Panama Canal Commission

Engineering Division

Geotechnical Branch

THE RISK OF LANDSLIDES IN GAILLARD CUT

by

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CONTENTS

I. INTRODUCTION

The objective of this report is to evaluate the risks of channel encroachments due to landslides along the entire extension of Gaillard Cut. Once the critical areas are identified, the PCC can allocate it's limited landslide control resources efficiently, to reduce the overall cost of landslide activity.

It is convenient to review the National Research Council's classification of landslide cost reduction methods (Ref. 20). The NRC groups these methods into two categories: emergency management, and long-term hazard reduction.

Emergency management focuses on minimizing damage and restoring critical public facilities when landslides occur. It includes:

1) The anticipation, prediction & issuance of warnings of landslides.
2) The response that is required when landslides do occur.
3) The identification of landslide-prone areas and the planning, training & preparing necessary to insure that the warning and response will be effective.

Long-term hazard reduction focuses on landslide prevention and on limiting the extent of potential damage before a crisis is imminent. It includes:

1) The avoidance of landslide-prone terrain, by restricting developments in such areas.
2) The use of Design, Building and Grading Codes as tools for achieving desirable construction practices, which do not promote slope instability. This includes designing to avoid slides, and protecting structures against slides by shielding them or making them able to withstand the loads.
3) The implementation of Landslide Control and Stabilization measures. Hydraulic and mechanical remedial measures can dramatically reduce the risk of sliding, but are very expensive.
4) The use of Insurance. Provides a means for distributing the cost of landslides over a larger population or over a longer period of time, but does not reduce them. Requires a better understanding of the hazard (potential damage and loss of life) in each area, and the likelihood of failure.

In the past, the P.C.C. has relied mainly on the continuous monitoring of the slopes and the implementation of remedial measures when a problem arises or is imminent.

The avoidance of landslide-prone terrain and to a large extent, the use of adequate design standards, are measures implemented in the planning and design stages of a project. They are not applicable, in general, to an existing structure like Gaillard Cut. The overall trend of less landslide activity with time, does suggest that design standards have improved as experience has accumulated.

Recently, the use of insurance has been implemented to a limited extent. However, reliance on insurance policies should not constitute the basis for Landslide Control in Gaillard Cut. The loss of confidence in the Canal by the shipping industry is potentially far more costly than cleanup operations following a landslide. It is a measure that complements the Commission's main landslide control strategy: the detection of incipient slides and their stabilization with appropriate remedial measures.

When a landslide has occurred in the past, the response of the Panama Canal Commission has generally been vigorous, and the event takes top priority among the pertinent P.C.C. units. However, emergency measures have usually been improvised, depending on the specific circumstances. A.P.Mann proposed the "Landslide Emergency Action Program" (LEAP) in 1986 (Ref. 11). It presents considerations for improving the P.C.C.'s response to such emergencies. For the reasons stated in the previous paragraph, emergency management should also be considered a complementary landslide cost reduction measure.

Given that the Panama Canal Commission's main tool for reducing landslide costs is the implementation of landslide control and stabilization measures, a better understanding of the way the slopes have behaved in the past is of great importance. The zonation of Gaillard Cut is the starting point towards the achievement of this goal. It sets a framework for organizing existing data on past landslide activity in a rational manner. Each zone is defined in a manner such that it presents relatively uniform geologic and topographic conditions. It is expected that inferences regarding future patterns of activity should be similar to what has occurred in the past.

II. DISCUSSION

A. The Zonation of Gaillard Cut

Two criteria were considered convenient in the process of dividing Gaillard Cut into zones:

1) major changes in topography

2) major changes in geologic conditions

These discriminating factors, used for establishing zone boundaries, share the common characteristic of being based on available objective information, that involves little, or no interpretation. Judgemental considerations regarding risk levels did not enter a-priori in the process of zoning the Cut. Estimates of relative risk levels for potential mechanisms which may develop within the established zones, will involve subjective judgement, and will be one of the results of this study.

This manner of dividing Gaillard Cut can be seen as a way to establish a series of "units" (zones), that present a relatively uniform geologic and topographic environment. This strategy presents the advantage of minimizing changes in the location of zone boundaries. As we gather more information on the geology, on groundwater conditions, and on slope behavior in general, we increase our understanding of the mechanisms developing in each zone without having to redefine its boundaries. The use of lateral slide extent for defining zone boundaries is not practical. In areas of recurring landslide activity, the evidence is that the width of the sliding mass changes from one slide event to the next. In some cases, slides overlap.

We expect that the zonation process will offer a rational basis for optimizing the allocation of the limited resources available to the Landslide Control Program.

Figure 1 presents a map of Gaillard Cut with the proposed zonation scheme (24 zones). Table 1 presents a compilation of the criteria used for selecting the inter-zone boundaries in each case. Appendix B presents a list of the cross section(s) considered representative of each zone, in terms of topography and geology.

B. <u>History of Past Landslides</u>

Appendix A presents a compilation past landslides in Gaillard Cut. The information is derived from Reference 1, from internal P.C.C. reports, especially on the more recent slides (References 6 through 18), from the Geologic Cross Sections prepared by P.C.C.

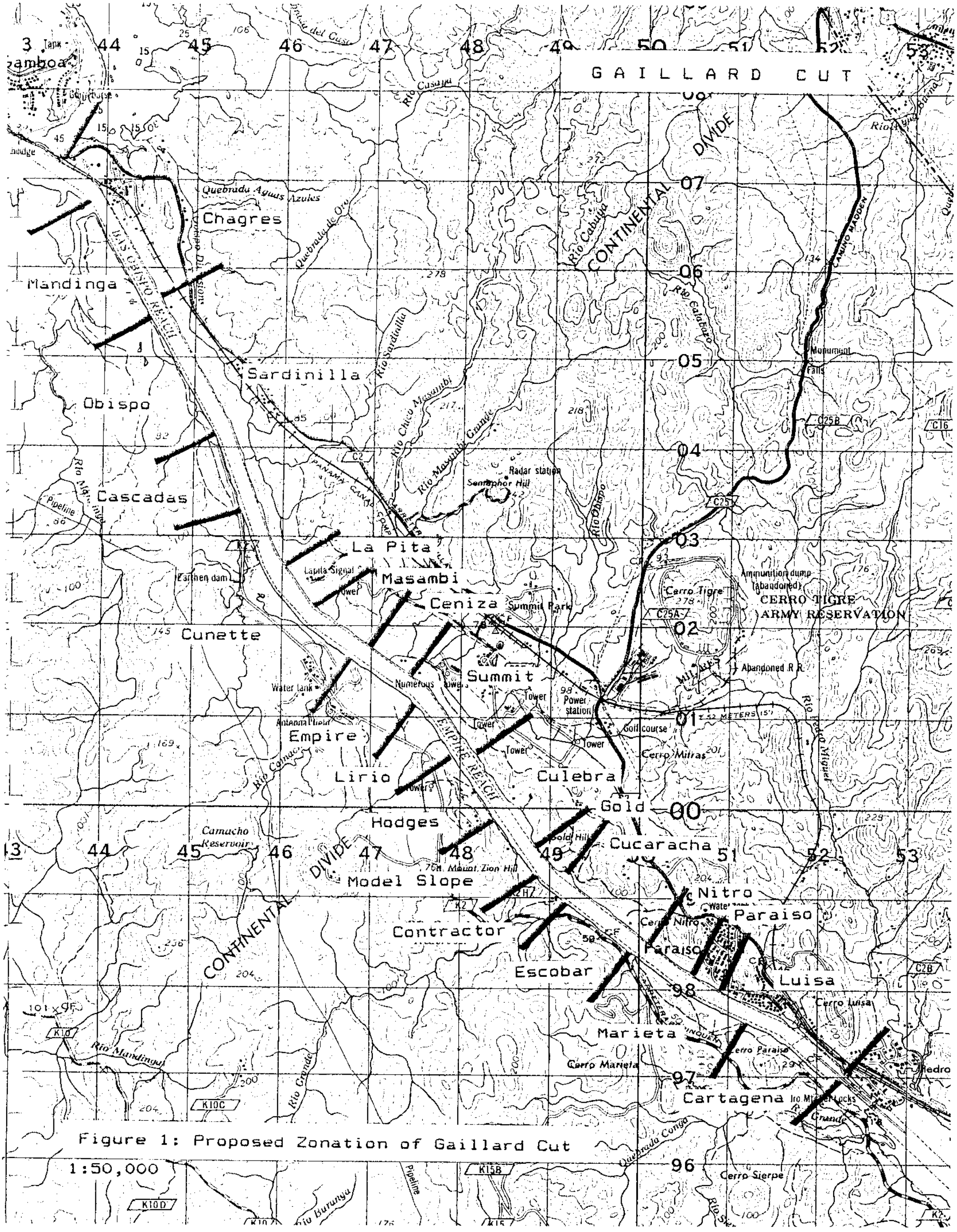


Figure 1: Proposed Zonation of Gaillard Cut

Table 1: Zonation of Gaillard Cut

WEST BANK

Zone	limit	change	limit	change	main formations
Mandinga	1660	--	1710	formation	Bas Obispo
Obispo	1710	formation	1763	topo/form	Las Cascadas
Cascadas	1763	topo/form	1800	topography	La Boca/Cascadas
Cunette	1800	topography	1861	formation	La Boca/Cascadas
Empire	1861	formation	1892	formation	(transition)
Lirio	1892	formation	1925	topo/form	Culebra/Gatuncillo
Hodges	1925	topo/form	1947	topo/form	P.M./Cucar/Culebra
Model Sl.	1947	topo/form	1969	topo/form	Basalt/Cucaracha
Contractor	1969	topo/form	1986	topo/form	P.M./Cucaracha
Escobar	1986	topo/form	2014	formation	Basalt/Cucaracha
Marieta	2014	formation	2060	topo/form	Cucaracha/P.M.
Cartagena	2060	topo/form	2090	--	P.M./La Boca

EAST BANK

Zone	limit	change	limit	change	main formations
Chagres	1645	--	1705	formation	Bas Obispo
Sardinilla	1705	formation	1825	topography	Cascadas/La Boca
La Pita	1825	topography	1842	topography	Cascadas
Masambi	1842	topography	1865	formation	Cascadas
Ceniza	1865	formation	1887	formation	(transition)
Summit	1887	formation	1928	formation	Culebra/Gatuncillo
Culebra	1928	formation	1961	topo/form	Cucaracha/Culebra
Gold	1961	topo/form	1973	topo/form	Basalt/P.M.
Cucaracha	1973	topo/form	2017	topo/form	Cucaracha/Basalt P.M./Culebra
Nitro	2017	topo/form	2037	topo/form	Basalt
Paraiso	2037	topo/form	2048	formation	Cucaracha/Culebra
Luisa	2048	formation	2090	--	P.M./La Boca

geologists, and from recent experience. The documentation on some slide events has not been found, but it is believed that all slide areas and most slide events have been identified. Tables 6, 7, and 8 in Appendix A, present a summary of the descriptive statistics of the physical dimensions of the sliding masses. The values are given for each zone, for each bank (East and West), and for the entire Cut.

Figures 2 and 3 present compilations of all slide events in the east and west banks, respectively.

The periods of Canal excavation are noted in each figure. Most of the slides coincide with this activity. The Canal was gradually widened (from 300 feet to 500 feet) by excavation along the West Bank. The progress of this excavation can be traced in Figure 3. Many post-construction instabilities in the West Bank were associated with this project.

Figures 2 and 3 provide an additional distinction between slide events: those which were fully developed slides and those which were incipient slides (manifested by surface cracks, and movements). In recent years most of the incipient slides have been detected by means of instrumentation (of the Landslide Control Program). However, in a number of cases the potential instabilities have been first discovered through field inspections. Surface cracks, tilted posts, damaged penetration roads, and other similar manifestations of instability have been detected prior to the examination of the surveillance program. Sometimes, these observations have discovered

EAST BANK SLIDES

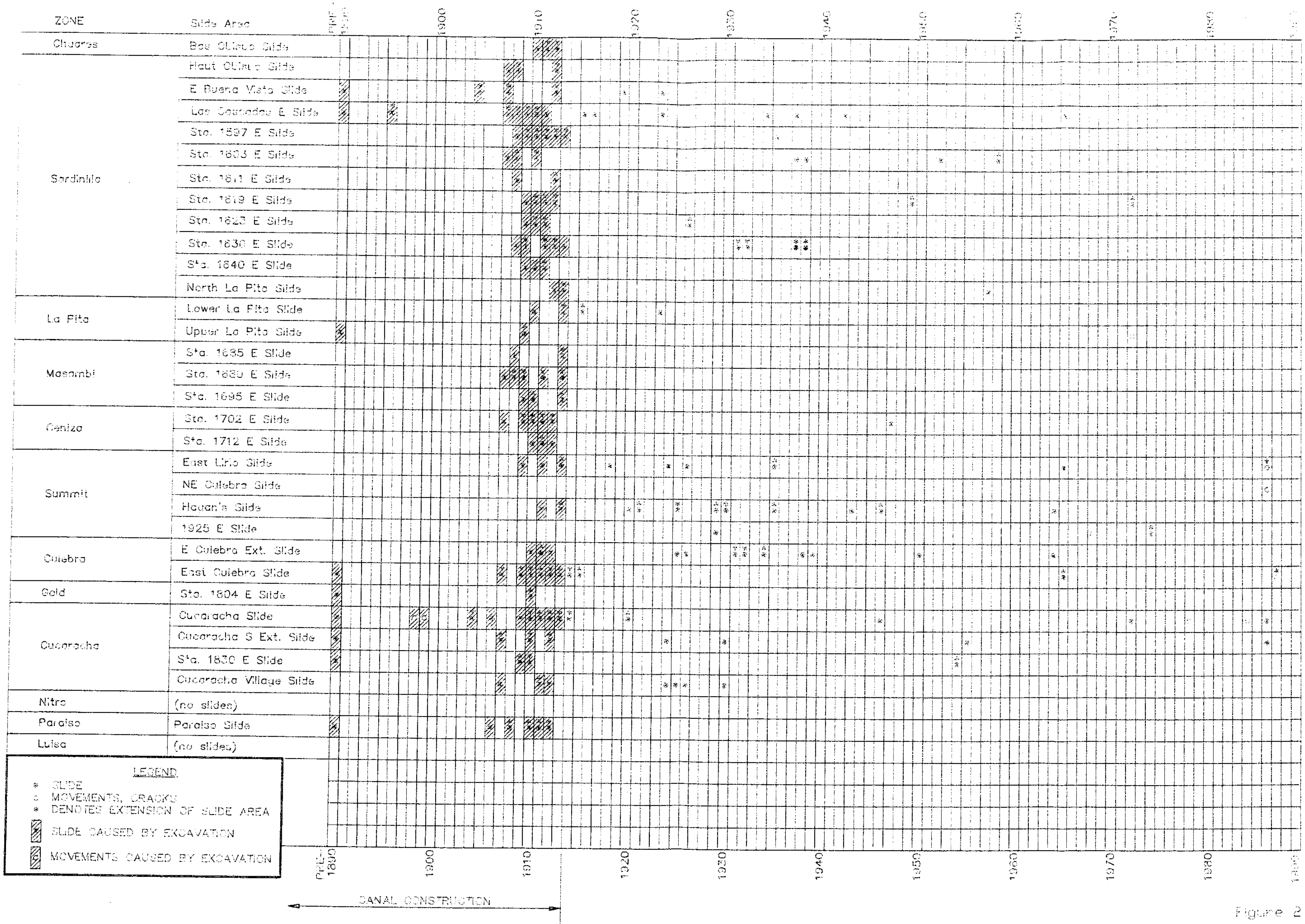


Figure 2

WEST BANK SLIDES

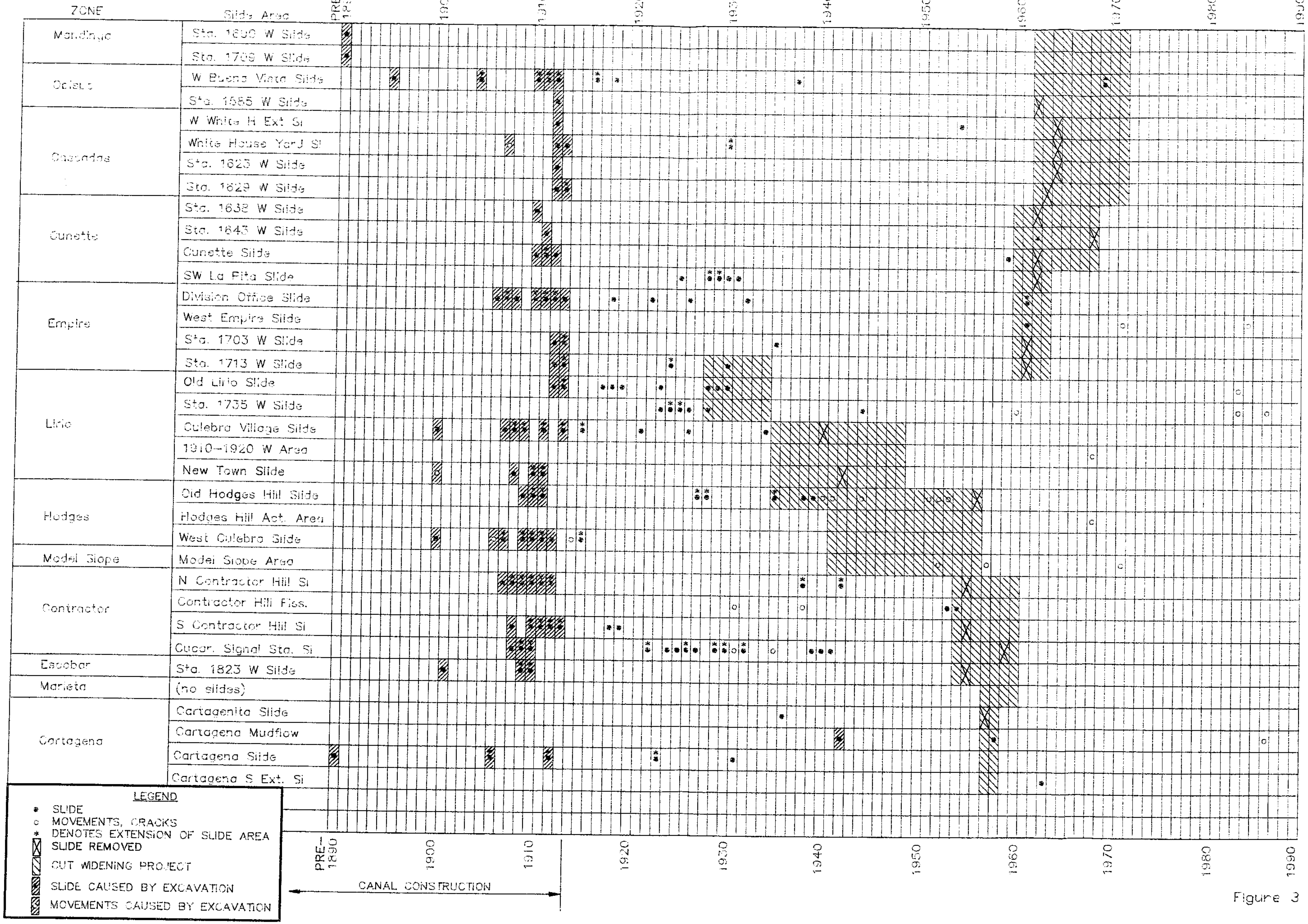


Figure 3

activity in areas that escape the resolution of the monitoring system.

C. Past Channel Encroachments

The encroachment of the navigation channel by earth and rock debris resulting from landslides, is the parameter used to evaluate the consequences of a slide. Actual encroachments are the real tangible damage caused by the slides. Large slides, sufficiently removed from the navigation channel, do not cause (directly) the problem that smaller slides with significant encroachment cause.

As discussed in the Introduction, Canal closures can have an economic impact that far surpasses the cost of removing the encroaching slide material. Table 2 presents a list of Canal closures compiled by A. P. Mann (Reference 7).

In 1946, Wilson V. Binger (Reference 3) wrote an internal P.C.C. memorandum in which he states his impressions regarding potential channel encroachments in the event of a slide. He emphasizes that his criteria are "educated guesses", however offers the following values:

Slope	Encroachment beyond the toe
1V:2H (26°)	Height of the cut
1V:4H (14°)	1.25 x Height of the cut
1V:6H (10°)	1.50 x Height of the cut

Table 2: Canal Closures due to Slides in Gaillard Cut
(compiled by A. P. Mann in Ref. 7, except *)

Slide	Starting Date	Ending Date	Total Time
East Culebra	10/14/14	10/20/14	6 days
East Culebra	10/31/14	11/04/14	4 days
E & W Culebra	08/07/15	08/10/15	3 days
E & W Culebra	09/04/15	09/10/15	5 days
E & W Culebra	09/18/15	04/15/16	7 months
Cucaracha Slide	08/30/16	09/07/16	8 days
E Culebra Slide	01/10/17	01/11/17	2 days
Cucaracha Slide	03/21/20	03/24/20	3 days
E Culebra Exten.	11/09/31	11/11/31	2 days
1925 E	10/10/74	10/10/74	2.5 hours
Cucaracha Slide *	10/13/86	10/13/86	12 hours

Table 3 presents a compilation of all the encroachments found documented in the literature (31 cases). A number of possible correlations, between encroachment and other parameters were explored. Relationships exist between encroachment and slope height, and between encroachment and length of the sliding mass. Both dimensions are measured with respect to the toe of the sliding mass. Encroachments are projections beyond this same point. In five cases, the slide movement was limited by the presence of the opposing bank. Photographs and descriptions show that the encroachment would have been much larger if this physical restriction hadn't been present.

Other variables as the relative strength of the materials, the mechanism of failure, the shape of the sliding mass, the slope angle, etc., did not appear to affect encroachment in a consistent manner. No type of correlation was evident when the statistical analyses included these factors. Perhaps this is an indication that the potential energy of the sliding mass, by virtue of its height, is the main factor affecting the amount of encroachment. All other internal forces and conditions seem to have a secondary impact on this parameter.

Figures 4 and 5 present these relationships. Although both have approximately the same correlation coefficient, the correlation with slope height is probably more useful because this variable involves less uncertainty than the length of the sliding mass. However, in some cases the length of the sliding mass may be relatively well defined. This information could come from previous sliding of the

Table 3: Record of Past Channel Encroachments
(dimensions in feet)

Event#	Slope	Date	Slope Height	Mass Length	Encroachment
1	Cascadas E	Dec 10, 1910	140	630	160
2	East Lirio	May, 1913	165	480	250
3	Cucaracha E	Sept, 1913	510	1700	>300
4	1630 E	Oct, 1913	125	460	60
5	Hagan's Sl.	Oct, 1913	170	680	140
6	Old Lirio W	Oct, 1913	160	520	110
7	East Culebra	Oct 14, 1914	350	800	>300
8	East Culebra	Aug, 1915	330	1400	>300
9	West Culebra	Aug, 1915	320	1080	>300
10	Cucaracha E	Feb 21,1920	480	1800	>300
11	Hagan's Sl.	Jul 14, 1921	170	750	180
12	1735 W	Aug 28, 1923	150	480	180
13	Cartagena Sl	Sept 9, 1923	180	500	50
14	Hagan's Sl.	Jul 22, 1925	160	300	70
15	1735 W	Aug 4, 1925	100	340	80
16	E Culebra Ext	Nov 1, 1925	190	400	100
17	Cucar Sig Sta	May 1, 1926	100	220	110
18	E Culebra Ext	Jul 2, 1926	190	400	80
19	Sta. 1735 W	Jul 29,1926	100	340	40
20	1735 W	Aug 29, 1928	150	350	100
21	Cucar Sig Sta	Jun 20, 1929	100	220	120
22	Hagan's Sl	Jun 21, 1929	150	400	130
23	E Culebra Ext	Nov 9, 1931	190	800	300
24	Old Hodges H	Aug 15, 1935	180	375	60
25	Hagan's Sl.	Nov 22, 1935	160	150	105
26	1830 E	Aug 7, 1954	160	100	30
27	W White H Ext	Oct 16, 1954	110	230	70
28	Cartag S Ext	Oct, 1964	130	440	100
29	1619 E	1972	150	400	80
30	1925 E	Oct 10, 1974	200	600	250
31	Cucaracha E	Oct 13, 1986	380	1300	650

Table 4: Past Failure Rates

East Bank (post-construction slides)

zone	#slide events	period (years)	#slides/yr
Chagres	0	75	.000
Sardinilla	23	75	.307
La Pita	3	75	.040
Masambi	0	75	.000
Ceniza	1	75	.013
Summit	19	75	.253
Culebra	13	75	.173
Gold	0	75	.000
Cucaracha	15	75	.200
Nitro	0	75	.000
Paraiso	0	75	.000
Luisa	0	75	.000

West Bank (post-construction slides)

zone	#slide events	period (years)	#slides/yr
Mandinga	0	75	.000
Obispo	4	75	.053
Cascadas	2	75	.027
Cunette	7	75	.093
Empire	11	75	.147
Lirio	23	75	.307
Hodges	14	75	.187
Model Slope	3	75	.040
Contractor	21	75	.280
Escobar	0	75	.000
Marieta	0	75	.000
Cartagena	7	75	.093

West Bank (post-widening slides)

zone	#slide	period	#slides/yr
Mandinga	0	17	.000
Obispo	0	17	.000
Cascadas	0	17	.000
Cunette	0	20	.000
Empire	2	25	.080
Lirio	5	41	.122
Hodges	1	32	.031
Model Slope	2	32	.063
Contractor	0	27	.000
Escobar	0	27	.000
Marieta	0	27	.000
Cartagena	2	29	.069

Table 5: Range of Maximum Potential Encroachments (dimensions in feet)

East Bank

Zone	El. max	Encr	El. min	Encr
Chagres	200	270	110	90
Sardinilla	220	310	160	190
La Pita	310	490		
Masambi	250	370	200	270
Ceniza	200	270		
Summit	235	340	200	270
Culebra	210	290	150	170
Gold				
Cucaracha	450	770	300	470
Nitro				
Paraiso	210	290	140	150
Luisa	150	170	115	100

West Bank

Zone	El. max	Encr	El. min	Encr	L	Encr
Mandinga	220	310	150	170		
Obispo	200	270	140	150		
Cascadas	370	610	280	430		
Cunette	200	270				
Empire	330	530	220	310		
Lirio	235	340				
Hodges	380	630	150	170	550	318
Model Slope	300	470	140	150	800	430
Contractor						
Escobar					400	250
Marieta	150	170	110	90		
Cartagena	350	570	250	370	800	430

mass, or from the observation of cracks and other features on the ground surface. In some cases, the presence of a rigid boundary (for example: a block of basalt) could limit the extent of the sliding mass and offer an upper bound to the predicted encroachment. Somewhat more tenuous, but possible, is the delimitation of the potential sliding mass by surface movements detected by the Landslide Control Program. In any case, both relationships are available. The five special cases in which the channel width was smaller than the projection of the sliding mass, did not enter in the statistical analyses. These cases are shown as dashed lines in Figures 4 and 5 that denote that the encroachment would have been greater than 300 feet (the channel width at the time).

We performed regression analyses to quantify the confidence that can be placed on these predictions. Figures 4 and 5 show the 90% confidence intervals on the predictions. The higher limit in each case offers a conservative upper bound on the amount of expected encroachment in case of a slide. These values can be represented by the following relationships:

$$\text{encroachment} = 2\,(\text{slope height}) - 50 \quad (\text{in feet})$$

$$\text{encroachment} = 0.45\,(\text{length of the sliding mass}) + 70 \quad (\text{in feet})$$

Potential future encroachments can be conservatively predicted by these empirical relationships.

Figure 4: Channel Encroachment vs Slope Height

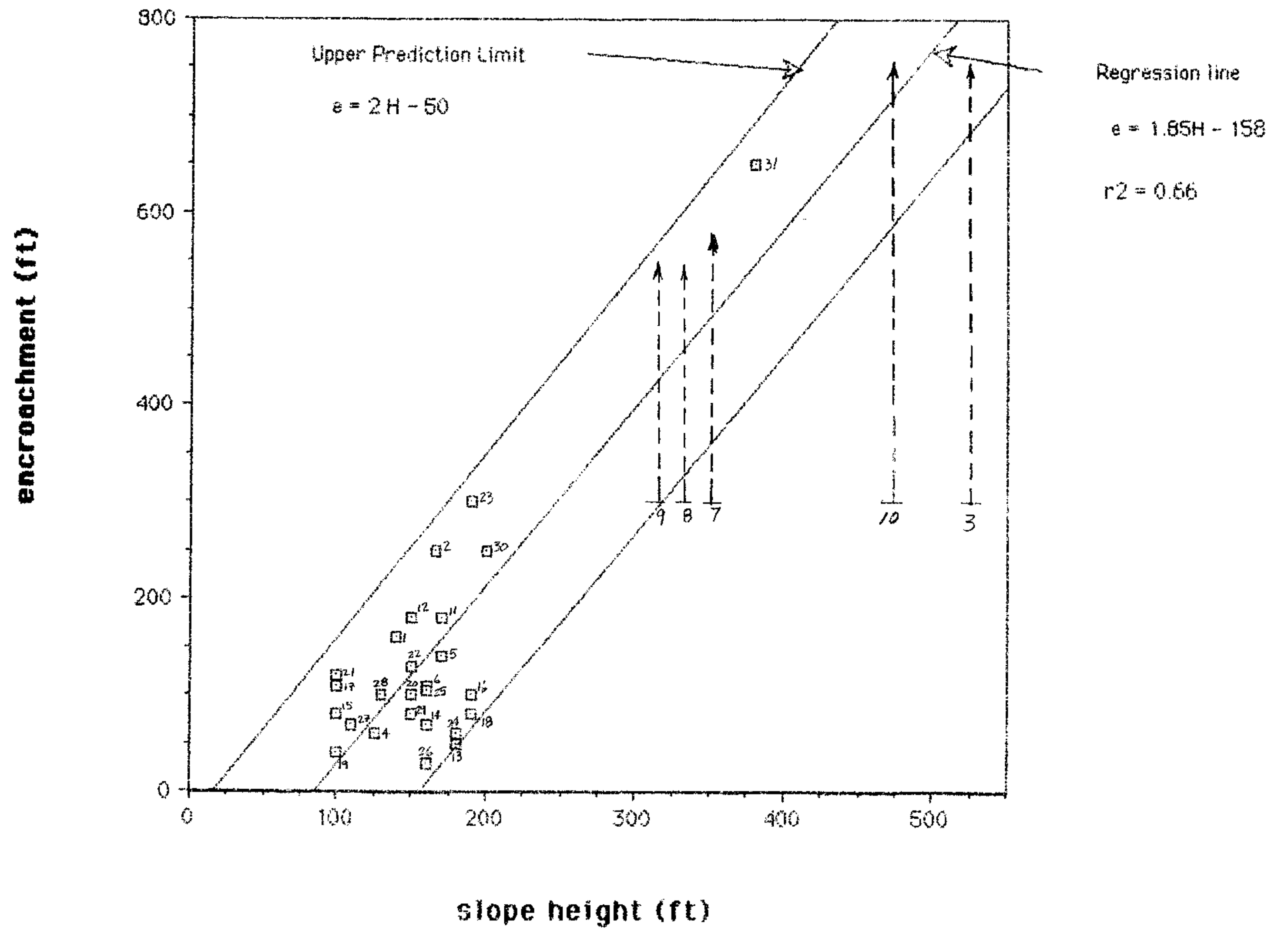
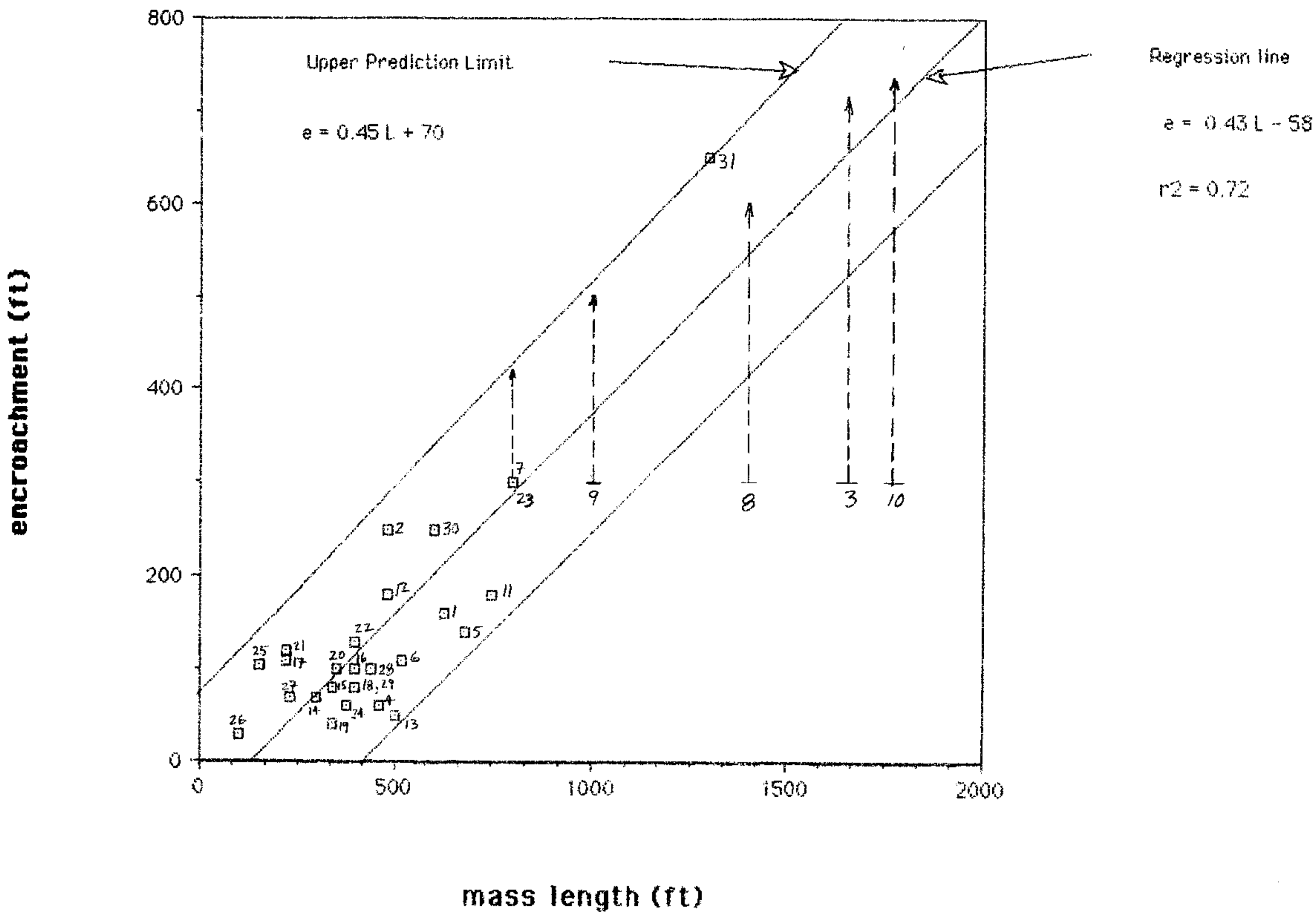


Figure 5: Channel Encroachment vs Length of Slide



D. Evaluation of the Risk of Landslides

This study uses the probability of failure as the basic measure of risk. It is an index that quantifies a state of knowledge regarding the likelihood of failure of a structure. This statement involves the so-called subjective interpretation of the term probability (References 30, 31, 36, and 38). It does not imply a unique correlation between the occurrence of a physical phenomenon (for example: failure), and the probability of such occurrence. In effect, a change in the amount of information available on the structure under consideration, can affect the estimated level of risk. Different observers would most likely assign different estimates of risk to the structure, due to their different backgrounds and experience. The structure itself however, remains unchanged by subjective considerations. A better understanding of the structure being evaluated, offers the means for making better estimates of risk. This however, does not guarantee a specific behavior of the prototype. Such estimates do not represent a tangible, measurable entity.

Reference to an objective, "true" probability of failure, considered an intrinsic property of the structure, is fundamentally flawed. It conveys the idea that the estimate attempts to predict the true probability of failure, rather than the fact that the a-priori estimate of the future behavior of the structure, is the probability of failure itself.

The information on which probability assignments are based can include objective and subjective components. The final assessment of probabilities represents the engineer's best estimate of the uncertainties surrounding the behavior of the structure under study. The subjective component of a probability assignment must satisfy two requirements: it must be consistent with all available information, and it should be maximally vague about what is not known (References 30, 36, and 38).

Probability theory in no way constitutes a substitute for experience and engineering judgement. It is just a convenient language that the engineer can utilize to make statements regarding safety in a convenient and systematic manner.

There is a growing body of literature dedicated to the evaluation of the probability of failure of geotechnical structures. It shows that procedures for estimating the probabilities of failure can be classified into two broad groups.

Procedures in the first group, propose calculating probabilities of failure from a quantification of the uncertainties associated with the capacity of the structure, and the uncertainties associated with the demand placed on the structure. The reliable assessment of these uncertainties is possible in some circumstances, making the task of estimating risks in this manner, simpler than attempting to do so directly. Straightforward solutions exist for calculating probabilities. The difficulty, in the case of complex systems or structures, lies in the possible occurrence of modalities of failure, which were not contemplated in the formulation of the model that represents the prototype. The more complex the structure, the greater the risk of unsuspected mechanisms controlling the behavior of the structure (Figure 6). On the other hand, if an attempt is made to incorporate all possible mechanisms we assume may exist, even when there is no information that substantiates these assumptions, most designs would prove to be very costly (Figure 7). To increase site investigation efforts in an attempt to determine whether these potential weaknesses do in fact exist, would also be very costly (in most cases), and still no guarantee would be had, that such defects are not present.

In the second group of procedures proposed for evaluating probabilities of failure, the analysis of records of past behavior of the structure, or other similar structures are the basis for the evaluation. This offers the advantage of being able to incorporate, on an empirical basis, the effect of all modalities of failure (Figure 8). The disadvantage is that it requires that experience be had in dealing with the structure under consideration. Having no previous records on the behavior of such structure is a strong limitation. Comparisons with similar structures remain as the only option. In the case of a truly new structure or an unprecedented condition, this approach is unapplicable.

An attempt to assess the risks of failure of the slopes in Gaillard Cut, must rely mostly on the evaluation of past behavior.

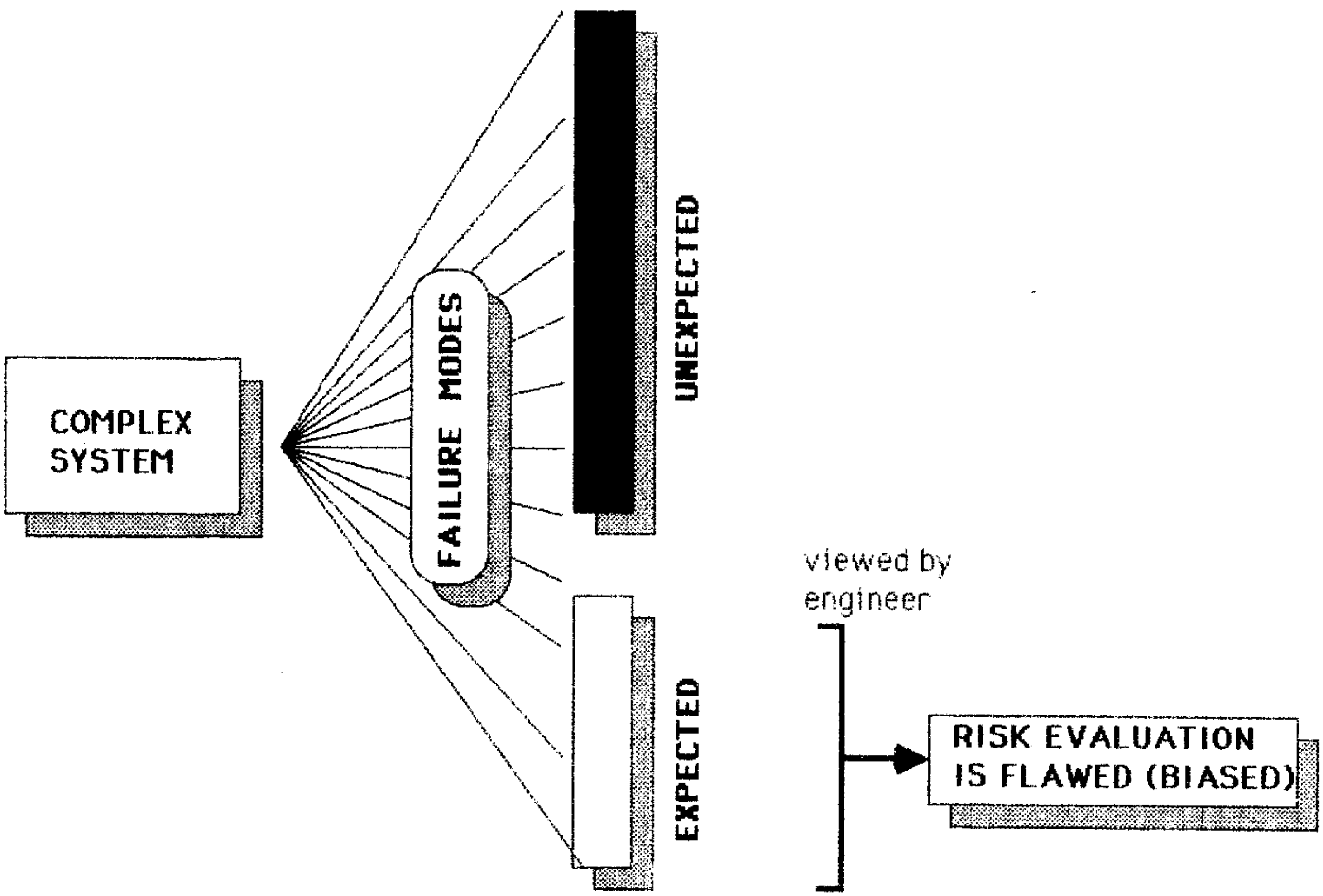


Figure 6: Risk Evaluation based on Analytical Models

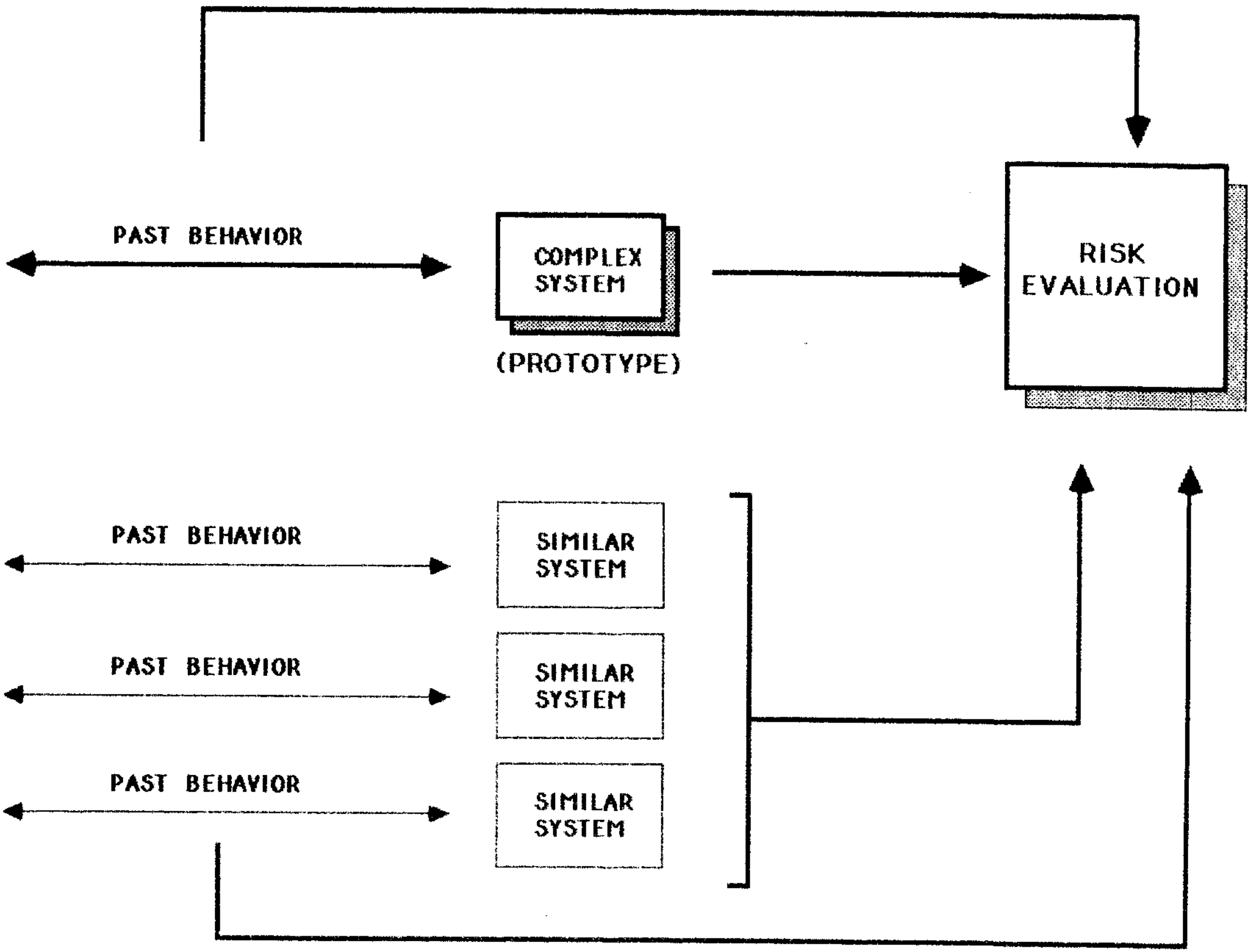


Figure 8: Risk Evaluation based on Analysis of Historical Records

The complex geological nature of the formations present in Gaillard Cut and the complex groundwater regimes, preclude the reliable use of analytical models to predict possible future landslide activity.

The assessment of risks requires a qualitative understanding of the causes of failure. By viewing the information contained in figures 2 and 3 on the slide history of Gaillard Cut, valuable insights may be gained in understanding the nature of the landslide problem. Consider the following observations:

1) Slides are almost always extensions or reactivations of previous slides. We use the term extension to denote sliding in previously stable material surrounding a previously existing slide. It can be a "lateral" extension if the slide area increases in width, or a "backward" extension (or "retrogression") if the slide area increases in length. The term reactivation refers to sliding along a pre-existing slip surface. Few slide areas have developed after the construction of the Canal, the Cut Widening Project or another similar, isolated "disturbing" factor. Experience indicates that slide areas rarely develop without strong external factors.

2) These recurring slide areas almost always involve some weakness plane or geologic detail that differentiates the failed area from the surrounding slopes.

3) With the exception of Hodges Hill, no slide activity has been detected in the large igneous hills in Gaillard Cut. Problems are basically confined to the weathered tuff formations (Cucaracha, La Boca, Culebra, Gatuncillo, and Las Cascadas Formations).

4) Virtually all slides not related to excavation occur during periods of peak precipitation or periods of high precipitation coupled with surface drainage problems (Ref. 1, Report 2). The manner in which we believe this rainfall affects the stability of the slopes is discussed in a subsequent section of this report. However, the effectiveness of surface drainage systems is notable in a number of cases. For example, consider the recurring landslide activity in Sardinilla. In 1975 remedial drainage work was performed in the area (Ref. 10). No instabilities have been observed since.

5) Slopes do not appear to fail suddenly without warning. Recent experiences with the Landslide Control Program and many descriptions of previous slide activity (Ref. 1, Report 2) support this statement.

This understanding of the conditions and events that led to slope failures in Gaillard Cut in the past, is perhaps the best information available for predicting future landslide activity.

The rates of failure after construction (after widening in the West Bank), offer good estimates of risk. The slopes in Gaillard Cut provide a rare opportunity to observe slope behavior over a relatively long period of time. The post-construction failure rates offer information that incorporates all the internal complexity of the slopes and all the rigors of the tropical, high precipitation environment. Whatever the actual combination of conditions that took place, these were the necessary ones to cause failure. And the observed rates of failure reflect the frequency with which these circumstances took place.

Although it is true that stabilization works increase the safety of the slopes in most cases, the aggressive environment damages remedial works (drainages in particular). The cyclic variations in safety produced by these opposing (and compensating) forces, are all implicitly contemplated in the observed rates of failure.

Table 4, and Figures 9 and 10 present the post-construction/ post-widening rates of failure in the East Bank and West Bank, respectively. These can be used as adequate estimates of the probabilities of failure for each zone.

For zones that have not failed in the past, the concept of "base-line" or "default" probability of failure is useful (Ref. 27). A probability of failure of pf=0.01 is a conservative and unbiased estimate of the annual probability of failure for these zones, given that they have not failed in almost a century, and their failure does not appear to be imminent. Combining this concept with Figures 9 and 10, we can arrive at estimates for the probability of failure for

Post-Construction Failure Rates
East Bank

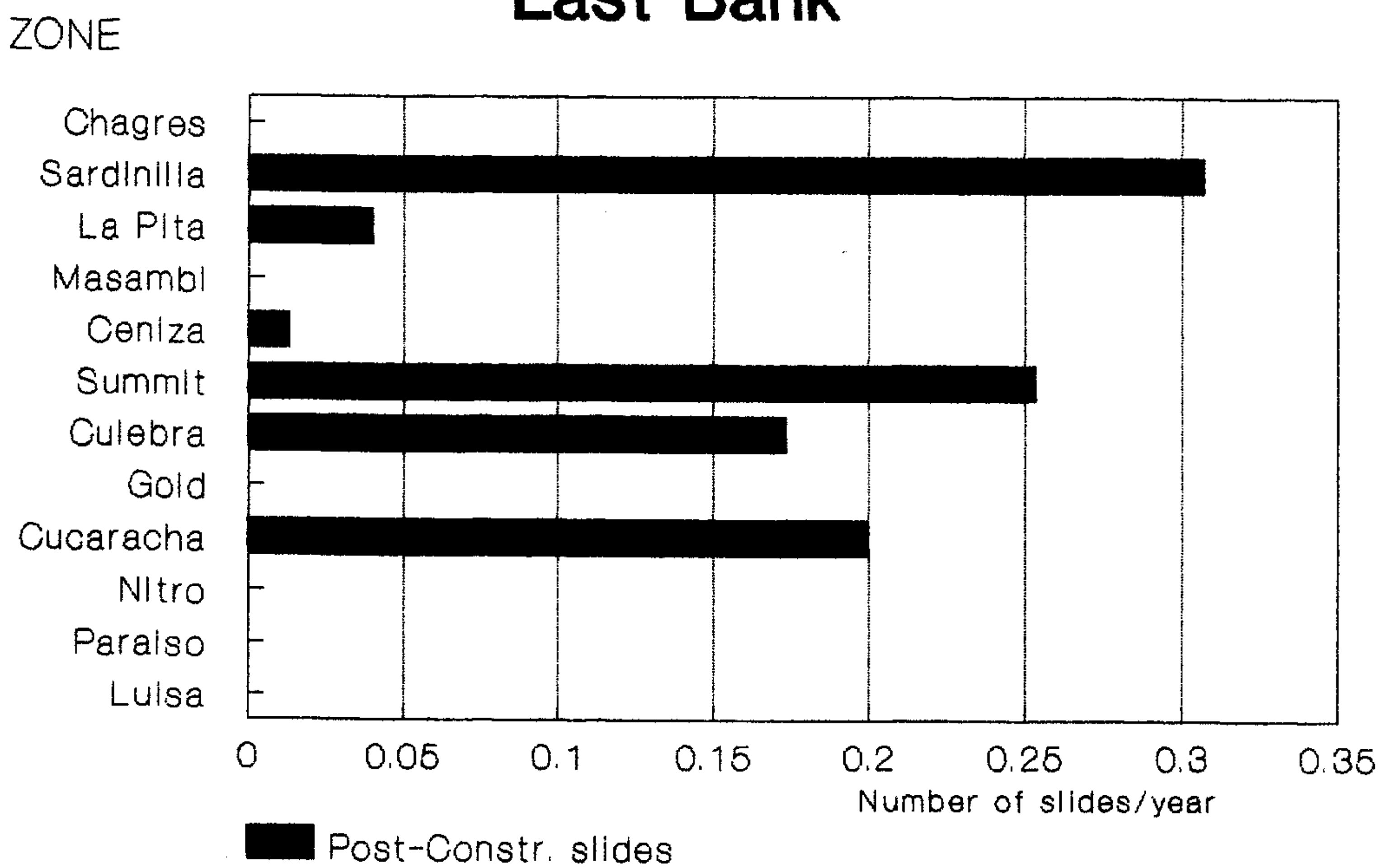


Figure 9

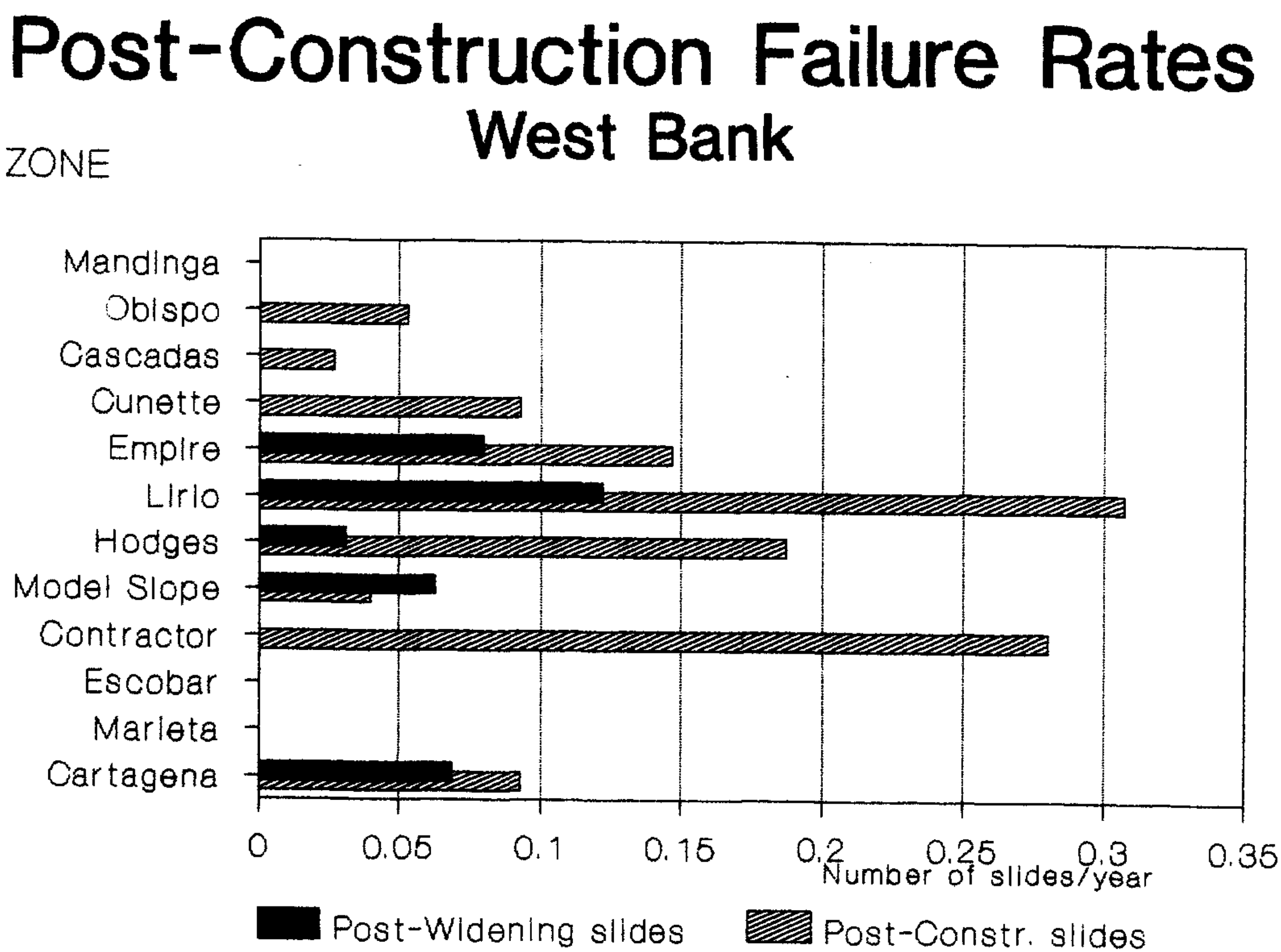

Post-Construction Failure Rates
West Bank
ZONE
Mandinga
Obispo
Cascadas
Cunette
Empire
Lirio
Hodges
Model Slope
Contractor
Escobar
Marieta
Cartagena
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Number of slides/year
Post-Widening slides
Post-Constr. slides

Figure 10

all zones (Figures 11 and 12). Although the period of time after the Cut Widening Project is variable for the West Bank zones, and in all cases less than a century, the same default value of risk (pf=0.01) will be maintained for slopes that have not manifested post-widening landslide activity. There are several reasons to support this decision. First, most slides which were active during the pre-widening period, were removed during the widening. Second, this project was carried out with a technological knowledge far superior to that which existed during Canal construction. The designs for the Cut Widening had a rational basis. Third, the behavior of these slopes, that have had no post-widening activity, seems very similar to that of east bank slopes that have been quiescent since Canal construction. Hence, the writer feels that the stated default value of risk is a better representation of the state of these slopes than a higher risk level that corresponds, say to the inverse of the post-widening periods for each case.

The probabilities of failure discussed up to this point are the probabilities that a given slope will show signs of distress in a given year. The probabilities that encroachments will occur are much smaller than the former, in view of the Landslide Control Program.

The Landslide Control Program is an valuable tool for reducing the consequences of landslide activity in the Cut. The overall risk of channel encroachments is significantly reduced by the fact that many uncertainties are effectively bypassed by observation. Of the 20 instabilities detected by the Landslide Control Program since its

Figure 11: Estimated Annual Probabilities of Failure (East Bank)

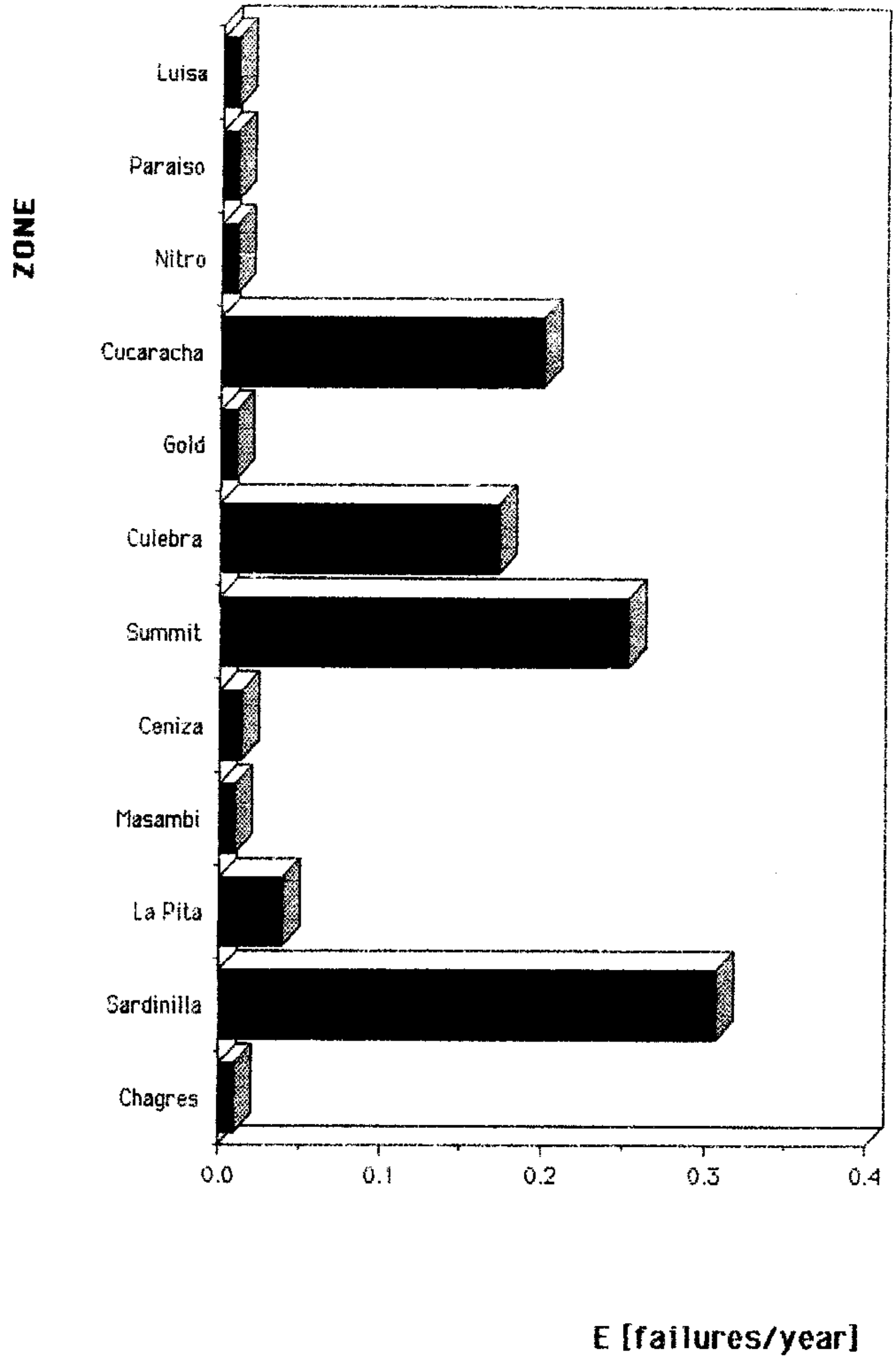
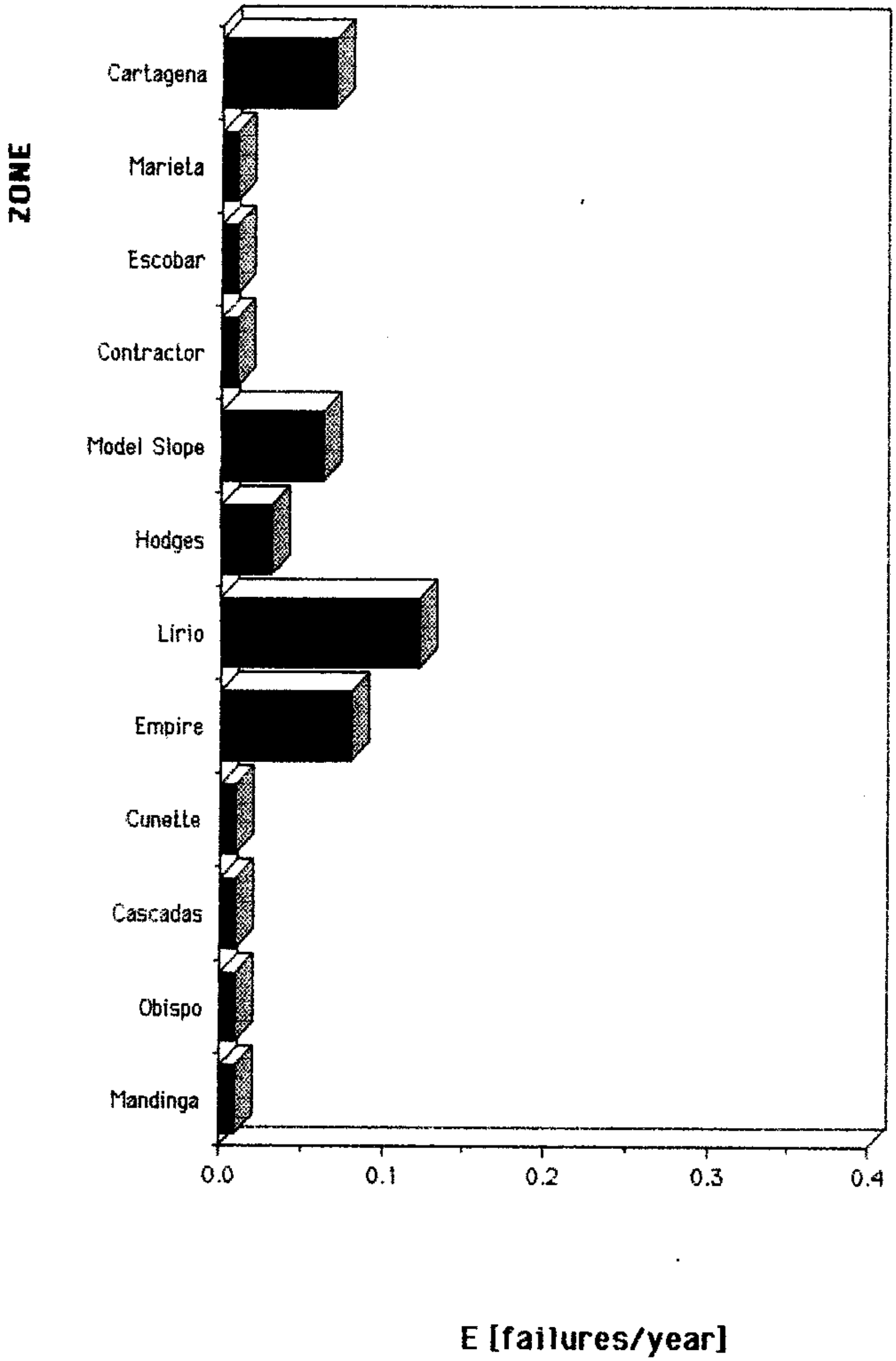


Figure 12: Estimated Annual Probabilities of Failure (West Bank)



inception, only two have caused channel encroachments. The risk of such encroachments is then roughly an order of magnitude less than the risk of a slope manifesting instability.

Figure 13 shows the movements that took place prior to a slide in selected slopes (Ref. 8). The figure shows that the magnitude of the movements that lead to a fully developed failure are very dissimilar from one slope to another. No specific "signature" associated with a fully developed slide is readily evident. For example, the Cucaracha Slide exhibited much larger movements than the 1925 E Slide before reaching failure.

We can hypothesize a mechanism which is consistent with much of the observed information. During critical periods of high precipitation (Ref. 39), rainfall causes saturation of the potentially unstable mass. This increases its weight significantly and exerts pressures on the sliding mass by filling cracks along its periphery. This overstresses the materials along the slip surface, causing in many cases strain-softening. This in turn manifests itself on the ground surface as movements. Continued movements of a slope (even if at a constant rate) should suggest that remedial measures be implemented promptly. This represents a change with respect to our current practice that recommends remedial measures only when the rate of movements increases continuously.

If this change is adopted, the costs of maintenance will increase somewhat, but the risk of channel encroachments will be further

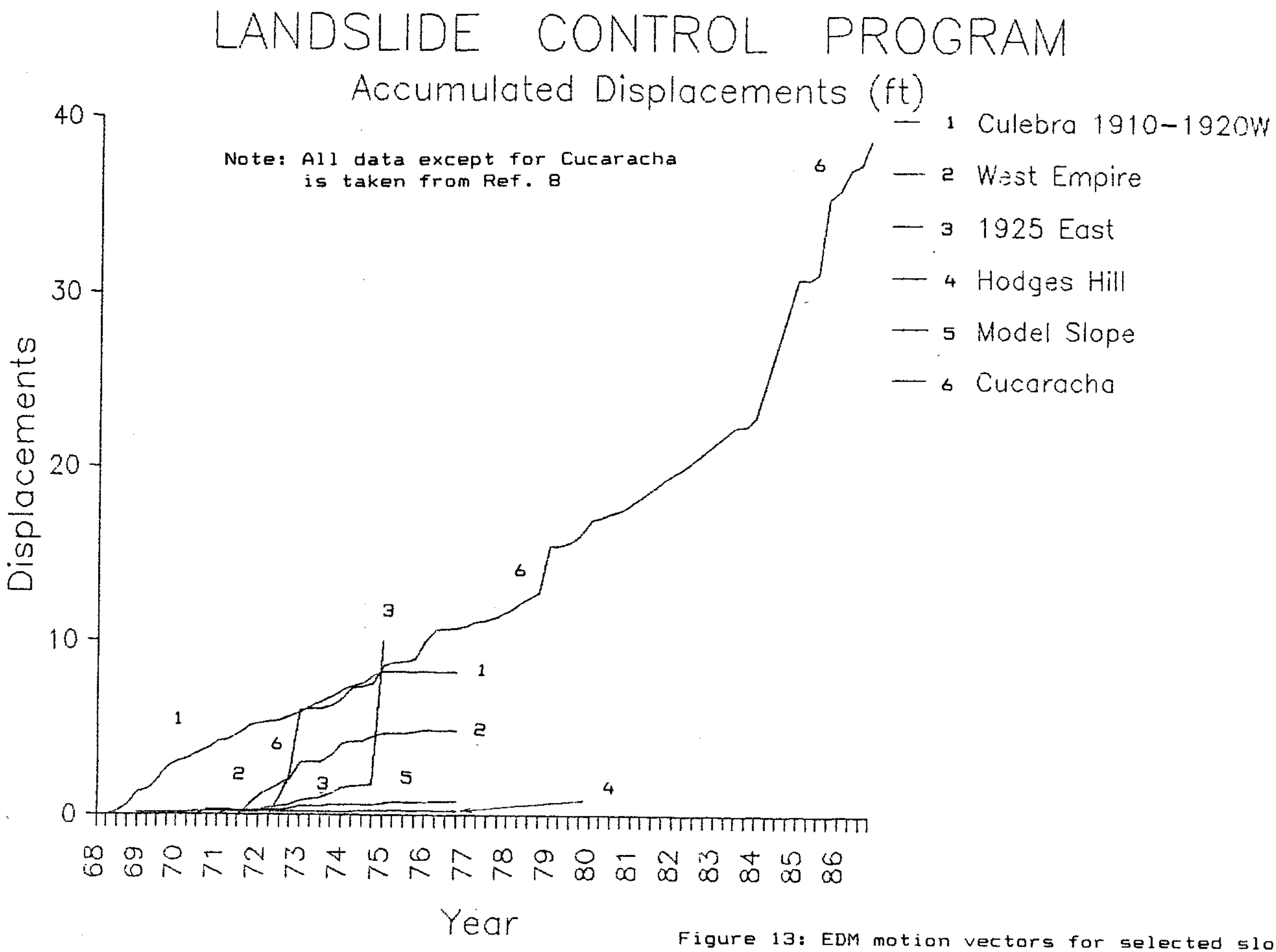


Figure 13: EDM motion vectors for selected slopes

reduced. The 1925 E Slide and the Cucaracha Slide would not have taken place under such conditions. The writer doubts that the cost of the additional remedial works implied by the change in strategy would have been comparable to the costs generated by these two slides.

All previous discussions refer to slides in the weathered tuff formations; the type of events that have occurred in the past. The potential future instabilities explored are of the same type. What is the chance that a new type of phenomenon takes place? Of particular interest is the potential instability of one of the large igneous hills. We could hypothesize that the probability of such an event taking place should be no larger than 0.001 or 0.0001. This is consistent with the much greater strength and apparent integrity of these masses. These values are one or two orders of magnitude smaller than the probability of failure of one of the slopes in the weathered tuff formations that have not experienced instabilities in the past.

The past quiescence of these slopes, contrasted with the high degree of activity of the other areas, has justifiably biased all landslide control efforts in favor of the latter. However, although the risk of failure is small in these igneous slopes, the consequences of failure would be so high that the situation merits further study. An attempt to eliminate the problem (flattening the slopes or entirely removing the bulk of the material in question), may not be economically feasible. It is reasonable, however, to devise and implement monitoring practices that effectively extend the scope of the Landslide Control Program to these areas.

These considerations take on a much greater significance if improvement projects take place which alter the configuration of these slopes. The proposed Cut Widening Project is the most prominent case. It involves substantial excavation in Gold Hill and Nitro Hill. These are perhaps the best examples of the case in point.

E. Evaluation of Potential Channel Encroachments

Table 5 presents a prediction of the greatest potential encroachments in each bank. These are not expected encroachments; just the maximum values predicted by the analysis presented in Section II.C of this report. The regression line in Figures 4 and 5 coincide reasonably well with the criteria proposed by Binger in 1946. However, the upper prediction limits (which are effectively upper bounds to all the observed data contained in Table 3), were used to generate the conservative values of encroachments shown in Table 5. Figures 14 and 15 present a graphic representation of these maximum encroachments in the East and West Banks respectively.

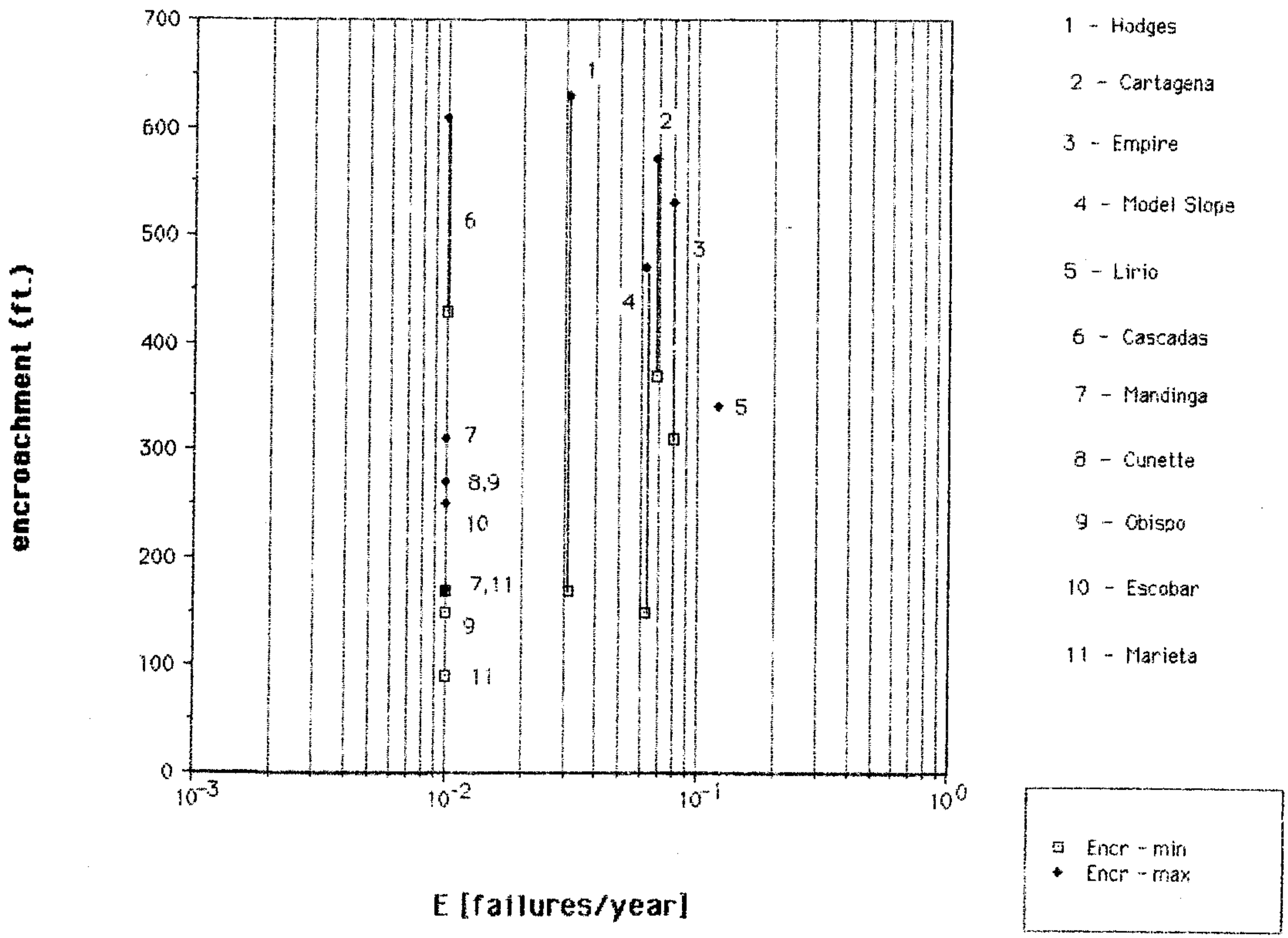
As stated previously, practically all the slide in Gaillard Cut have occurred in weathered tuffs (Cucaracha, Culebra, Gatuncillo, La Boca, and Las Cascadas Formations). Therefore the relationships used to estimate encroachments are only valid in these materials. No slide has occurred in one of the large igneous hills, except for the movements observed in Hodges Hill in 1968. The maximum encroachment predicted for Zone Hodges is the only value that contemplates the potential failure of the igneous hill. All other zones containing igneous hills present potential encroachment which do not contemplate a slide in the igneous materials.

F. Comparison of Relative Risks

Figures 16 and 17 present a comparison of the the potential for channel encroachments due to landslides in each zone. By plotting the estimated probabilities of failure (of manifesting instability) v.s. the (range of) potential encroachments for each zone, the zones that present the greatest danger of hindering or blocking navigation are easily detected. The range of potential encroachments refers to the variety of encroachments which can occur in a given zone due to variations in conditions within the zone. These are typically variations in slope height, the presence of igneous masses, etc.

As discussed previously, the Landslide Control Program effectively reduces the risk levels by approximately an order of magnitude. Still, the areas that present the largest probabilities of manifesting instabilities, and pose the greatest dangers of encroaching the navigation channel, are the ones we wish to see highlighted in this figure. Such information provides valuable guidance in the process of allocating advantageously the resources available for landslide control.

Figure 17: Comparison of West Bank Zones



Whitman (Ref. 24) has published criteria (proposed by Baecher) for assessing the probabilities of failure of slopes and other structures, based on past experiences. Figure 18 summarizes this information. We have added three additional items to this figure, for comparison purposes. These are:

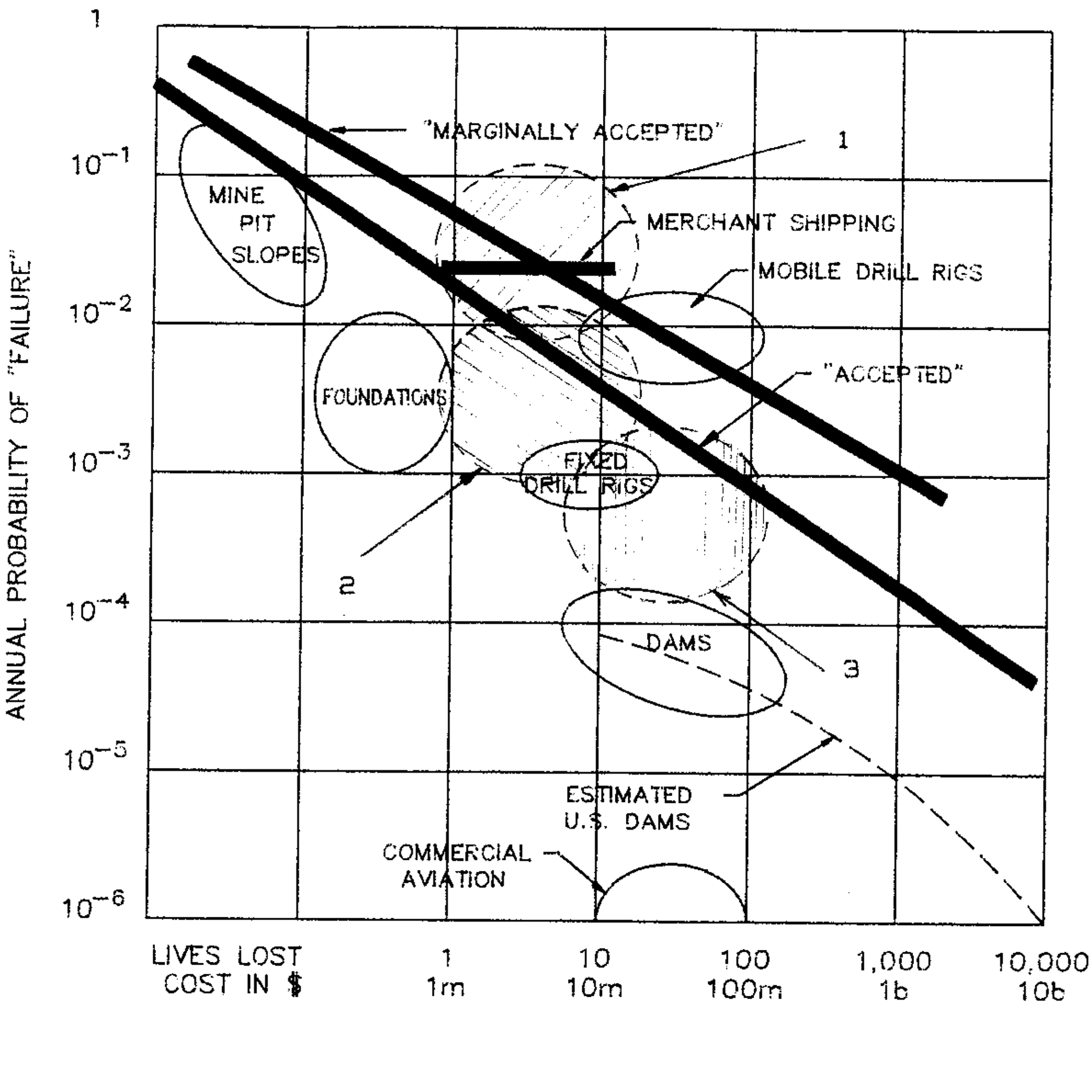
1. The ranges applicable to the (tuffaceous) slopes in Gaillard Cut, when the probabilities that the slopes will manifest distress are used as the probabilities of failure (these would most likely be the probabilities of failure if no Landslide Control Program were available).

2. The ranges applicable to the same slopes, but using probabilities approximately an order of magnitude lower, due to the implementation of the Landslide Control Program.

3. The ranges applicable to the large igneous hills in Gaillard Cut.

The costs are rough estimates based on the cost of the 1986 Cucaracha Landslide. The risks were discussed in Section II.D of this Report. The impact of the Landslide Control Program is evident.

Figure 18: Risks for Selected Engineering Projects (Ref. 24)



1 - Slopes in Gaillard Cut (no LCP)
2 - Slopes in Gaillard Cut (with LCP)
3 - Large Igneous Hills in Gaillard Cut

LCP: Landslide Control Program

III. CONCLUSIONS

1. The criteria on which the zonation scheme was based, appear to be reasonable. Each zone presents a relatively homogeneous geologic environment. The patterns of behavior in each zone do seem to be characteristic of the zone. Consequently we can expect to predict behavior patterns within each zone, reasonably well.

2. Almost all the zones that have shown distress after the construction of the Canal, have presented problems earlier. Unless there are significant changes in conditions (like channel deepening or widening), slides rarely occur in previously stable slopes. On the other hand, zones that do present slides, normally present an ongoing process of activity that has many slide events.

3. Two types of activity have been normally associated with a slide area: the reactivation of an old slide and the extension of the slide area by unstabilizing previously stable terrain behind the slide (backward extension) or laterally adjacent to the slide (lateral extension). These two phenomena are believed to result from progressive deterioration of the strength that maintains these slopes stable. It is conjectured that this deterioration is caused by strong rainfall events that overstress the slip surface and by the gradual deterioration of previously implemented remedial works (particularly drainage systems) in the aggressive tropical environment. Then, a critical rainfall event (with

respect to the degree of deterioration of the slope) triggers the fully developed slide. The fact that rainfall appears to be the main source of failures, suggests that greater emphasis should be placed on controlling surface drainages.

4. The limited information available on past channel encroachments, leads us to believe that the height of a sliding mass (with respect to its toe), is a useful parameter for predicting potential encroachments. The former can be interpreted as an index that quantifies the potential energy of the sliding mass. When the slide occurs, this energy is converted into motion.

5. Figures 11 and 12 show the estimated probabilities that each zone will manifest some sort of distress in a given year. When these risks are viewed together with the potential encroachments that could result from a slide in the corresponding zone (Figures 16 and 17), the zones requiring more attention are highlighted. These are:

<u>EAST BANK</u>	<u>WEST BANK</u>
Cucaracha	Hodges
Summit	Cartagena
Sardinilla	Empire
La Pita	Model Slope
Culebra	Lirio
	Cascadas

Notice that abundant landslide activity, does not necessarily eliminate the risk of encroachment in a given zone. Many slides leave a great deal of mass in place. This mass is reflected by the potential encroachments shown in Figures 14 and 15.

6. Slides do not develop suddenly (at least in the weathered tuffs). This observation yields a very valuable benefit: the Landslide Control Program can detect incipient slides before they develop fully. Consequently, the risks that slides will cause channel encroachments are substantially less than the risks that those same slides will manifest distress. This reduction is estimated to be at least one order of magnitude with current practice. The writer believes that these risks can be reduced by an additional order of magnitude or more with a systematic program of inspections and maintenance, and the proposed change in interpretation of the monitoring data (Section II.D of this report).

IV. RECOMMENDATIONS

1. It is essential to document systematically all slope activity in great detail. This information is the key to understanding the underlying mechanisms which control the landslide processes, and hence the key to our capabilities for predicting potential future activity. This is especially true given the fact that the landslide history in the Cut shows that slide activity consists mainly of reactivations and extensions of previous slides.

2. A number of modifications to the surveillance operations of the Landslide Control Program should be considered:

a. Correlate EDM monuments with specific potential mechanisms (reactivation, lateral extension, or backward extension) related to a slide area. Add new monuments to areas in which a potential extension or reactivation is not adequately covered. Identify those monuments that are not directly related to an existing slide area. Their activity would indicate the formation of a new slide area.

b. Explore failure mechanisms which can potentially affect the large igneous hills. Then investigate the types of monitoring that could warn of such events, and implement them.

c. Study motion records systematically in order to attempt to understand typical "signatures" that signal imminent landslide activity. Until this phenomenon is better understood, consider implementing remedial measures in areas that show a constant rate of movement, if such movements are consistent, or even in areas that show intermittent movements if these are substantial.

3. We must establish a program of systematic inspections of each of the zones in Gaillard Cut. This was one of the main recommendations of the Geotechnical Advisory Board during its first meeting held in September 1987. This measure is very

important in two ways: engineers at the site can detect signs of distress to which the surveillance system is not sensitive to (for example impeded surface drainages); and they can observe areas that escape the resolution of the surveillance system. Additional resources are required in order to enable the Geotechnical Branch to perform this task adequately. New penetration roads, inspection footpaths, extensive clearing and grubbing of the more densely vegetated areas, and perhaps more personnel, are necessary.

4. We must establish a systematic program of maintenance to repair drainage systems and other remedial works that deteriorate steadily in the local environment. This program should be guided by to the inspections outlined above.

5. Given the hypothesis that precipitation is usually the main cause of slope deterioration, and the event that usually triggers the slide, it seems natural that we should utilize surface drainages to a greater extent. Drainage systems are much more economical and probably more effective than excavation projects. This is especially true before a slide develops fully.

6. In the event that insufficient resources are available for adequate landslide control (funds, manpower or both), it is important to improve existing emergency management measures. Channels of communication between the various Panama Canal Commission units involved in post slide remedial efforts, and

explicitly stated responsibilities must be well established before a crisis begins. A. P. Mann's LEAP Program (Ref. 11) is a good starting point.

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APPENDIX A: Summary of Past Landslides in Gaillard Cut

APPENDIX A: Compilation of Past Landslides in each Zone

EAST BANK

ZONE: Chagres

Bas Obispo Slide. Sta. 1682-1688 E/ Bas Obispo Formation.
Dates of activity: 1910 to 1912.
1910 - Initial slide in dump & weathered rock
d=60' L=250' d/L=0.24

ZONE: Sardinilla

Haut Obispo Slide. Sta. 1709-1710 E/ Las Cascadas Formation
Dates of activity: 1907 to 1912
1908 - Initial slide in soil & weathered rock
d=30' L=160' d/L=0.19 theta=7 deg.
1912 - Initial slide in materials weakened by faulting
d=35' L=120' d/L=0.29

East Buena Vista Slide (includes Station 1561 E Slide). Sta. 1720 - 1730 E/ Las Cascadas Formation
Dates of activity: 1912 to 1923
1907 - Initial slide in weathered rock
d=25' L=100' d/L=0.25

Las Cascadas E Slide ("Spillway Slide"). Sta. 1746-1755 E/ Las Cascadas Formation
Dates of activity: pre-1888 to 1965
1908 - Initial slide in soil & weathered rock
d=50' L=310' d/L=0.16 Theta=15 deg.
1910 - Initial slide along bedding
d=50' L=630' d/L=0.08 Theta=12 deg.
1942 - Initial slide along bedding
d=50' L=600' d/L=0.08 Theta=10 deg.

Station 1597 E Slide (part of East White House Slide). Sta. 1760-1765 E/ La Boca Formation
Dates of activity: 1908 to 1935
1912 - Initial slide mainly along bedding
d=40' L=170' d/L=0.24 Theta= 18 deg.

Station 1603 E Slide (part of East White House Slide). Sta. 1766-1776 E/ La Boca Formation
Dates of activity: 1907 to 1958
1907 - Initial slide along bedding
d=25' L=130' d/L=0.19 Theta=5 deg.
1908 - Initial slide along bedding
d=50' L=220' d/L=0.23 Theta=9 deg.
1910 - Initial slide along bedding
d=50' L=410' d/L=0.12 Theta=6 deg.

1914 - Reactivated slide
d=230' L=1640' d/L=0.14 theta=6 deg.

1920 - Reactivated slide
d=170' L=1260' d/L=0.13 theta=8 deg.

1972 - Reactivated slide
d=100' L=800' d/L=0.13 theta=7 deg.

1986 - Reactivated slide
d=150' L=1500' d/L=0.10 theta=7 deg.

Cucaracha South Extension Slide. Sta. 1983-1992 E/ Cucaracha Formation and Culebra Formation.
Dates of activity: 1885 to 1986

1907 - Initial slide in dump fill & weathered rock
d=40' L=200' d/L=0.2 theta=10 deg.

1910 - Initial slide along bedding
d=80' L=650' d/L=0.12 theta=5 deg.

1912 - Reactivated slide
d=130' L=540' d/L=0.24 theta=4 deg.

1986 - Reactivated slide
d=50' L=500' d/L=0.1 theta=4 deg.

Station 1830 E Slide. Sta. 1996-2000 E/ Cucaracha Formation and Culebra Formation.
Dates of activity: 1909 to 1954

1910 - Initial slide in soil & weathered rock
d=30' L=510' d/L=0.06 theta=9 deg.

Cucaracha Village Slide. Sta. 2007-2010 E/ Cucaracha Formation and Culebra Formation
Dates of activity: 1907 to 1930

1912 - Reactivated slide
d=60' L=520' d/L=0.12 theta=11 deg.

ZONE: Nitro

(No slides)

ZONE: Paraiso

Paraiso Slide. Sta. 2040-2048 E/ Cucaracha Formation and Culebra Formation
Dates of activity: 1888 to 1912

1908 - Reactivated slide
d=45' L=580' d/L=0.08 theta=9 deg.

ZONE: Luisa

(No slides)

WEST BANK

ZONE: Mandinga

Station 1690 W Slide. Sta. 1689-1692 W/ Bas Obispo Formation
Dates of activity: unknown (early construction period)
- First time slide along (assumed) preexisting defects
  d= ? L=450' max. (200' widening + 250' visible)

Station 1709 W Slide. Sta. 1709-1710 W/ Bas Obispo Formation
Dates of activity: unknown (early construction period)
- First time slide along (assumed) preexisting defects
  d= ? L=300' max. (200' widening + 100' visible)

ZONE: Obispo

West Buena Vista Slide. Sta. 1731-1733 W/ Las Cascadas Formation
Dates of activity: pre-1895 to 1916
1904 - Reactivated slide (TWR/TSR ?)
  d=40' L=160' d/L=0.25 theta=14 deg.
1912 - Extension (Retrogression of 1904 slide) TWR/TSR ?
  d=55' L=270' d/L=0.20 theta=13 deg.

Station 1585 W Slide. Centered @ Sta. 1751 W/ Las Cascadas Formation
Dates of activity: 1912
1912 - Initial slide in material weakened by faulting
  d=40' L=80' d/L=0.5

ZONE: Cascadas

West White House Extension Slide. Centered @ Sta. 1770 W/ La Boca Formation
Dates of activity: 1912 to 1964
1912 - Initial slide in material weakened by faulting
  d=25' L=140' d/L=0.18
1954 - Initial slide along a fault (3D wedge)
  d=50' L=250' d/L=0.2 theta=30 deg.

White House Yard Slide. Centered @ 1783 W/ La Boca Formation and Las Cascadas Formation
Dates of activity: 1907 to 1930
1930 - Initial slide along fault & material weakened by faulting (3D wedge)
  d=70' L=300' d/L=0.23 theta=21 deg.

Station 1623 W Slide. Centered @ Sta. 1790 W/ Las Cascadas Formation
Dates of activity: 1912
1912 - Initial slide across bedding
d=20' L=130' d/L=0.15
(possible weakness plane ?)

Station 1629 W Slide. Centered @ Sta. 1796 W/ Las Cascadas Formation
Dates of activity: 1912 to 1913
1913 - Initial slide across bedding
d=35' L=130' d/L=0.27

ZONE: Cunette

Station 1638 W Slide. Centered @ Sta. 1806 W/ Las Cascadas Formation
Dates of activity: 1910
1910 - Initial slide across bedding
d=45' L=140' d/L=0.32

Station 1643 W Slide. Centered @ Sta. 1809 W/ Las Cascadas Formation
Dates of activity: 1962
1962 - Initial slide across bedding
d=40' L=200' d/L=0.2

Cunette Slide. Centered @ Sta. 1835 W/ Las Cascadas Formation
Dates of activity: 1910 to 1912
1910 - Initial slide across bedding
d=70' L=260' d/L=0.27

Southwest La Pita Slide. Centered @ Sta. 1840 W. Las Cascadas Formation
Dates of activity: 1925 to 1931
1929 - Initial slide across bedding
d=65' L=190' d/L=0.34 rotational

ZONE: Empire

Division Office Slide. Centered @ Sta. 1864 W/ Pedro Miguel and La Boca Formation.
Dates of activity: 1906 to 1961
1912 - Initial slide along & across bedding ?
d=120' L=400' d/L=0.3
1913 - Reactivated slide
d=120' L=650' d/L=0.18

West Empire Active Area. Centered @ 1864 W/ Pedro Miguel and La Boca Formation (Cucaracha Formation ?)
Dates of activity: 1961 to 1986
1961 - First time slide along faults (3D wedge)
d=100' L=900' d/L=0.11

Station 1703 W Slide. Centered @ 1870 W. Pedro Miguel
Dates of activity: 1912 to 1935
1912 - Initial slide across bedding
d=55' L=180' d/L=0.31

Station 1713 W Slide. Centered @ 1881 W. Pedro Miguel
Dates of activity: 1912 to 1930
1912 - Initial slide mainly along a fault plane
d=30' L=140' d/L=0.21
1913 - Initial slide mainly along a fault plane
d=25' L=70' d/L=0.36

ZONE: Lirio

Old Lirio Slide (Part of the now called West Lirio Slide).
Sta. 1888-1896 W/ Pedro Miguel and Culebra Formation
Dates of activity: 1912 to 1983
1912 - Initial slide mainly across bedding
d=80' L=300' d/L=0.27 theta=7 deg.
1913 - Initial slide mainly across bedding
d=115' L=520' d/L=0.22 theta=8 deg.
1983 - Rotational extension of slide in weathered rock
d=45' L=400' d/L=0.11

Station 1735 W Slide (Part of the now called West Lirio Slide). Centered @ Sta. 1902 W/ Culebra and Gatuncillo Formations
Dates of activity: 1923 to 1986
1924 - Initial slide mainly across bedding
d=140' L=480' d/L=0.29 theta=7 deg.
1983 - Rotational extension of slide in weathered rock
d=45' L=500' d/L=0.09
1986 - Reactivation of 1983 Slide

Culebra Village Slide (Part of the now called West Lirio Slide). Centered @ Sta. 1910 W/ Cucaracha Formation and Culebra Formation
Dates of activity: 1899 to 1934
1908 - Reactivated slide
d=40' L=150' d/L=0.27 theta=3 deg.
1909 - Initial slide along bedding ?
d=60' L=415' d/L=0.14 theta=4 deg.
1913 - Initial slide along bedding ?
d=100' L=570' d/L=0.18 theta=3 deg.

1910 W-1920 W Problem Area. Sta. 1910-1920 W/ Culebra Formation
Dates of activity: large surface motions were detected in the period 1968 to 1975. Geotechnical Branch implemented remedial measures in 1975.

New Town Slide. Centered @ Sta. 1920 W/ Culebra Formation
Dates of activity: pre 1908 to 1911
1908 - Initial slide in dump fill & weathered rock
d=50' L=220' d/L=0.23

ZONE: Hodges

Old Hodges Hill Slide. Sta. 1927 - Sta. 1939 W/ Pedro Miguel, Cucaracha Formation and Culebra Formation
Dates of activity: 1909 to 1951
1912 - Initial slide mainly along bedding ?
d=150' L=690' d/L=0.22 theta=7 deg.
1912 - Initial slide along & across bedding ?
d=130' L=640' d/L=0.20

Hodges Hill Active Area. Centered @ Sta. 1935 W/ Pedro Miguel, Cucaracha Formation and Culebra Formation
Dates of activity: 1968 to 1969
1968 - Initial slide across bedding
d=120' L=800' d/L=0.15

West Culebra Slide. Sta. 1939 - Sta. 1962 W (extends well within the adjacent sector: Model Slope) / Cucaracha Formation
Dates of activity: 1900 to 1915
1900 - Initial slide along & across bedding
d=85' L=240' d/L=0.35
1915 - Initial slide mainly along bedding
d=200' L=1080' d/L=0.19

ZONE: Model Slope

West Culebra Slide. (see description in previous zone)

Model Slope Area. Sta. 1962-1971 W/ Cucaracha Formation and Culebra Formation
Dates of activity: 1951-1971
1971 - Initial slide mainly across bedding (rotational).
Perhaps intensive faulting is involved in the failure mechanism (material weakened by faulting).

ZONE: Contractor

North Contractors Hill Slide. Centered @ Sta. 1970 W/ Pedro Miguel Agglomerate and Cucaracha Formation
Dates of activity: 1907 to 1943
1906 - Initial slide in soil
d=35' L=110' d/L=0.32 rotational

1911 - Initial slide in soil
d=40' L=135' d/L=0.30 rotational
1912 - Initial slide in soil
d=30' L=100' d/L=0.30 rotational
1912 - Initial slide across bedding
d=40' L=250' d/L=0.16 rotational

<u>Contractors Hill Fissures</u>. Centered @ Sta. 1976 W/ Pedro Miguel Agglomerate and Cucaracha Formation
Dates of activity: 1954
(no information available)

<u>South Contractors Hill Slide</u>. Centered @ 1982 W/ Pedro Miguel Agglomerate and Cucaracha Formation
Dates of activity: 1908 to 1919
1908 - Initial slide in soil & weathered rock
d=35' L=100' d/L=0.35 rotational
1911 - Initial slide across bedding
d=65' L=260' d/L=0.25 rotational

<u>Cucaracha Signal Station Slide</u>. Centered @ 1985 W/ Cucaracha Formation
Dates of activity: 1908 to 1941
1910 - Initial slide in soil & weathered rock
d=25' L=100' d/L=0.25 rot?
1924 - Initial slide across bedding
d=65' L=290' d/L=0.22 rotational

ZONE: Escobar

<u>Station 1823 W Slide</u>. Centered @ 1991 W/ Cucaracha Formation
Dates of activity: 1901 to 1910
1909 - Initial slide in soil & weathered rock
d=20' L=140' d/L=0.14 rotational
1910 - Initial slide in soil & weathered rock
d=35' L=160' d/L=0.22 rotational

ZONE: Marieta

(No slides)

ZONE: Cartagena

<u>Cartagenita Slide</u>. Sta. 2065-2070 W/ Pedro Miguel Agglomerate
Dates of activity: 1936
1936 - Initial slide across bedding
d=50' L=250' d/L=0.2 weakness plane ?

Cartagena Mudflow. Sta. 2070-2073 W/ Pedro Miguel Agglomerate
Dates of activity: pre-1942 to present

1958 - Reactivated slide
d=50' L=670' d/L=0.07 slide along the "Top of sound rock" line.

1986 - Reactivated Slide (approximately same dimensions as the 1958 slide).

Cartagena Slide. Sta. 2073-2080 W/ La Boca Formation
Dates of activity: 1889 to 1931

1907 - Reactivated slide (weathered rock ?)
d=40' L=290' d/L=0.14

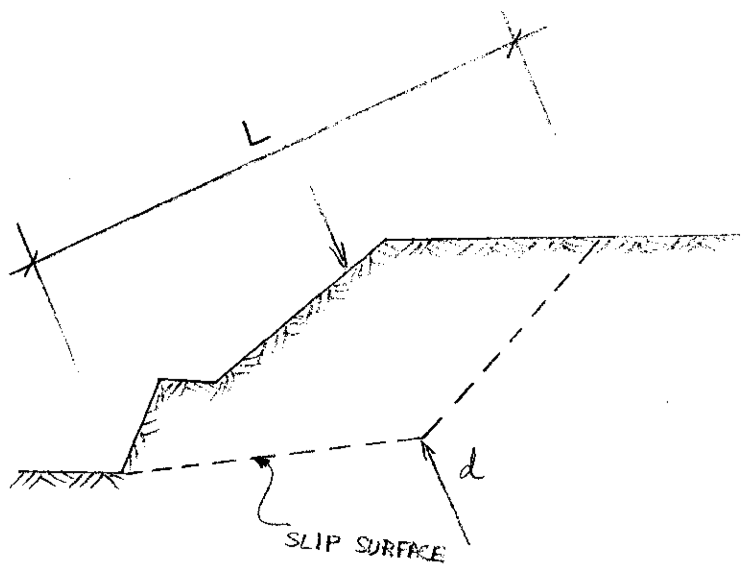
1931 - Initial slide across bedding
d=80' L=510' d/L=0.16

Cartagena South Extension Slide. Sta. 2080-2085 W/ La Boca Formation
Dates of activity: 1964

1964 - Initial slide mainly across bedding (rotational)
d=110' L=440' d/L=0.25

TABLE 6

SUMMARY OF DESCRIPTIVE STATISTICS OF SLIDING MASSES										
CASE	n	$\overline{d}$	Vd	RANGE	$\overline{L}$	VL	RANGE	$\overline{d/L}$	Vd/L	RANGE
ALL SLIDES	110	76'	75%	20' - 380'	402'	82%	70' - 1640'	0.23	45%	0.06 - 0.79
EAST BANK (ALL)	62	81'	80%	25' - 380'	452'	83%	100' - 1640'	0.22	52%	0.06 - 0.79
WEST BANK (ALL)	48	68'	65%	20' - 200'	338'	73%	70' - 1080'	0.23	35%	0.07 - 0.50
EAST BANK (POST CONST.)	44	94'	78%	25' - 380'	542'	75%	100' - 1640'	0.21	60%	0.06 - 0.79
WEST BANK (POST CONST.)	35	78%	62%	25' - 200'	400'	66%	70' - 1080'	0.22	34%	0.07 - 0.36



n = NUMBER OF SLIDE EVENTS
$\overline{d}$ = AVERAGE DEPTH OF SLIDING MASS
Vd = COEF. OF VARIATION OF "d"
$\overline{L}$ = AVERAGE LENGTH OF SLIDING MASS
VL = COEF. OF VARIATION OF "L"
$\overline{d/L}$ = AVERAGE DEPTH TO LENGTH RATIO
Vd/L = COEF. OF VARIATION OF "d/L"

TABLE 7

SUMMARY OF DESCRIPTIVE STATISTICS OF SILIDING MASSES PER SECTOR
EAST BANK

SECTOR	n	$\overline{d}$	Vd	RANGE	$\overline{L}$	VL	RANGE	$\overline{d/L}$	Vd/L	RANGE
CHAGRES	1	–	–	–	–	–	–	–	–	–
SARDINILLA	20	45'	46%	25' – 100'	240'	56%	100' – 630'	0.21	32%	0.08 – 0.34
LA PITA	3	75'	20%	60' – 90'	222'	12%	200' – 250'	0.46	63%	0.24 – 0.79
MASAMBI	6	54'	31%	35' – 70'	215'	37%	120' – 310'	0.26	16%	0.23 – 0.79
CENIZA	3	52'	28%	35' – 60'	173'	41%	110' – 250'	0.31	22%	0.24 – 0.38
SUMMIT	6	99'	45%	50' – 180'	390'	63%	120' – 700'	0.31	36%	0.14 – 0.43
CULEBRA	8	165'	68%	80' – 380'	750'	54%	215' – 1440'	0.23	36%	0.11 – 0.37
GOLD	1	–	–	–	–	–	–	–	–	–
CUCARACHA	13	105'	57%	30' – 230'	854'	51%	200' – 1640'	0.13	38%	0.06 – 0.24
NITRO	–	–	–	–	–	–	–	–	–	–
PARAISO	1	–	–	–	–	–	–	–	–	–
LUISA	–	–	–	–	–	–	–	–	–	–

TABLE 8

SUMMARY OF DESCRIPTIVE STATISTICS OF SLIDING MASSES PER SECTOR
WEST BANK

SECTOR	n	$\overline{d}$	Vd	RANGE	$\overline{L}$	VL	RANGE	$\overline{d/L}$	Vd/L	RANGE
MANDINGA	2	-	-	-	-	-	-	-	-	-
OBISPO	3	45'	19%	40' - 55'	170'	56%	80' - 270'	0.32	51%	0.20 - 0.50
CASCADAS	5	40'	51%	20' - 70'	190'	42%	130' - 300'	0.21	22%	0.15 - 0.27
CUNETTE	4	55'	27%	40' - 70'	198'	25%	140' - 260'	0.28	22%	0.20 - 0.34
EMPIRE	6	75'	58%	25' - 120'	390'	84%	70' - 900'	0.25	38%	0.11 - 0.36
LIRIO	9	74'	49%	40' - 140'	395'	36%	150' - 570'	0.20	38%	0.08 - 0.29
HODGES	5	137'	31%	85' - 200'	658'	45%	240' - 1080'	0.23	30%	0.19 - 0.35
MODEL SLOPE	3	162'	41%	85' - 200'	773'	60%	240' - 1080'	0.25	36%	0.19 - 0.35
CONTRACTOR	8	42'	36%	25' - 65'	168'	49%	100' - 290'	0.27	23%	0.16 - 0.35
ESCOBAR	2	27'	39%	20' - 35'	150'	9%	140' - 160'	0.18	31%	0.14 - 0.22
MARIETA	-	-	-	-	-	-	-	-	-	-
CARTAGENA	5	66'	44%	40' - 110	432'	39%	250' - 670'	0.16	41%	0.07 - 0.25

APPENDIX B: Representative Cross-Sections in each Zone

APPENDIX B: Representative Cross Sections in each Zone

East Bank

Zone: Chagres

Sta. 1661 - Highest elevations in the Zone
Sta. 1686 - Through the Bas Obispo Slide

Zone: Sardinilla

Sta. 1709 - Through the Haut Obispo Slide
Sta. 1725 - Through the East Buena Vista Slide
Sta. 1750 - Through the Las Cascadas Slide
Sta. 1763 - Through the Sta. 1597 E Slide
Sta. 1770 - Through the Sta. 1603 E Slide
Sta. 1777 - Through the Sta. 1611 E Slide
Sta. 1786 - Through the Sta. 1619 E Slide
Sta. 1792 - Through the Sta. 1623 E Slide
Sta. 1796 - Through the Sta. 1630 E Slide
Sta. 1805 - Through the Sta. 1640 E Slide
Sta. 1818 - Through the North La Pita Slide

Zone: La Pita

Sta. 1829 - Through the Upper La Pita and Lower La Pita Slides

Zone: Masambi

Sta. 1854 - Through the Sta. 1685 E Slide
Sta. 1858 - Through the Sta. 1689 E Slide
Sta. 1862 - Through the Sta. 1695 E Slide

Zone: Ceniza

Sta. 1870 - Through the Sta. 1702 E Slide (East Empire Slide)
Sta. 1880 - Through the Sta. 1712 E Slide
Sta. 1884 - Through a potentially dangerous condition (especially if the area is excavated): a mass of Pedro Miguel Agglomerate acts as abutment in front of the weaker La Boca Formation

Zone: <u>Summit</u>

Sta. 1890 – Through the East Lirio Slide
Sta. 1892 – Through the East Lirio Slide (with Culebra formation in the cross section)
Sta. 1904 – Representative of the stable area between the East Lirio Slide and the Northeast Culebra Slide
Sta. 1912 – Through the Northeast Culebra Slide
Sta. 1919 – Through Hagan's Slide
Sta. 1925 – Through the 1925 E. Slide (Culebra formation)
Sta. 1928 – Through the 1925 E. Slide (Cucaracha formation)

Zone: <u>Culebra</u>

Sta. 1934 – Through the East Culebra Extension Slide
Sta. 1940 – Representative of the stable area between the East Culebra and the East Culebra Extension Slides
Sta. 1948 – Typical Section through the East Culebra Slide
Sta. 1958 – Critical Section through the East Culebra Slide

Zone: <u>Gold</u>

Sta. 1967 – Representative section through Gold Hill

Zone: <u>Cucaracha</u>

Sta. 1976 – Typical section through the Cucaracha Slide
Sta. 1980 – Section through the Cucaracha Slide (close to the Purple Rock basalt dike)
Sta. 1983 – Through the Purple Rock basalt dike
Sta. 1988 – Through Cucaracha South Extension Slide
Sta. 1995 – Representative of the area between Cucaracha South Extension Slide and the Sta. 1830 E Slide
Sta. 1999 – Through the Sta. 1830 E Slide
Sta. 2004 – Representative of the area between Sta. 1830 E Slide and the Cucaracha Village Slide
Sta. 2009 – Through the Cucaracha Village Slide

Zone: <u>Nitro</u>

Sta. 2025 – Representative section through Nitro Hill

Zone: <u>Paraiso</u>

Sta. 2039 – Through the Paraiso Slide
Sta. 2044 – Through the Paraiso Slide

Zone: Luisa

Sta. 2053 - Representative Section
Sta. 2066 - Representative Section
Sta. 2090 - Representative Section through Luisa Hill

West Bank

Zone: Mandinga

Sta. 1659 - Through the Tonto Penninsula
Sta. 1683 - Through Tres Pesos Hill

Zone: Obispo

Sta. 1732 - Through the West Buena Vista Slide

Zone: Cascadas

Sta. 1786 - Through Las Cascadas Hill

Zone: Cunette

Sta. 1805 - Through Northern portion of Cunette Zone, where La Boca Formation appears prominently

Sta. 1847 - Representative of southern portion of Cunette Zone

Zone: Empire

Sta. 1866 - Through the Division Office and West Empire Slides
Sta. 1874 - Representative Section of the stable area between the West Empire Slide and the Lirio Slides
Sta. 1885 - Through a potentially dangerous condition (especially if the area is excavated): a mass of Pedro Miguel Agglomerate acts as abutment in front of the weaker La Boca Formation
Sta. 1889 - Through the Old Lirio Slide (in La Boca Formation)

Zone: Lirio

Sta. 1892 - Through the Old Lirio Slide (in the Culebra and Gatuncillo Formations)
Sta. 1902 - Through the 1735 W Slide
Sta. 1910 - Through the Culebra Village Slide
Sta. 1916 - Representative of the 1910-1920 W Problem Area
Sta. 1920 - Through the New Town Slide

Zone: <u>Hodges</u>

Sta. 1935 - Through the Old Hodges Hill Slide and the Hodges Hill Active Area
Sta. 1943 - Through the West Culebra Slide
Sta. 1947 - Through the West Culebra Slide

Zone: <u>Model Slope</u>

Sta. 1954 - Through the West Culebra Slide (Lirio Hill)
Sta. 1960 - Through the West Culebra Slide (Lirio Hill)
Sta. 1965 - Through Model Slope

Zone: <u>Contractor</u>

Sta. 1971 - Through Contractor's Hill

Zone: <u>Escobar</u>

Sta. 2000 - Through Cerro Escobar

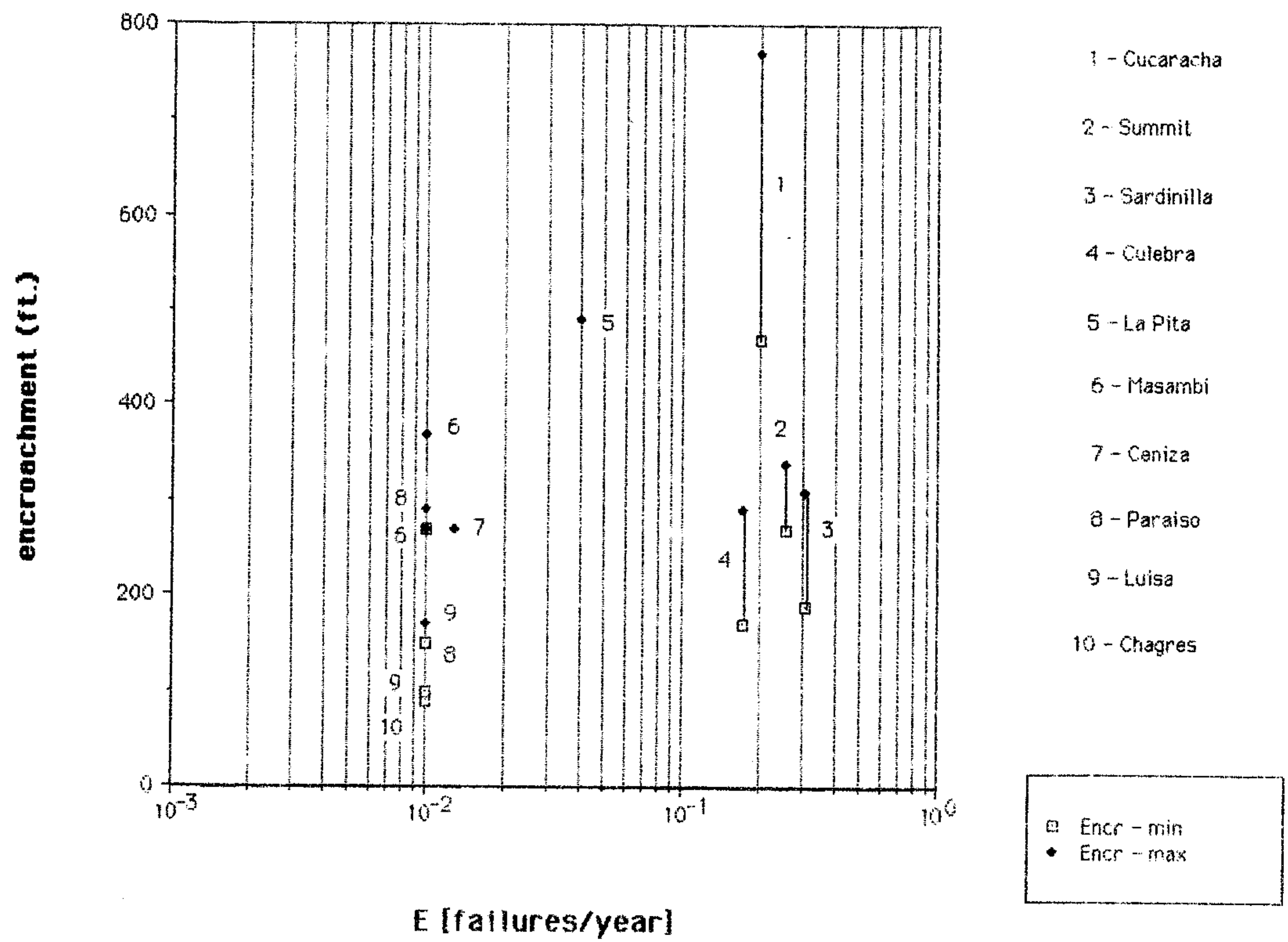
Zone: <u>Marieta</u>

Sta. 2017 - Representative section in Zone Marieta
Sta. 2035 - Representative section in Zone Marieta (through the Rio Grande Hill)
Sta. 2056 - Through the Paraiso Tie-Up Station

Zone: <u>Cartagena</u>

Sta. 2066 - Through the Cartagenita Slide
Sta. 2072 - Through the Cartagena Mudflow
Sta. 2078 - Through the Cartagena Slide
Sta. 2083 - Through the Cartagena South Extension Slide

Figure 16: Comparison of East Bank Zones



Station 1611 E Slide (part of East White House Yard Slide).
Centered @ 1777 E/ La Boca Formation
Dates of activity: 1908 to 1968

1912 - Initial slide along bedding
d=50' L=160' d/L=0.31 Theta=15 deg.

Station 1619 E Slide (also called East Power House Slide in some maps and references and Cascadas E Slide in A.P. Mann's files). Sta. 1784-1789 E/ Las Cascadas Formation
Dates of activity: 1909 to 1972

1910 - Initial slide along bedding
d=25' L=120' d/L=0.21 Theta=19 deg.

1911 - Initial slide along bedding
d=40' L=290' d/L=0.14 Theta=16 deg.

1972 - Initial slide along bedding
d=80' L=400' d/L=0.20 Theta=11 deg.

Station 1623 E Slide (part of East Powder House Slide). Sta. 1789-1794 E/ Las Cascadas Formation
Dates of activity: 1909 to 1926

1908 - Initial slide in weathered rock
d=25' L=190' d/L=0.13 Theta=15 deg.

1910 - Initial slide mainly along bedding
d=60' L=360' d/L=0.17 Theta=18 deg.

Station 1630 E Slide (part of East Powder House Slide). Sta. 1794-1801 E/ Las Cascadas Formation
Dates of activity: 1908 to 1937

1908 - Initial slide in weathered rock
d=25' L=100' d/L=0.25 Theta=11 deg.

1911 - Initial slide along bedding
d=35' L=170' d/L=0.21 Theta=18 deg.

1912 - Initial slide along bedding
d=80' L=290' d/L=0.28 Theta=18 deg.

1913 - Reactivated slide
d=70' L=460' d/L=0.15 Theta=12 deg.

Station 1640 E Slide (part of East Powder House Slide). Sta. 1802-1809 E/ Las Cascadas Formation
Dates of activity: 1909 to 1911

1910 - Initial slide along bedding
d=30' L=175' d/L=0.17 Theta=19 deg.

North La Pita Slide. Sta. 1815-1820 E/ Las Cascadas Formation
Dates of activity: 1912 to 1957

1912 - Initial slide along bedding (base plane) and across bedding (backscarp)
d=100' L=290' d/L=0.34 Theta(base)=10 deg.
Theta(backscarp)=62 deg.

1957 - Reactivation (?)

ZONE: La Pita

Lower La Pita Slide. Sta. 1822-1832 E/ Las Cascadas Formation
Dates of activity: 1910 to 1922
1910 - Initial slide in material weakened by a fault
d=90' L=200' d/L=0.79

Upper La Pita Slide. Sta. 1822-1832 E/ Las Cascadas Formation
Dates of activity: 1886 to 1909
1885 - Initial slide in soil & weathered rock
d=75' L=215' d/L=0.35 Theta(base)=12 deg.
1910 - Initial slide in soil & weathered rock
d=60' L=250' d/L=0.24 Theta(base)=7 deg.
Theta(backscarp)=63 deg.

ZONE: Masambi

Station 1685 E Slide. Sta. 1853-1854 E/ Las Cascadas Formation
Dates of activity: 1908 to 1913
1908 - Initial slide in weathered rock
d=35' L=145' d/L=0.24 Theta=8 deg.
1912 - Initial slide across bedding
d=50' L=210' d/L=0.24

Station 1689 E Slide. Sta. 1855-1859 E/ Las Cascadas Formation
Dates of activity: 1907 to 1913
1911 - Initial slide mainly along bedding
d=65' L=195' d/L=0.33 Theta=17 deg.
1913 - Initial slide along bedding
d=70' L=310' d/L=0.23 theta=15 deg.

Station 1695 E Slide. Sta. 1861-1863 E/ Las Cascadas Formation
Dates of activity: 1909 to 1913
1909 - Initial slide in soil & weathered rock
d=35' L=120' d/L=0.29
1913 - Initial slide along bedding
d=70' L=310' d/L=0.23 theta=20 deg.

ZONE: Ceniza

Station 1702 E Slide ("East Empire Slide"). Sta. 1867-1872 E/ La Boca Formation
Dates of activity: 1907 to 1913 (in 1947 it was observed that post-1913 movements had occurred)
1909 - Initial slide in highly weathered rock
d=35' L=110' d/L=0.32
1912 - Initial slide along bedding
d=60' L=250' d/L=0.24 theta=18 deg.

Station 1712 E Slide. Sta. 1878-1882 E/ Pedro Miguel Agglomerate.
Dates of activity: 1910 to 1912
1911 - Initial slide in material weakened by faulting
d=60' L=160' d/L=0.38 rotational

ZONE: Summit

East Lirio Slide. Sta. 1887-1893 E/ Culebra Formation
Dates of activity: 1909 to 1986
1909 - Initial slide mainly along bedding
d=50' L=120' d/L=0.42 theta=17 deg.
1913 - Initial slide mainly along bedding
d=110' L=480' d/L=0.23 theta=9 deg.
1935 - (little information available)
L=425'
1986 - (small) extension of the slide (behind the old scarp). Dimensions not available

Northeast Culebra Slide (small extension of Hagan's Slide). Centered @ Sta. 1912 E/ Culebra Formation
Dates of activity: 1986
1986 - Small slide, mainly along bedding
(no information available)

Hagan's Slide. Sta. 1913-1923 E/ Culebra Formation
Dates of activity: 1911 to 1946
1911 - Initial slide along & across bedding
d=85' L=200' d/L=0.43 theta(base)=2 deg.
theta(backscarp)=61 deg.

1913 - Initial slide along and across bedding
d=180' L=630' d/L=0.29 theta(base)=2 deg.
theta(backscarp)=60 deg.

1925 E Slide. Sta. 1922-1930 E/ Culebra Formation w/some Cucaracha Formation on the southern part
Dates of activity: 1929 to 1974
1929 - Initial slide along bedding
d=70' L=210' d/L=0.33 theta=8 deg.

1974 - Initial slide along bedding plane (extension of the 1929 slide)
d=150' L=600' d/L=0.25 theta=8 deg.

ZONE: Culebra

East Culebra Extension Slide. Sta. 1928-1936 E/ Cucaracha Formation and Culebra Formation.

Dates of activity: 1910 to 1950
1910 - Initial slide mainly along bedding
d=80' L=380' d/L=0.21 theta(bedding)=3 deg.
1911 - Extension of slide. Initial slide mainly along bedding
d=90' L=490' d/L=0.18 theta(bedding)=3 deg.
1932 - Initial slide mainly along bedding
d=115' L=640' d/L=0.18 theta=5 deg.
1932 - Extension of slide. Initial slide mainly along bedding
d=155' L=760' d/L=0.20 theta=5 deg.

<u>East Culebra Slide</u>. Sta. 1938-1963 E/ Cucaracha Formation and Culebra Formation
Dates of activity: pre-1886 to 1987
1886 - Initial slide along bedding
d=120' L=1080' d/L=0.11 theta=5 deg.
1908 - Initial slide across bedding
d=80' L=215' d/L=0.37
1914 - Initial slide along & across bedding
d=300' L=1000' d/L=0.3 theta(base)=3 deg.
theta(backscarp)=54 deg.
1915 - Reactivation and backward extension of slide
d=380' L=1440' d/L=0.26 theta(base)=3 deg.
theta(backscarp)=50 deg.
1965 - Backward extension of slide
(no information available)
1987 - Backward extension of slide
(no information available)

ZONE: Gold

<u>Station 1804 E Slide</u>. Centered @ 1971/ Pedro Miguel and Cucaracha Formation (flank of Cucaracha Slide)
Dates of activity: 1884 to 1910
1889 - Initial slide in soil. This slide was incorporated into the Cucaracha slide in 1911.
d/40' L=450' d/L=0.09 theta=6 deg.

ZONE: Cucaracha

<u>Cucaracha Slide</u>. Sta. 1972-1983 E/ Cucaracha Formation and Culebra Formation.
Dates of activity: 1884 to 1986
1889 - Initial slide in soil
d=60' L=840' d/L=0.07 theta=9 deg.
1909 - Initial slide along bedding
d=100' L=860' d/L=0.12 theta=9 deg.
1910 - Reactivated slide
d=160' L=1280' d/L=0.13 theta=6 deg.

FIGURE 14: MAXIMUM POTENTIAL ENCROACHMENTS
EAST BANK

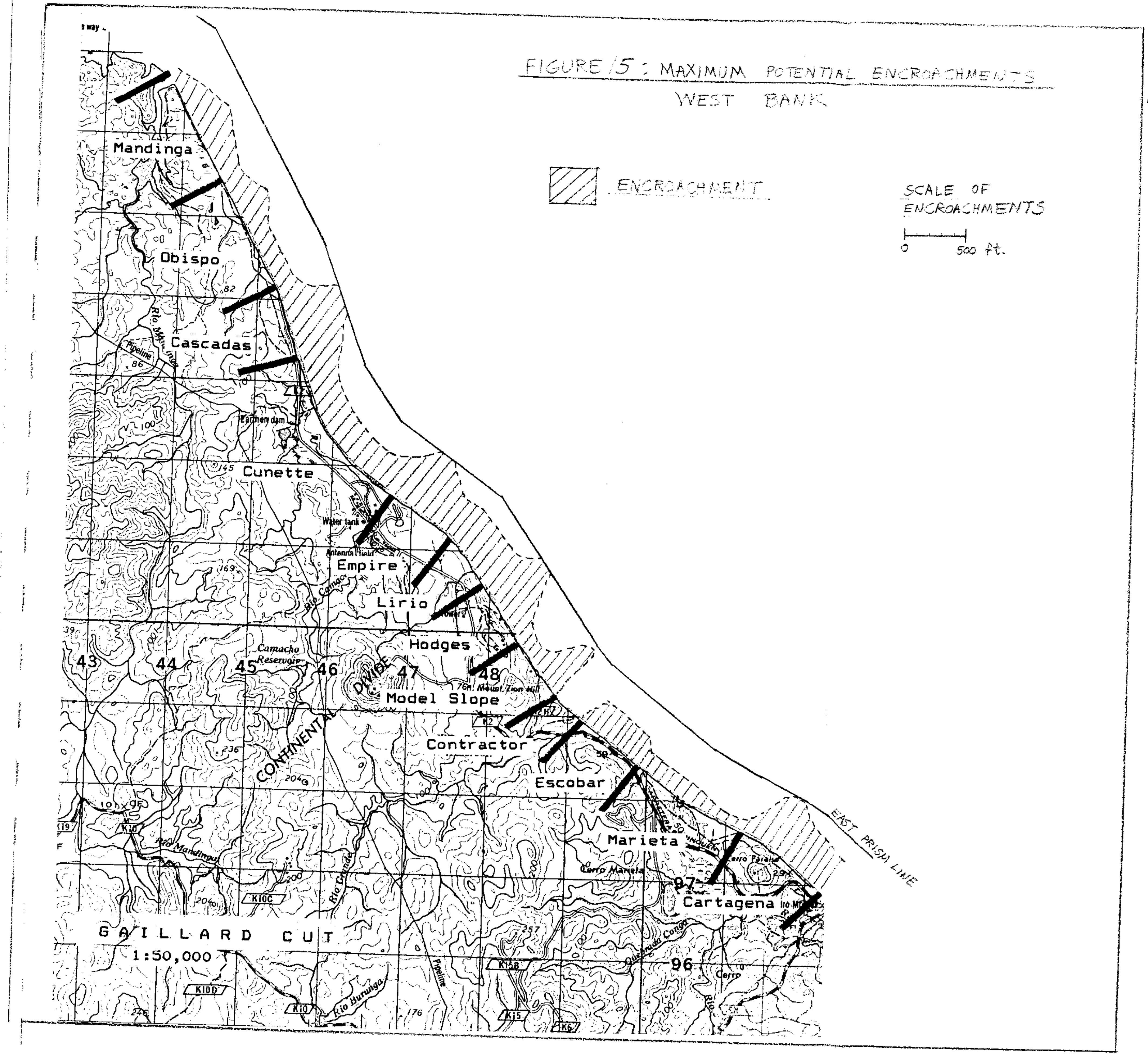


FIGURE 5: MAXIMUM POTENTIAL ENCROACHMENTS
WEST BANK
ENCROACHMENT
SCALE OF ENCROACHMENTS
0 500 ft.
EAST PRISM LINE
Mandinga
Obispo
Cascadas
Cunette
Empire
Lirio
Hodges
Model Slope
Contractor
Escobar
Marieta
Cartagena
CONTINENTAL DIVIDE
Camacho Reservoir
Water tank
Earthen dam
Pipeline
Rio Mandinga
Rio Grande
Rio Burunga
Cerro Marieta
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GAILLARD CUT
1:50,000

ABSTRACT

This study evaluates the risks of channel encroachments due to landslides in Gaillard Cut. The knowledge gained contributes towards the goal of reducing the overall cost of landslide activity in the Panama Canal.

The first step was to develop a zonation scheme for Gaillard Cut. The 24 resulting zones contain segments of the Cut characterized by similar topographic and geologic conditions. The history of past slides within each zone, afforded the means for making reasonable estimates of future activity. The history of past channel encroachments, permitted us to evaluate the consequences of such activity.

This analysis highlights the zones that pose the greatest risk of encroaching the navigation channel significantly. We can then focus our resources on these areas of greater concern.

The final recommendations provide means to improve the overall reliability of the Landslide Control Program. This in turn, can substantially reduce the chances that large slides will encroach the navigation channel in the future.