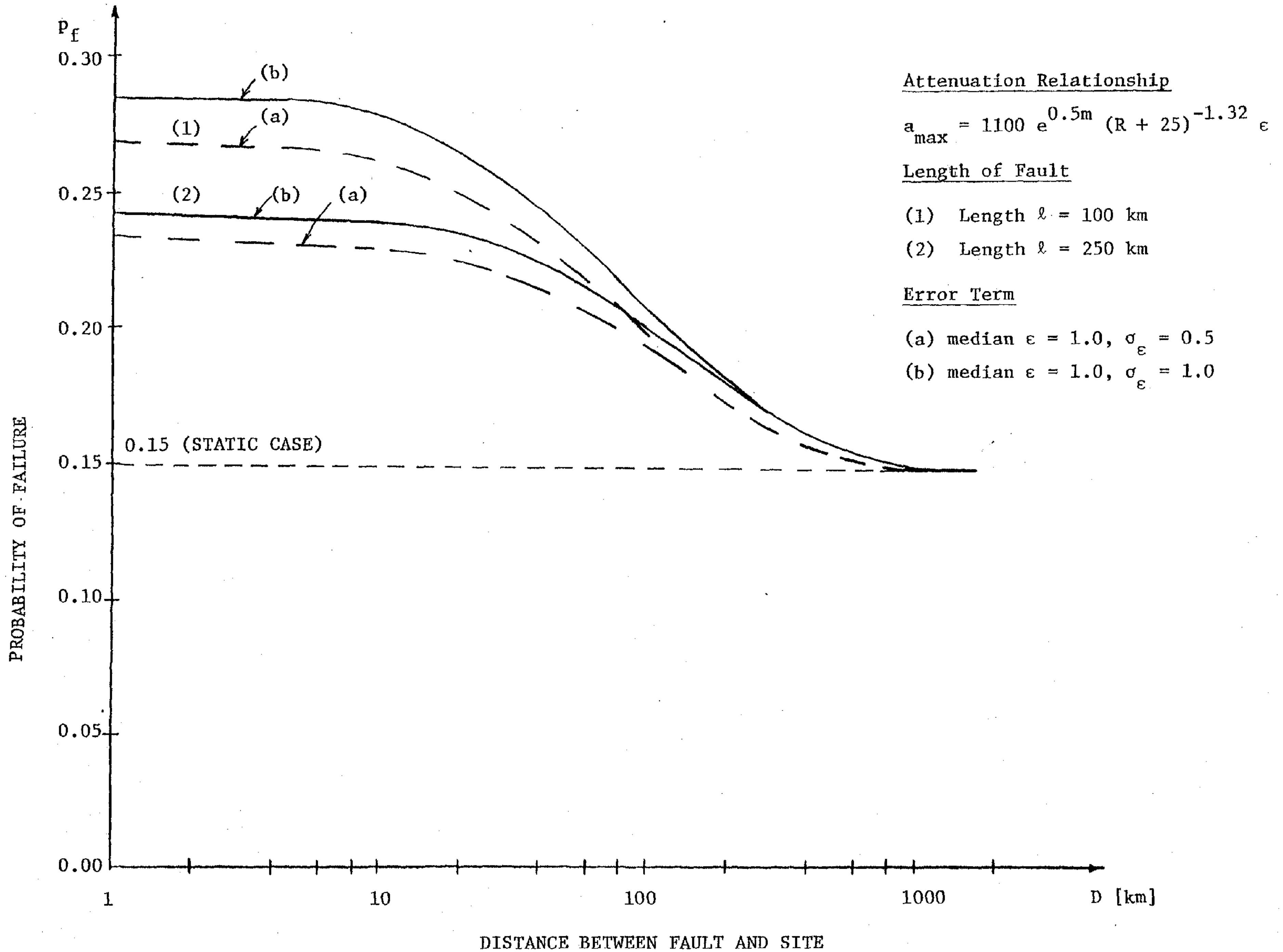


FIGURE 11. PROBABILITY OF FAILURE VS. DISTANCE BETWEEN FAULT AND SLOPE (θ = 45° - WITH ERROR TERM - CASE 1)

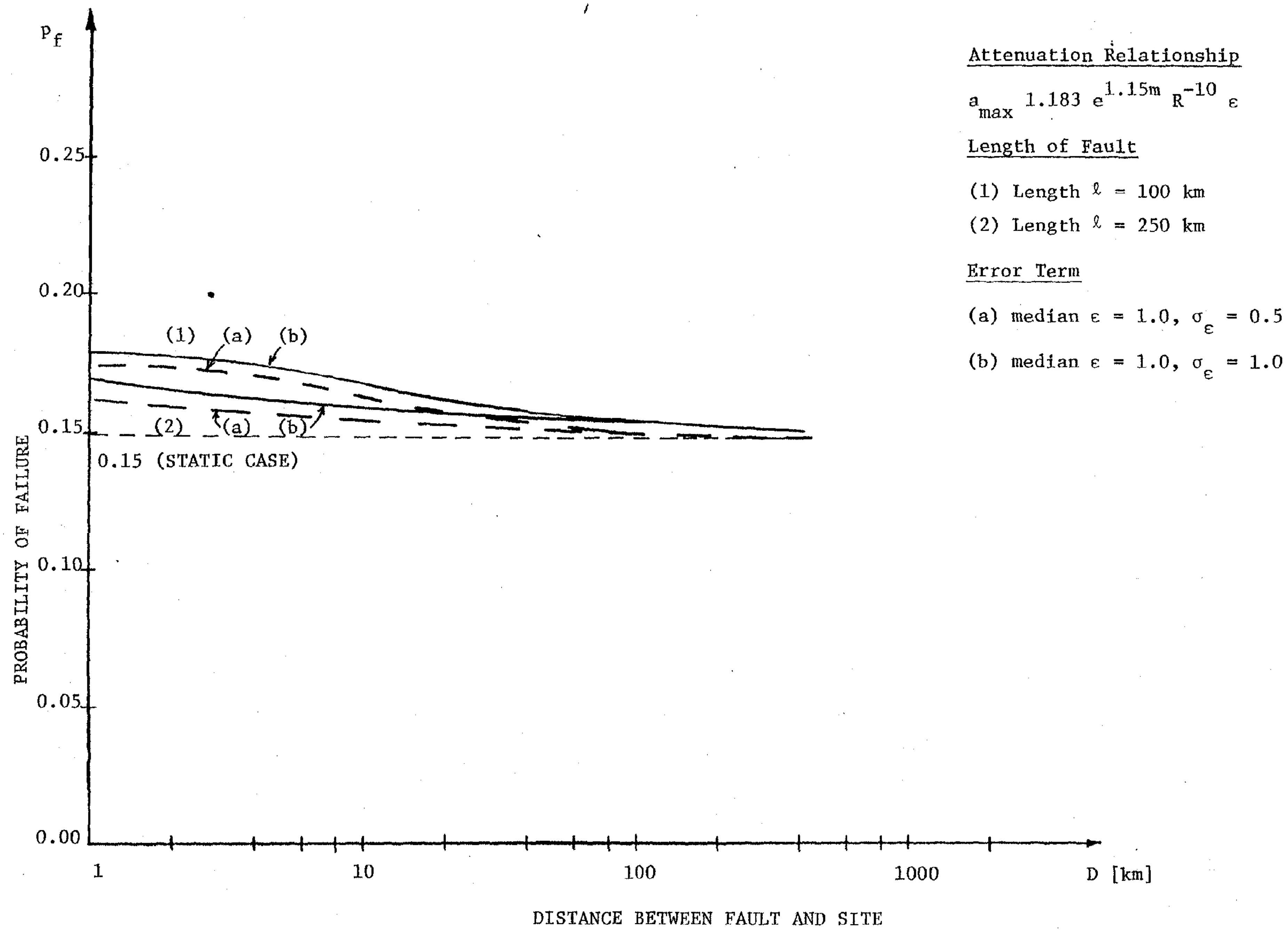


FIGURE 12. PROBABILITY OF FAILURE VS. DISTANCE BETWEEN FAULT AND SLOPE
(θ = 45° - WITH ERROR TERM - CASE 2)

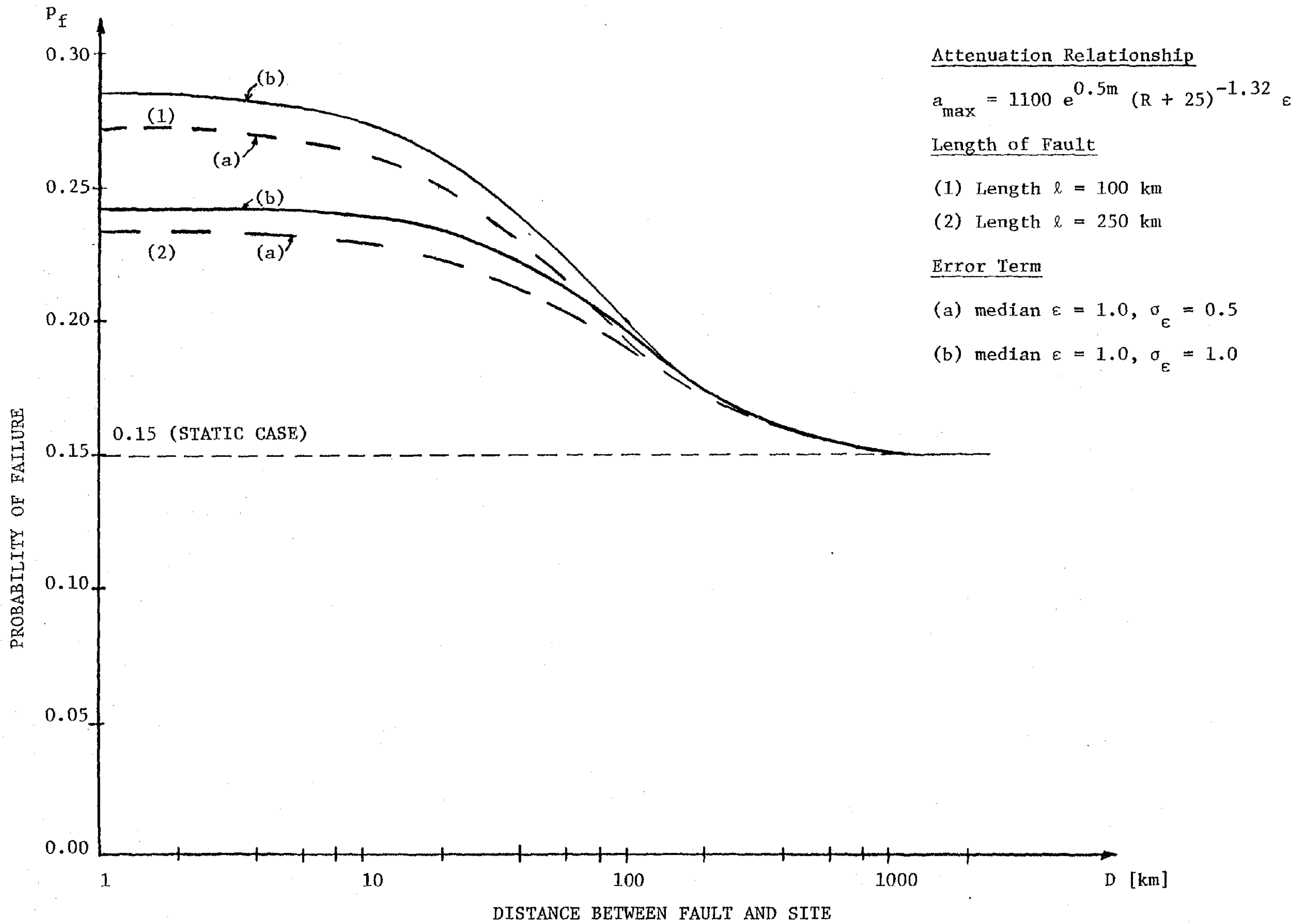


FIGURE 13. PROBABILITY OF FAILURE VS. DISTANCE BETWEEN FAULT AND SLOPE ($\theta = 90°$ – WITH ERROR TERM – CASE 1)

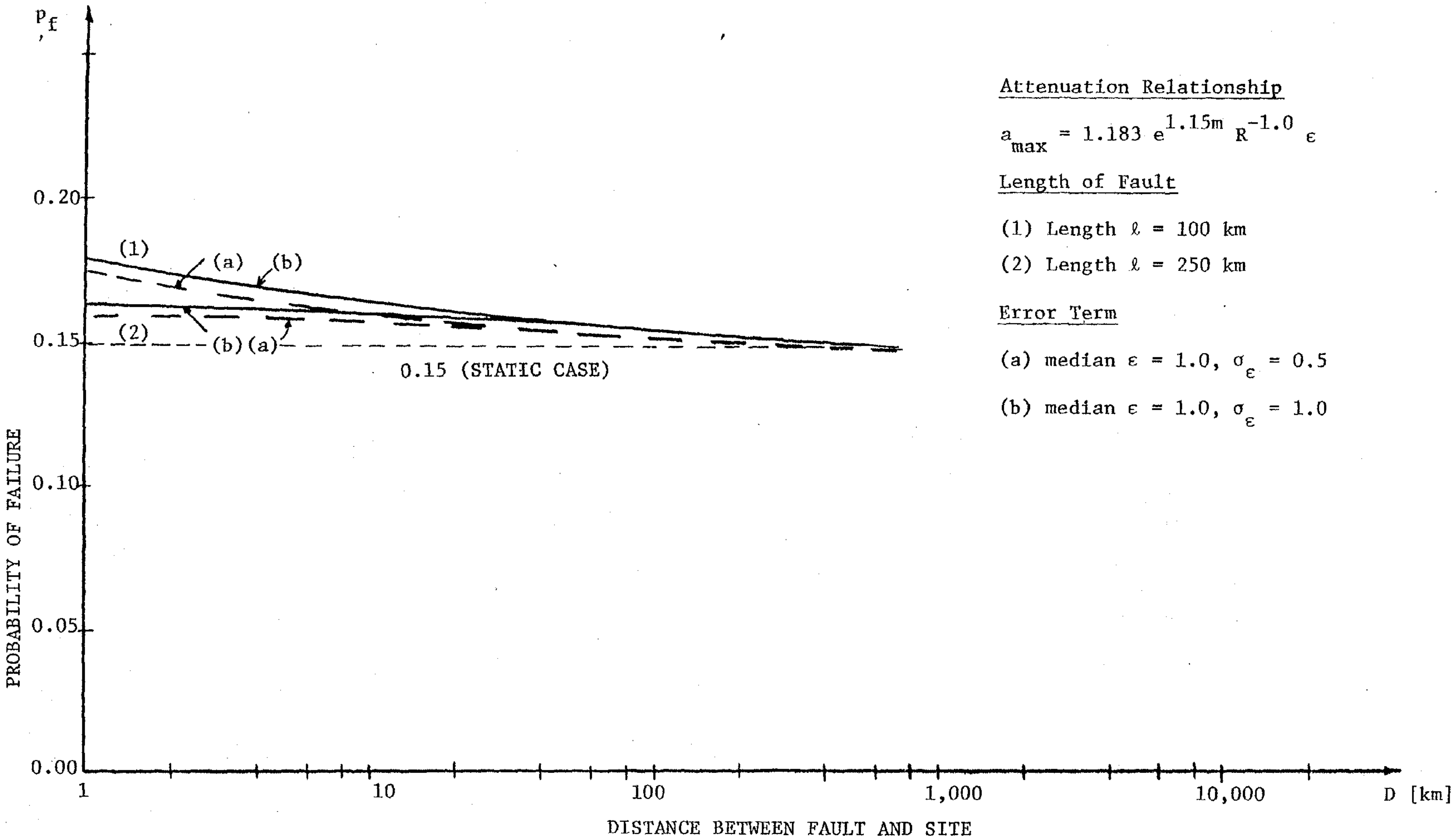


FIGURE 14. PROBABILITY OF FAILURE VS. DISTANCE BETWEEN FAULT AND SLOPE (θ = 90° - WITH ERROR TERM - CASE 2)

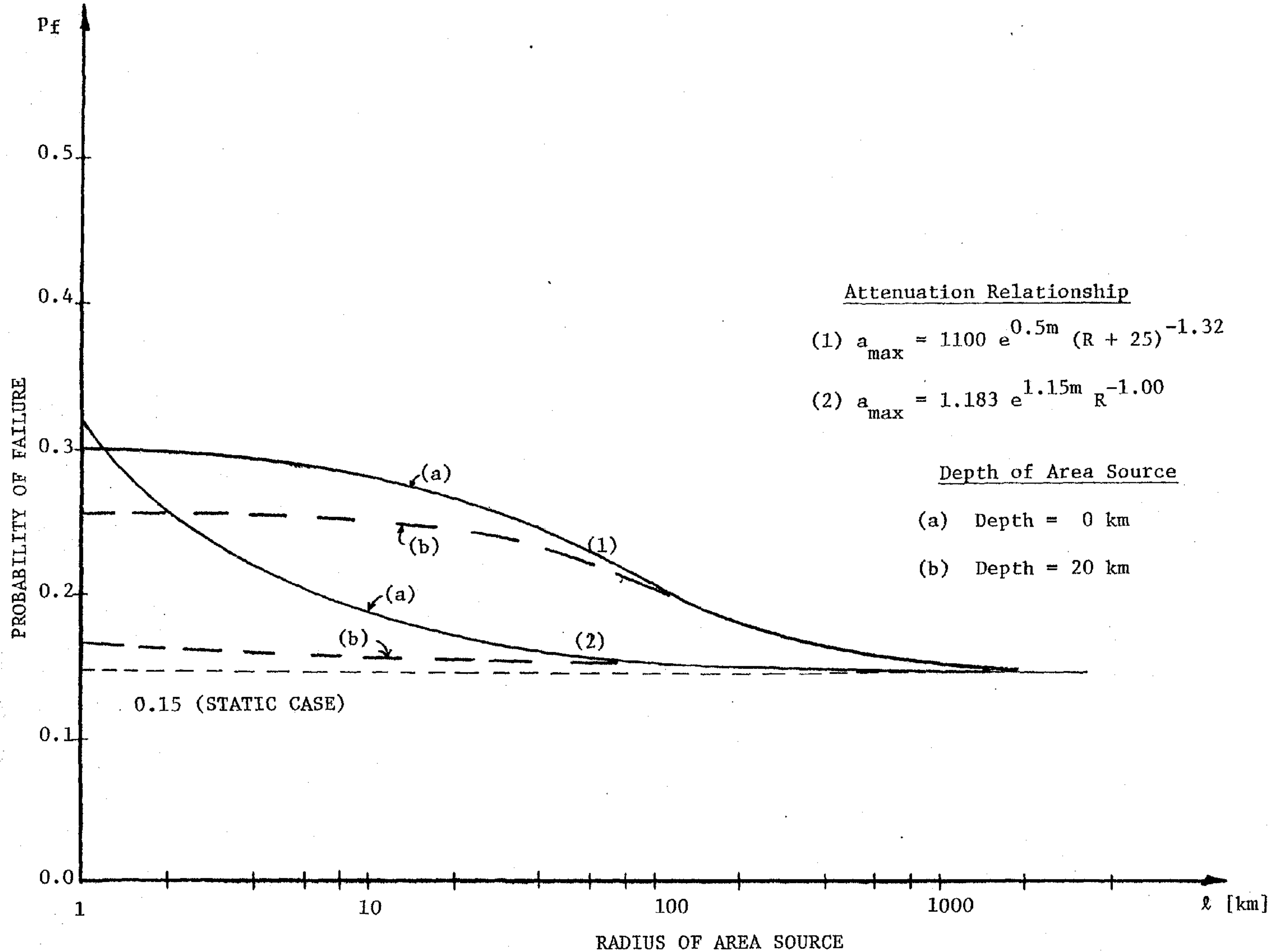


FIGURE 15. PROBABILITY OF FAILURE VS. RADIUS OF AREA SOURCE

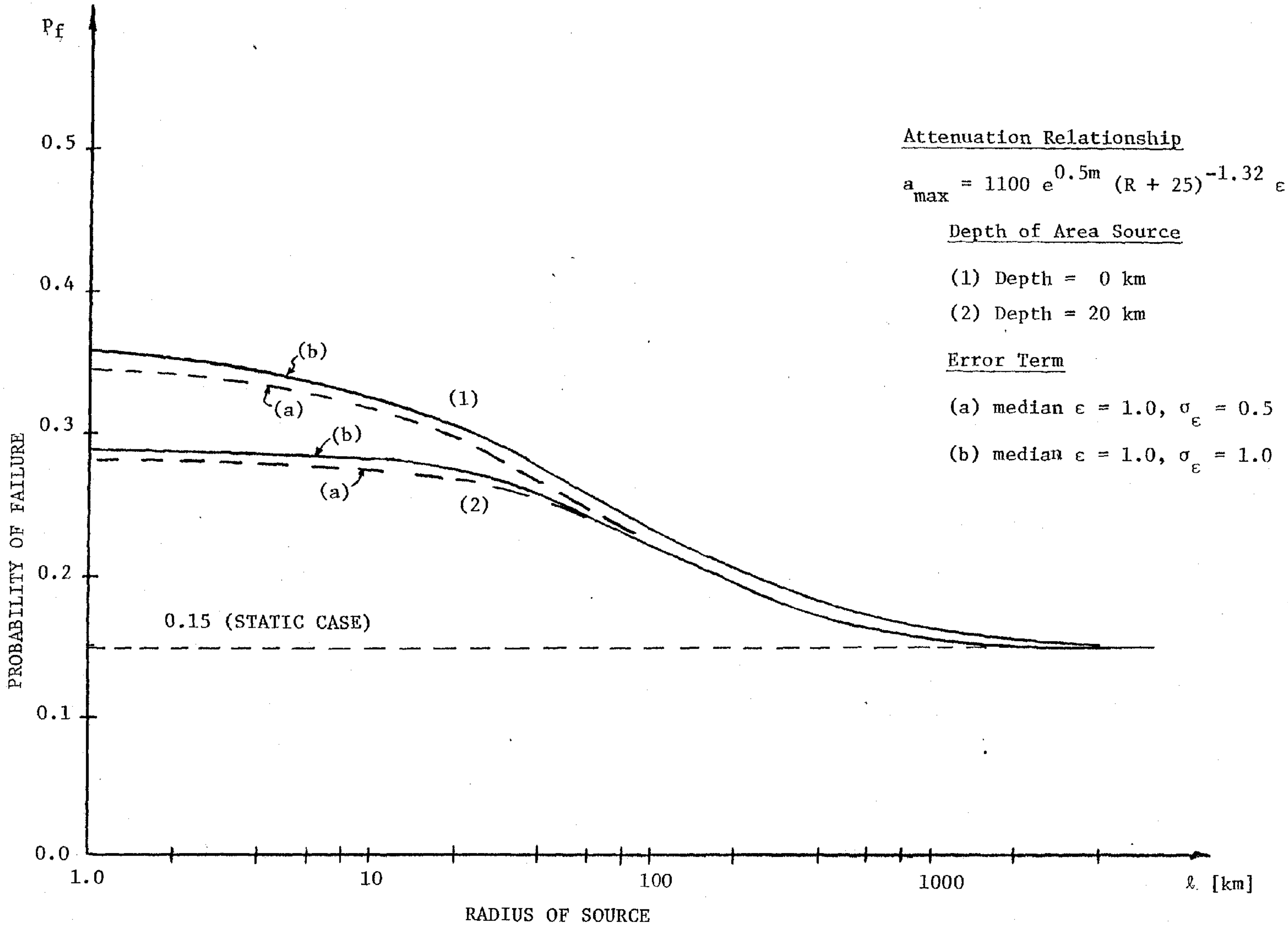


FIGURE 16. PROBABILITY OF FAILURE VS. RADIUS OF AREA SOURCE (WITH ERROR TERM - CASE 1)

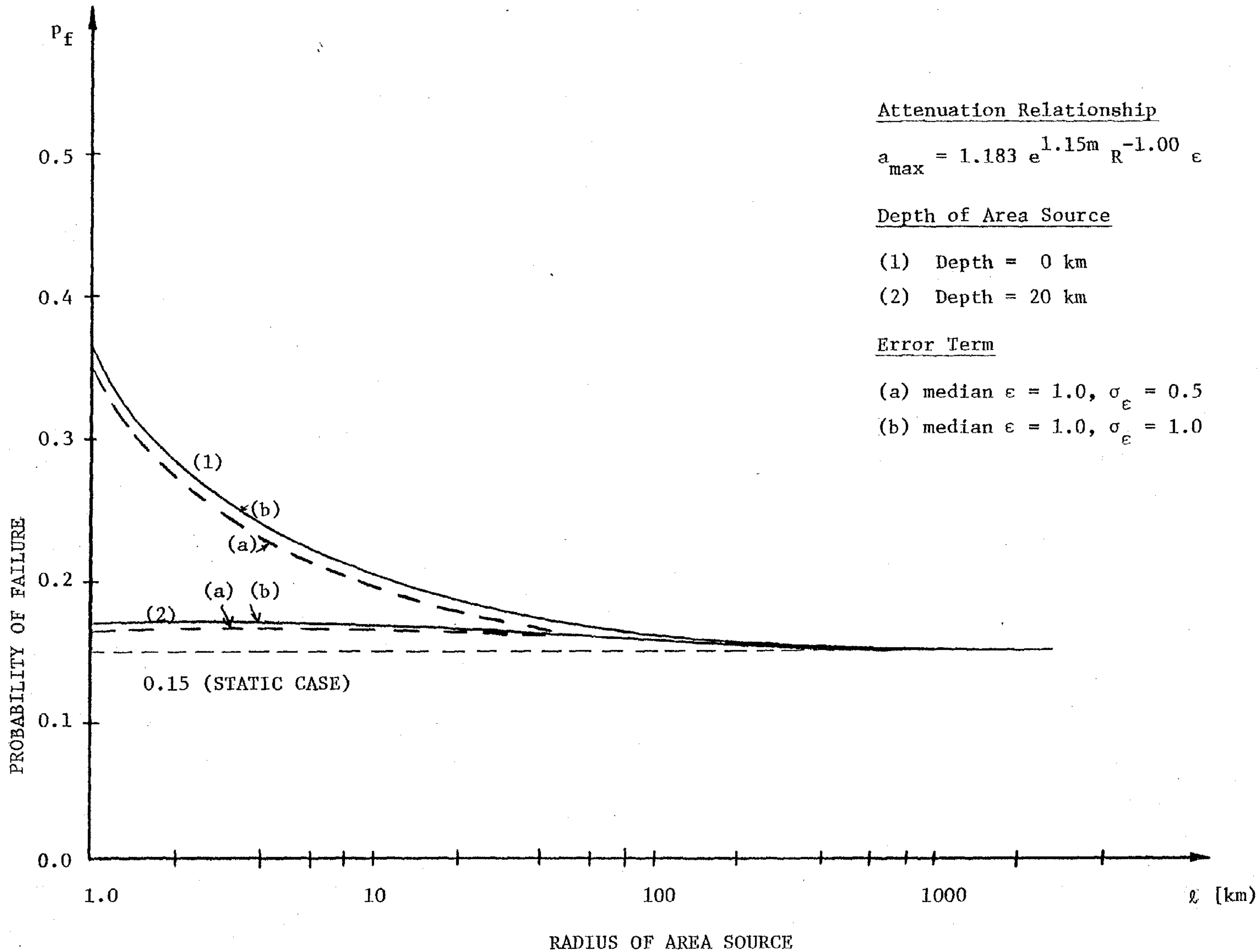


FIGURE 17. PROBABILITY OF FAILURE VS. RADIUS OF AREA SOURCE (WITH ERROR TERM - CASE 2)

3. DISCUSSION

The safety of a natural slope located near Slingerlands, New York, was measured in terms of its probability of failure (p_f) rather than the conventional factor of safety (FS). Using the previously developed computer program RASSUEL [3], the numerical values of p_f were determined under both static and seismic conditions.

In the case where no earthquake loading was considered, conventional methods of limiting equilibrium analysis provided values for the factor of safety FS varying between FS = 1.48 (Spencer's method) and FS = 1.63 (Bishop's modified method). The probability of failure of the slope was found to be approximately equal to 0.15 ($p_f = 0.15$). Such a surprisingly high value for the probability of failure appears to be in agreement with previously reported results on the relationship between p_f and FS. For example, Matsuo et al. [8], in a probabilistic analysis of the safety of embankments, found that an ordinary range of values of FS between 1.1 and 1.5 corresponded to an "unexpected high value" of p_f between 0.15 and 0.20. Similar results were also reported by A-Grivas [5] in a series of case studies involving slides of natural slopes. A lack of confidence in the values of the factor of safety of the Slingerlands slope was also expressed by Gray et al. [6] who remarked that "these values (i.e., FS = 1.48 - 1.63) are too high to adequately describe the observed failing of the slope". In Figure 18 are shown the various relationships that have been obtained between FS and p_f [5]. In the same figure are also shown the points that correspond to the results found in this study.

When an earthquake loading was considered, the seismic parameters that were used in the stability analysis were assumed to have values applicable to the seismic environment of the State of New York and Northeastern United States.

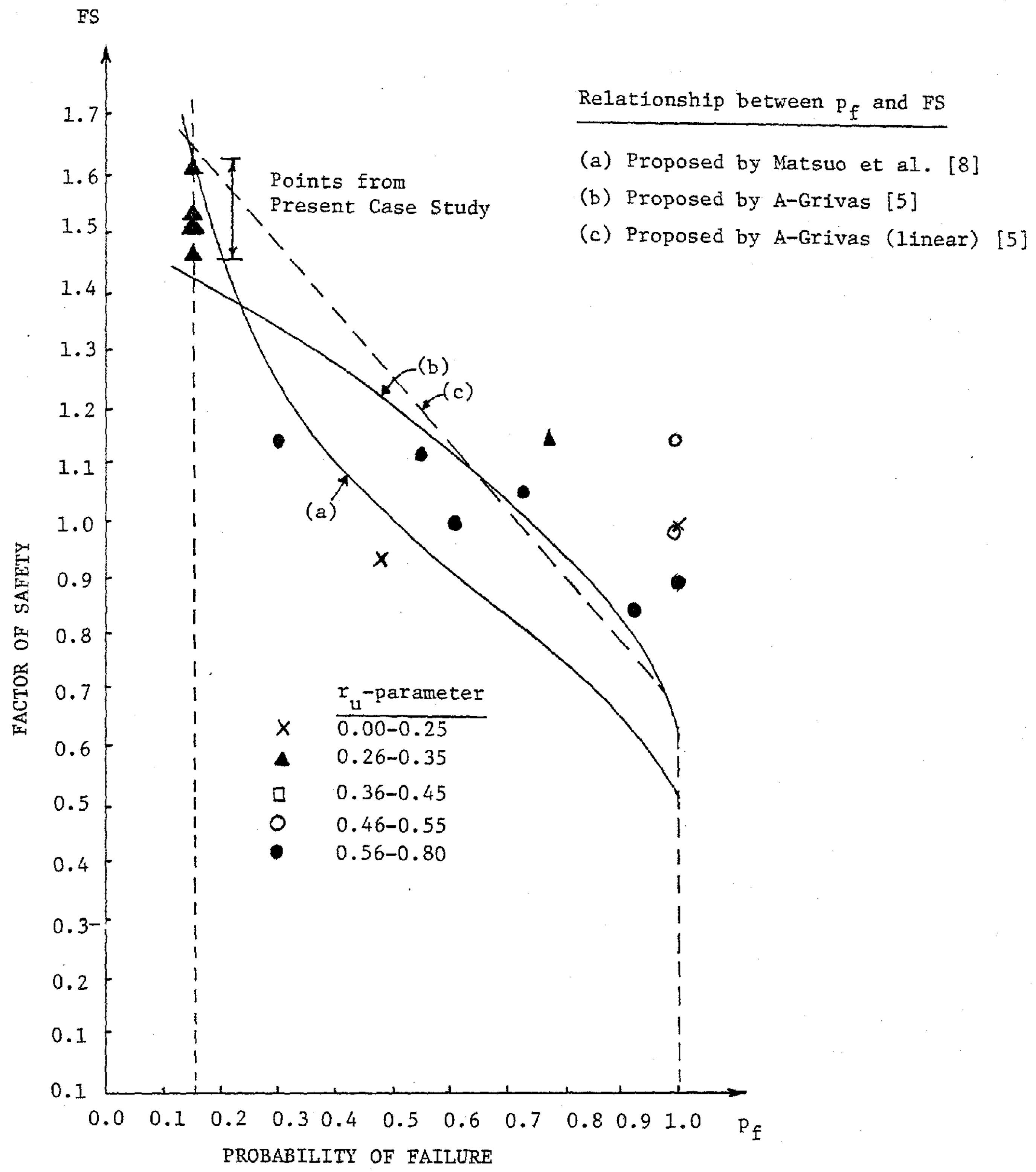


FIGURE 18. PROPOSED RELATIONSHIPS BETWEEN p_f AND FS.

Two different attenuation relationships, given by Equations (6a) and (6b), were used in the seismic analysis of the stability of the slope. As a rule, the first relationship (Case 1) resulted to higher values for the probability of failure p_f of the slope than the second (Case 2). In both cases, p_f attenuated to the value received under static conditions (i.e., $p_f = 0.15$) as the distance R between earthquake source and site of slope increased. This can be seen, for example, in Figures 7 and 8.

To improve the agreement between computed and observed values of the maximum ground acceleration, the former are often multiplied by an "error term ε" assumed to be log-normally distributed random variable with median equal to unity (median $\varepsilon = 1.0$). The present case study examined the effect of the standard deviation σ_ε of the "error term" by performing the stability analysis for two different values of σ_ε: (a) $\sigma_\varepsilon = 0.5$, and (b) $\sigma_\varepsilon = 1.0$. It was found that the higher value of σ_ε always resulted to larger values for p_f. In Table 2 are listed, for comparison purposes, some values of p_f that were found in these two cases, and also, in the case where no "error term" was considered. From Table 2 it can be seen that p_f received the lowest value in the case without the "error term".

Three types of earthquake sources were investigated, namely, a point, an area, and a line (or, fault) source. The point source (Figure 6a) constitutes the basic type of earthquake source and, in the present study, it was also employed to describe the other two types of sources [2]. An area source (Figure 6c) is often used when the earthquakes that have occurred at a certain site are almost uniformly scattered over an area, or when there is

TABLE 2. INFLUENCE OF "THE ERROR" TERM ON THE PROBABILITY OF FAILURE (POINT SOURCE)

DISTANCE R	PROBABILITY OF FAILURE p_f					
	Case 1			Case 2		
	Without ε	$\sigma_\varepsilon = 0.5$	$\sigma_\varepsilon = 1.0$	Without ε	$\sigma_\varepsilon = 0.5$	$\sigma_\varepsilon = 1.0$
1 km	0.30	0.34	0.36	0.27	0.28	0.30
5 km	0.28	0.33	0.34	0.18	0.21	0.23
10 km	0.26	0.29	0.31	0.12	0.18	0.19

limited seismic data and other information available for a particular site. In the present study, it was assumed that the area source had a circular shape that surrounded uniformly distributed points. Two different values for the depth of the area source were investigated (0 to 20 km) and it was found that the probability of failure of the slope was higher when the area source was on or near the ground surface (Figures 7, 10 and 11). For the cases examined, it was also found that the depth had a greater affect on the probability of failure of the slope than the error terms. The line source is used if a fault has been clearly identified in a region, or when a string of earthquakes occurred over a period of time along a well defined line. In modelling the line source, it was assumed that points of potential earthquakes were uniformly distributed along a certain length (ℓ) of the line (Figure 6b). Two different values of the length ℓ were considered in this case study (ℓ = 100 and 250 km) and it was found that the values of the probability of failure p_f were higher for a shorter length of the line source. A study of the dependence of p_f on the orientation θ of the fault (Figure 6b) revealed that, for the two values examined ($\theta = 45°$ and $\theta = 90°$), the orientation of the fault did not influence the results at any significant degree.

Finally, in all cases investigated in this study, the numerical values of the probability of failure were obtained during a Monte Carlo simulation and for one thousand trials. In general, the accuracy of the results is directly related to the number of trials used in the simulation. The error involved decreases with the reciprocal of the square-root of the number of trials ($1/\sqrt{n}$, where n is the number of trials). Thus, for the number of trials used in the present work (n = 1,000), the anticipated error in the values of p_f is, at most, of the order of 8-15% [9].

4. SUMMARY AND CONCLUSIONS

An investigation was made of the reliability of a natural soil slope located near Slingerlands, New York. Both static and seismic loading conditions were examined. A previously developed model was used to determine the probability of failure p_f of the slope for three types of earthquake sources, namely, a point, a line (or, fault), and an area source. The dependence of p_f on significant seismic parameters was examined and discussed.

On the basis of the results obtained in this case study, the following conclusions can be drawn:

(a) The present probabilistic model is useful in assessing the reliability of soil slopes under both static and seismic conditions.

(b) The probability of failure is a viable alternative to the factor of safety as a measure of the safety of soil slopes.

(c) The values of the probability of failure attenuate (as distance R between earthquake source and slope increased) to the value obtained under static conditions.

(d) From the two attenuation relationships that have been proposed for the Northeastern United States, Equation (6a) (Case 1) resulted in higher values for the probability of failure.

(e) Higher values of the standard deviation σ_ε of the "error term" produced a larger value for p_f.

(f) The probability of failure of soil slopes is greatly affected by the type of earthquake source used and by the values of the seismic parameters that are associated with it. Under the most unfavorable set of circumstances from among those examined in the present study, the probability of failure of the slope had a value $p_f \simeq 0.35$ (Figure 10) which was more than twice that found under static conditions ($p_f \simeq 0.15$).

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