International Conference on Case Histories in Geotechnical Engineering

(2008) - Sixth International Conference on Case Histories in Geotechnical Engineering

16 Aug 2008, 8:45am - 12:30pm

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D. N. Lindberg
LACO Associates, Eureka, CA

J. P. Buck
LACO Associates, Eureka, CA

G. L. Manhart
Formerly of LACO Associates, Eureka, CA

R. C. Chaney
Humboldt State University, Arcata, CA

F. R. Bickner
LACO Associates, Eureka, CA

See next page for additional authors

Recommended Citation

Lindberg, D. N.; Buck, J. P.; Manhart, G. L.; Chaney, R. C.; Bickner, F. R.; and Vadurro, G. A., "Probabilistic Estimation of Site Specific Fault Displacements" (2008). *International Conference on Case Histories in Geotechnical Engineering*. 20.
https://scholarsmine.mst.edu/icchge/6icchge/session03/20

Author

D. N. Lindberg, J. P. Buck, G. L. Manhart, R. C. Chaney, F. R. Bickner, and G. A. Vadurro

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D. N. Lindberg
LACO Associates
Eureka, California 95501

J. P. Buck
LACO Associates
Eureka, California 95501

G. L. Manhart
Formerly of LACO Associates
Eureka, California 95501

R.C. Chaney
Humboldt State University
Arcata, California 95521

F. R. Bickner
LACO Associates
Eureka, California 95501

G. A. Vadurro
LACO Associates
Eureka, California 95501

ABSTRACT

The College of the Redwoods (CR) located near Eureka, California would like to upgrade a series of existing buildings that are unfortunately located on secondary faults associated with the active Little Salmon Fault (LSF) zone. In the early 1990’s a deterministic value of the maximum dip-slip displacement that had occurred on one of these secondary faults located beneath the southeast building corner of the former library was measured to be 1.7 feet. This displacement was resolved into approximately 1.5 feet horizontal offset and 0.8 feet of vertical offset, based on the secondary fault plane dip. Geologically, it has not been possible to establish the actual dates of the occurrence of the displacements on the observed faults, therefore it was assumed that they all had occurred within the last 11,000 years. The structural engineer for the project has indicated that it was not possible to design for the observed ground displacement of 1.7 feet. This limited study was undertaken to assess the variation of ground displacements that were observed over the area of ground occupied by CR’s Administration, Science, and former Library buildings. The purpose of this study was to evaluate the reasonableness of using a deterministically determined maximum value of displacement in estimating, and designing mitigations for, the structural response, or whether a probabilistic approach could be utilized. The only data available within the limited time frame allowed for the study was from a series of trench logs made as part of a project for locating building sites on the campus in the early 1990’s. As a first step the frequency distributions of both horizontal and vertical displacements located in a volume of soil comprising the area occupied by the above buildings to a depth of 14 feet were examined. The 14 feet was the maximum depth of the trenches used to provide data for the study. Probability density functions (PDF) versus displacements were developed based on the frequency distributions. The area under the PDF curves between given displacement intervals represents the probability of occurrence (POC) of that displacement. A cumulative probability of occurrence for a displacement interval can be determined by adding the individual POC’s. Based on this it was estimated that a horizontal displacement of ≤ 1.0_foot has a probability of 89% of occurring in the next 11,000 years at the site. In contrast, a vertical displacement of ≤ 1.0 foot has a probability of 88% probability of occurrence.

INTRODUCTION

The College of the Redwoods (CR) needs to renovate and upgrade several existing buildings, constructed in the late 1960’s that are unfortunately located on active secondary faults associated with the Little Salmon fault zone. The CR campus, and the Little Salmon fault has been the subject of a number of previous fault studies, Bickner et al. (1995, 2001), Carver et al. (1991), Chaney (2001), and Woodward-Clyde Consultants (1980). In the early 1990’s a deterministic value of the maximum resultant displacement due to a single event that had occurred on one of these secondary faults located beneath the library was measured at 1.7 feet, irrespective of the time frame. Recently, the structural engineer has indicated that it was impossible to design for a ground displacement of 1.7 feet. It was therefore decided to conduct a limited study to assess the variability of ground displacements that were observed over the area of ground occupied by CR’s Administration, Science, and former Library buildings.

The relationship between fault displacement and earthquake magnitude has been studied by a number of authors. A recent comprehensive study has been presented by Wells and Coppersmith (1994), in which they presented displacement as a function of surface rupture length, fault type (i.e. strike slip, reverse, and normal) and moment magnitude. These relationships were based on fault movements from a large number of individual earthquakes that occurred at a variety of sites. In this study, displacements occurring on secondary faults at one site were studied. The main trace of the Little Salmon fault was never observed because the purpose of the fault trenching investigations was to assess potential new building sites on the campus, thus the trenches were located in areas hope to be free of ground rupture (faulting). The purpose of this limited study was to evaluate the reasonableness of using the deterministically determined maximum value of displacement, or whether a probabilistic approach could be utilized. The only available data available within the limited time frame available was a series of trench logs made as part of a project for locating building sites on the campus in the late 1980's and 1990's. It was decided as a first step to look at the frequency distribution of displacements located in a volume of soil comprising the area occupied by the above buildings to a depth of 14 feet. The 14 feet was the average depth of the trenches used to provide data for the original project. The use of the frequency distribution approach was to try to evaluate if it is reasonable to use the maximum observed displacement to estimate the structural response. This study was a first attempt to establish the basis for developing a probabilistically-based design criteria for displacements during earthquakes along the same lines as is utilized for accelerations. Ultimately it could potentially be used on older existing structures that had also been inadvertently sited on active faults prior to the enactment of the Alquist-Priolo Act. In the following, site geology, the nature of the data utilized, analysis of displacement data, and a discussion of results are presented.

SITE GEOLOGY

The CR campus was constructed in the 1960s on the scarp of the Little Salmon fault (LSF), prior to its recognition as an active fault. The LSF is a northwest-striking, northeast-dipping thrust fault with documented Holocene displacements on the order of tens of feet. In the early 1980s, after the College had been in operation for several years, the seismic potential of the LSF became apparent; the LSF was subsequently designated by the State of California as an active fault. In map view, the surface trace is sinuous and broadly convex to the southwest. In the area of CR, the LSF trace consists of two well-recognized segments. An eastern segment is located along the base of Humboldt Hill northeast of most campus developments. Surface morphology and subsurface investigations suggest the main trace of the western segment of the LSF is located at the northeast side of the campus parking lot, near the toe slope of the bluff on which the Science, Administration, and former Library buildings are located.

Deformation by secondary fault ruptures associated with movement of the western thrust segment has been observed to be distributed over a broad zone, 500 to 700 feet wide, within the hanging wall (the up-thrust block). Secondary, antithetic backthrusts and fore thrust fault ruptures, and high-angle normal fault ruptures, are common in the southwestern portion of this broad zone of deformation. Secondary faulting and folding of the up-thrust block is interpreted to occur concurrently with movement of the western segment of the LSF.

Uniformitarianism suggests that future fault ruptures are likely to occur where past fault ruptures have occurred, and faults with larger (or smaller) offsets are likely to behave similarly in the future. Site-specific field investigations (i.e. trenches) were necessary to ascertain the location of the existing fault ruptures on the campus. Other ground deformation associated with motion on the LSF (e.g. warping or fault-bend folding) was not considered in this analysis.

NATURE OF DATA USED IN STUDY

The data used in this study was taken from trench logs originally developed as part of a project on the CR campus to locate proposed new buildings at "faultless" locations on the campus. The location of each trench is presented in Figures 1a and 1b. Use of these trench logs had some basic drawbacks. The drawbacks are the following: (1) surficial soil deposits had been removed by grading when the campus was developed in the 1960's, and (2) faults were not age dated because it was beyond the scope of the original study. Because no age dating was available and the LSF zone is considered active, it was necessary to assume conservatively that all displacements had occurred within the last 11,000 (i.e. in Holocene time) years.

Displacement data was assembled from logs of trenches excavated near the Science building, the original College of the Redwoods Library, the Administration building, the Learning Resource Center (LRC), the Child Development Center (CDC), and the tennis courts. Displacements measured in trenches near the CR Art building, and in an area leased to the Humboldt Botanical Gardens Foundation (HBGF) were also part of the data set. Thus, the investigation involved a volume of soil covering the area of the above facilities and the approximate depth of the trenches. Displacements within this volume of soil are all postulated to have occurred as the result of movement on the LSF. Displacements could only be determined when an identified layer of soil was offset along a "crack" (i.e. secondary fault). In the area beneath the buildings in question there are a number of well displayed secondary faults (i.e. large crack features) and a larger number of smaller-displacement secondary faults. Thus, the displacements recorded on the trench logs were of four types. The first type was a large secondary fault that extended beyond the bottom of the trench to an unknown depth and continued up to the existing soil surface. The second type was a large secondary fault that extended beyond the bottom of the trench to an unknown depth but stopped, or became unrecognizable, before reaching the surface. The third type of observed secondary fault was one that stopped or became untraceable before reaching the bottom of the trench but extended to the soil surface. The fourth type of secondary fault did not extend to either the soil surface or bottom of trench. Displacements from all these types of faults are considered equal for the purposes of this study. Whether the final displacement data set utilized in the analysis is determined to be independent largely depends on how the raw data was assembled. Using displacement data from the above type of secondary faults raised a number of issues. The primary issue was trying to develop a set of data that was statistically independent. To try to accomplish this requirement a set of rules were developed to evaluate the raw data. In analyzing these data we have assumed the following:

1. When equal displacements were observed to have occurred along the same secondary fault, only one value was recorded. This was because it was felt that the observed displacements were likely to have been the result of one fault-motion event (i.e., one earthquake).
2. When displacements along the same secondary fault were not equal and the smaller one was closer to the surface. These displacements were treated as resulting from different seismic events and were treated as being independent of each other. A problem arising from this is that the deeper displacement is likely to represent the summation of a series of earthquake events. In such cases the bottom larger displacements were divided by two.
3. When equal displacements occur on separate secondary faults they were considered independent.

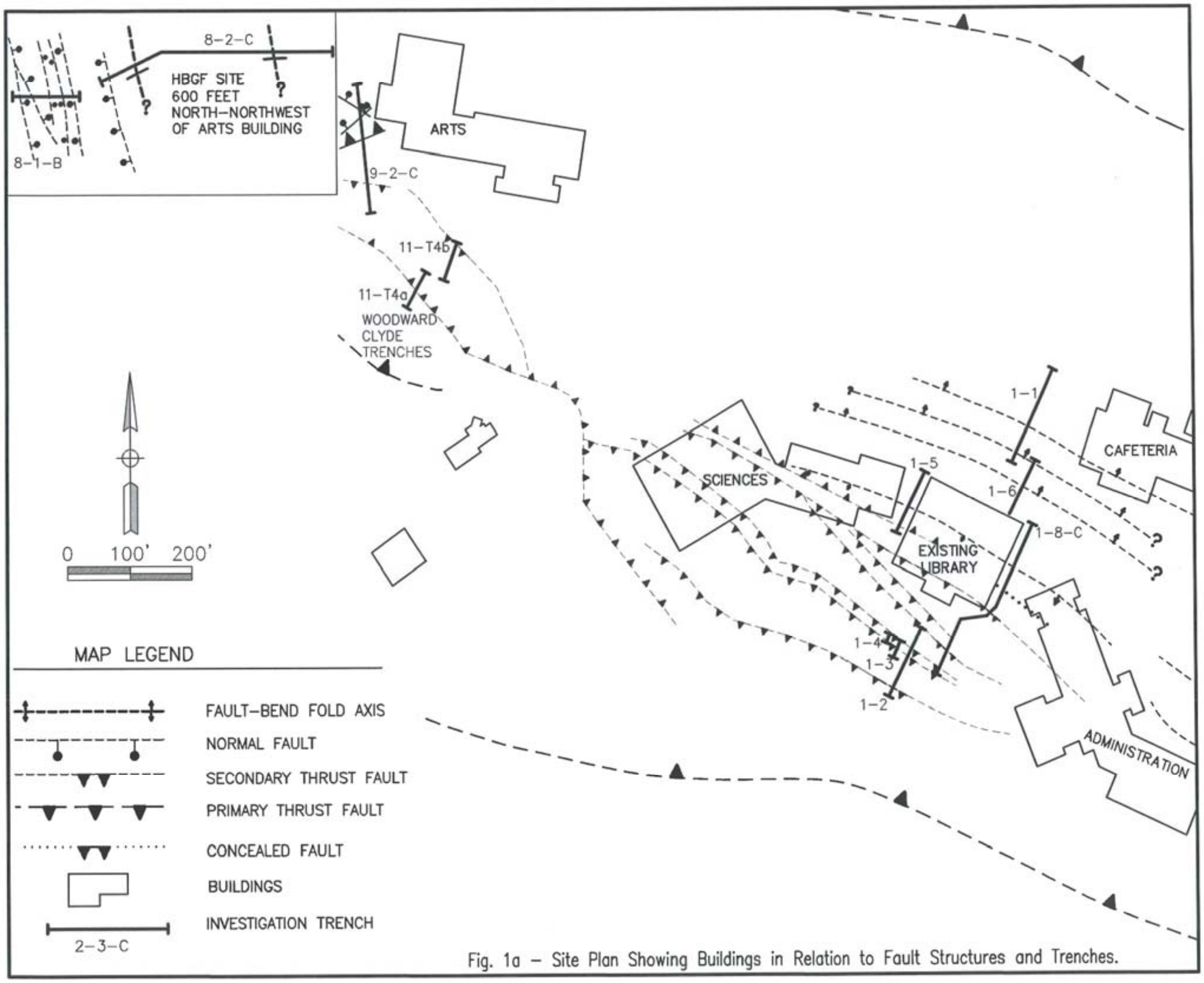

Fig. 1a – Site Plan Showing Buildings in Relation to Fault Structures and Trenches.

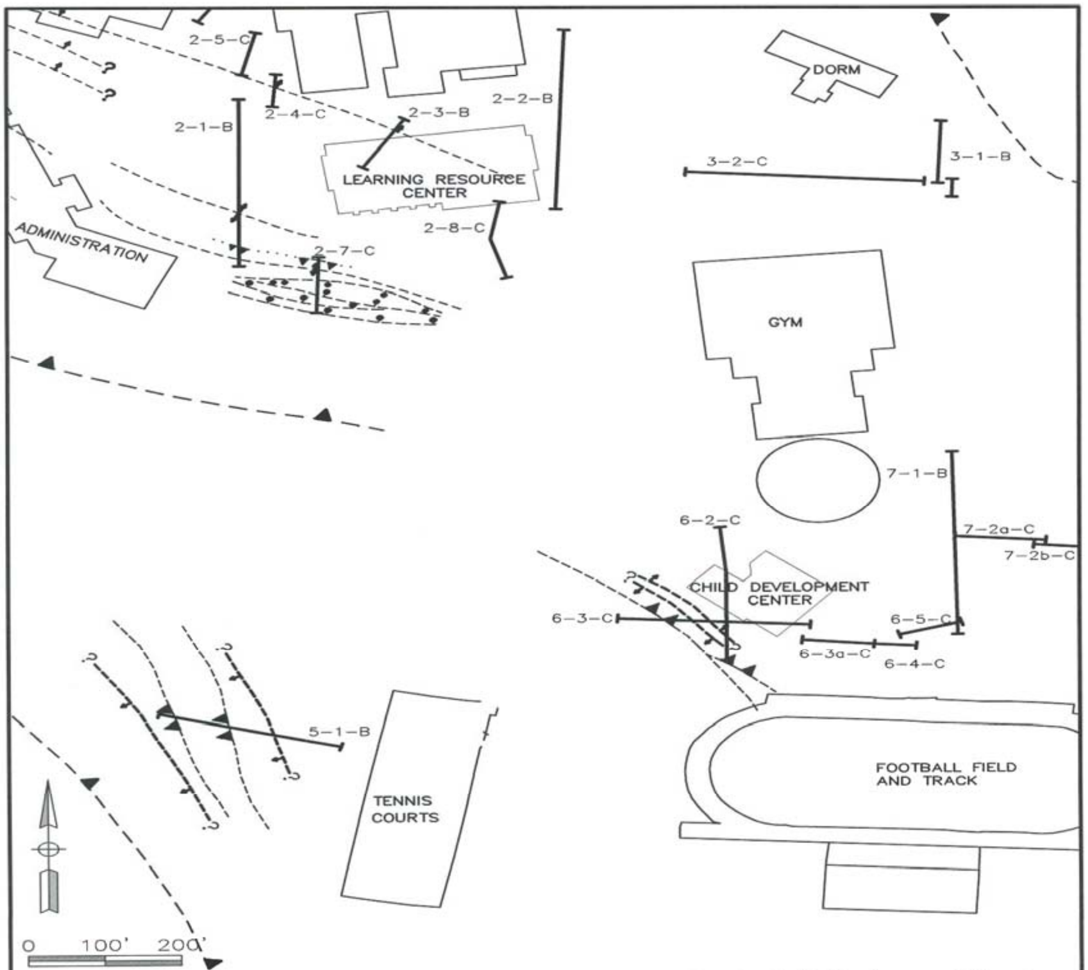

Fig. 1b – Site Plan Showing Buildings in Relation to Fault Structures and Trenches.

METHODS FOR FAULT DISPLACEMENT SUMMARY

The fault displacement data set was compiled by reviewing all fault trench logs prepared from 1989 to 1999. The orientations of all faults were measured cross-trench such that the reported strike and dip of these faults is true dip and not apparent dip. Due to lack of any observable evidence to suggest otherwise, all slip was assumed to be pure dip-slip. Dip-slip displacements were directly measured within the plane of the trench wall exposure and therefore represents apparent offset. Data for all measured faults were tabulated and organized by trench number and location (Appendix 1). Individual faults within each trench were identified by a station number that correlates with the original horizontal datum on the trench log. The true fault dip, sense of motion (r = reverse; n = normal), and apparent dip-slip displacement of individual faults are listed. The horizontal and vertical separations were computed by multiplying the amount of apparent dip-slip displacement by the cosine and sine of the true fault dip, respectively.

Age and recency of faulting, and number of slip events recorded by each observed fault was not discernible in the trench exposures. All faults were therefore conservatively assumed to be Holocene and active, as they were typically observed to be truncated by the grading that occurred during campus development. Evidence of progressively greater displacement on older deposits was observed only rarely. Therefore, the apparent dip-slip offsets observed, measured, and reported is interpreted to generally be the result of a single-event slip. Slip on secondary faults is postulated to occur co-seismically with slip events (earthquakes) on the main trace of the LSF. It is also our interpretation that, in future earthquake events on the LSF, the existing secondary antithetic backthrust and fore thrust fault ruptures, and the high-angle normal fault ruptures will be reactivated. We also acknowledge the possibility that similar new secondary faults will be generated in response to future events occurring on the LSF. New secondary antithetic backthrust and fore thrust fault ruptures, and high-angle normal fault ruptures could break the ground surface in areas where such deformation has not previously been observed. Other surface deformation observed on the campus in the up-thrust block of the west trace of the LSF (e.g. monoclinal warping or fault-bend folding), was documented during our investigations, but is not quantified at this time.

ANALYSIS OF DISPLACEMENT DATA

Displacement data was analyzed assuming the following:

1. The limited data set is representative of displacements within the specified soil volume.
2. Displacements are the result of single seismic events.
3. Displacements are independent of each other.
4. All faults within the specified soil volume are Holocene and ruptured the ground surface.

Our analysis of the horizontal and vertical displacement data presented in Appendix 1 consisted of the following:

1. Developing histograms of horizontal and vertical displacements, and
2. Preparing graphs of the cumulative percentage of displacements in an interval, combined with the percentages in all the preceding intervals.

Deformations interpreted to result from multiple events listed in Appendix 1 were conservatively divided into two equal displacements. The displacements were then treated as two separate movements.

PDF plots for both horizontal and vertical displacements were then developed. Histograms of the data presented in Table 1 were created using an Excel spread sheet. Horizontal and vertical displacement data were grouped into discrete intervals (bins). These bins increased in increments of 0.2 feet (e.g. 0-0.2', and 0.21-0.4', etc.). Histograms of both horizontal and vertical displacements were then plotted (Figures 2 and 3, below) as frequency (number of occurrences of data points in a given bin) versus displacement (i.e. bin interval).

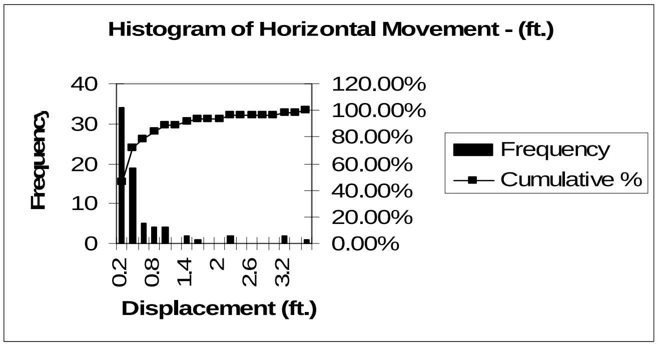

Fig. 2 – Histogram of Horizontal Movement

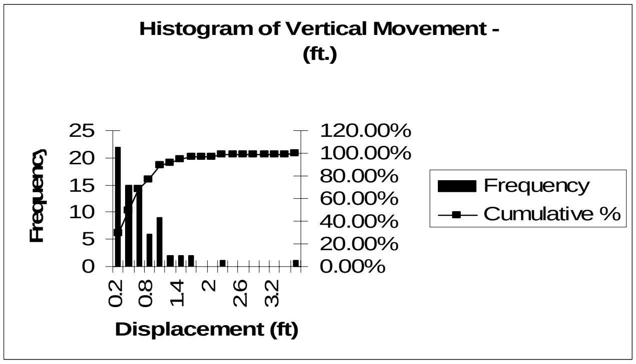

Fig. 3 – Histogram of Vertical Movement

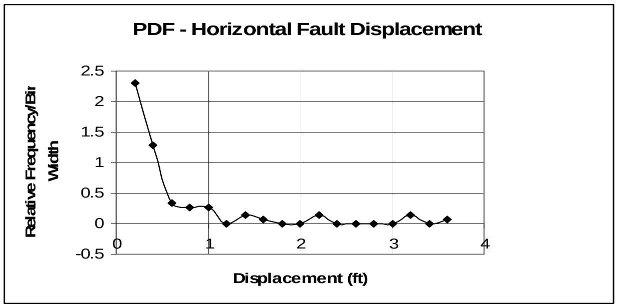

Fig. 4 – PDF of Horizontal Fault Displacement

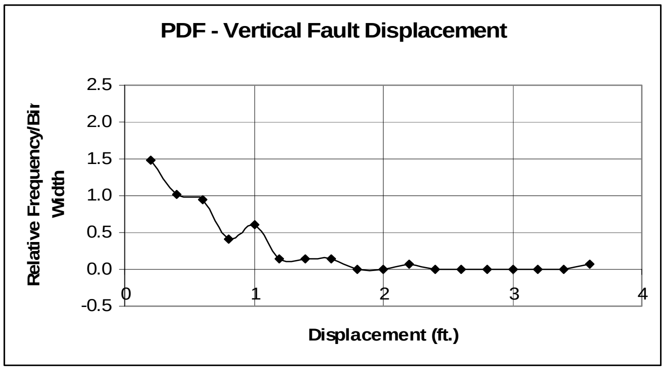

Fig. 5 – PDF of Vertical Fault Displacement

The corresponding probability density function curves were generated by first dividing the number of occurrences in each individual interval by the total number of data points (i.e. relative frequency), and then by the bin width (0.2 ft). Curves were then plotted as PDF versus displacement (i.e. bin interval) for horizontal and vertical displacements (Figures 4 and 5, above). The area under each curve, between given displacement intervals represents the probability of its occurrence

DISCUSSION OF ANALYSIS RESULTS

A review of Figures 2 and 3 indicates that approximately 90 percent of the observed horizontal and vertical displacements are less than 1 ft. Information concerning the probability of occurrence (POC) for individual displacement intervals, based on our limited empirical data set are presented in Tables 1 and 2, below. As indicated earlier, the POC is determined by calculating the area under the PDF curve that was shown in Figures 4 and 5.

Table 1 – Probability of Occurrence of Different Horizontal Displacement Intervals in 11,000 years.

Displacement Interval (ft)	Probability of Occurrence (%)	Cumulative Probability of Occurrence (%)
0-0.2	46	46
0.2-0.4	26	72
0.4-0.6	7	79
0.6-0.8	5	84
0.8-1.0	5	89
1.0-1.2	0	89
1.2-1.4	3	92
1.4-1.6	1	93

As an example, using the column entitled "Probability of Occurrence" (POC) in Table 1; the POC for horizontal displacements in the interval (bin) of 0.8 to 1.0 feet is five percent. In comparison, the probability of occurrence of *vertical* displacements from the interval 0.8 to 1.0 feet is 12 percent (Table 2). As a further example, to determine the probability of occurrence of vertical displacements in excess of 1.0 foot, use the column entitled "Cumulative Probability of Occurrence", and subtract the cumulative POC of 88 percent (Table 2) for the interval 0 to 1.0 foot from 100 percent. Thus, the probability of having a vertical displacement in excess of 1.0 foot is 100 minus 88 equals 12 percent. Similarly, the probability of horizontal displacements in excess of 1.4 feet can be shown to be seven percent (100 minus 93 equals 7) from the "Cumulative Probability of Occurrence" column of Table 1 for building sites. Additionally, some trenches (1-3-A and 1-4-A) were sited to provide specific additional data or to resolve questions about fault offset observed in an initial trench (1-2-A). Areas not considered as potential building sites were generally not trenched but may contain additional fault ruptures. Trench locations were also constrained by the existing infrastructure of the campus including underground utility corridors and high-pressure natural gas pipelines.

The California Geological Survey (CGS), after reviewing the study decided that under California state law building new structures over active fault traces is not allowed. The Alquist-Priolo Earthquake Fault Zoning Act of 1972 also prohibits alteration of structures sited on active faults when the cost of the alteration exceeds 50 percent of the value of the structure. Based on this, no new structures on fault traces are allowed and existing buildings may only be altered up to 50 percent of their value.

Table 2 – Probability of Occurrence of Different Vertical Displacement Intervals in 11,000 years.

Displacement Interval (ft)	Probability of Occurrence (%)	Cumulative Probability of Occurrence (%)
0-0.2	30	30
0.2-0.4	20	50
0.4-0.6	19	69
0.6-0.8	8	76
0.8-1.0	12	88
1.0-1.2	3	91
1.2-1.4	3	94
1.4-1.6	3	97

CONCLUSIONS

1. The site studied exhibited a wide variety of displacement magnitudes on secondary faults.
2. Horizontal displacement of $\leq$ 1.0 foot has an estimated probability of 89 percent of occurring in the next 11,000 years.
3. Vertical displacement of $\leq$ 1.0 foot has an estimated probability of 88 percent of occurring in the next 11,000 years.
4. Vertical displacement of > 1.6 feet has an estimated probability of 3 percent of occurring in the next 11,000 years.
5. The California Geological Survey chose to adhere to the 1972 Alquist-Priolo Earthquake Fault Zoning Act.

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APPENDIX 1 – Eureka College of the Redwoods Fault Displacement Measurements

Trench #/ Location	Station (Horizontal Datum)	Fault dip in degrees, measured cross-trench	Sense of displacement (r=reverse, n=normal)	Apparent dip-slip displacement (ft)	Resolved Horizontal Component (ft)	Resolved Vertical Component (ft)	Notes
1-8-C Admin. Library	179	29	r	1.7	1.5	0.8	Single event
	228	24	r	0.4	0.3	0.1	
	249	32	r	0.3	0.2	0.1	
	274	52	r	0.8	0.5	0.6	
	278	51	r	0.1	0.1	0.1	
	286	10	r	0.3	0.3	0.1	
	290	45	r	0.2	0.1	0.1	
	296	26	r	7.0	6.3	3.1	Multiple events
	299	52	r	0.2	0.1	0.2	
	300	72	r	0.3	0.1	0.3	
1-2-A S. of Library	5	70	r	1.9	0.6	1.8	Two events
	60	55	r	1.9	1.1	1.6	Multiple (2 or 3) events
	60	55	r	0.6	0.3	0.5	
	59	55	r	0.1	0.1	0.1	
1-3-A S. of Library	60	60	r	0.1	0.1	0.1	
	62	57	r	0.2	0.1	0.2	
	68	44	r	0.9	0.6	0.6	
1-4-A S. of Library	63	45	r	0.2	0.1	0.1	
	64	22	r	0.2	0.2	0.1	
	68	46	r	2.9	2.0	2.1	Multiple events (?)
1-5-A W. of Library	17	25	r	0.8	0.7	0.3	
2-1-B E. of Indust. Arts	292	25	r	0.4	0.4	0.2	
	294	31	r	0.3	0.2	0.1	
2-7-C	5	20	r	0.7	0.7	0.2	

E. of Admin. Bldg	41	90	n	0.2	0.0	0.2	
	42	90	n	0.4	0.0	0.4	
	45	90	n	0.2	0.0	0.2	
	48	75	n	1.1	0.3	1.1	
	50	75	n	1.2	0.3	1.2	
	50	75	n	0.3	0.1	0.2	
	51	75	n	0.3	0.1	0.3	
	58	76	n	0.9	0.2	0.9	
	59	75	n	0.5	0.1	0.5	
	62	70	n	0.2	0.1	0.2	
	70	75	n	0.5	0.1	0.5	
	75	64	n	1.1	0.5	0.9	
	80	75	n	0.6	0.2	0.6	
	85	63	n	1.0	0.5	0.9	
	86	75	n	0.2	0.1	0.2	
	89	75	n	0.6	0.2	0.6	
	91	66	n	0.6	0.2	0.5	
	97	75	n	0.5	0.1	0.5	
	98	75	n	0.5	0.1	0.5	
5-1-B Tennis Courts	16	30	r	5.0	4.3	2.5	Multiple (2) events
	86	30	r	3.2	2.8	1.6	Multiple (2) events
6-2-C CDC	12	31	r	0.4	0.3	0.2	
6-3-C CDC	160	32	r	1.0	0.8	0.5	
	170	32	r	13	11	7	
8-1-B N. of Art Bldg (HBG)	0	60	n	0.2	0.1	0.2	
	1	60	n	0.1	0.1	0.1	
	2	60	n	0.2	0.1	0.2	
	4	54	n	0.5	0.3	0.4	
	6	54	n	1.1	0.6	0.9	
	10	45	n	0.4	0.3	0.3	
	20	65	n	0.5	0.2	0.5	
	50	65	n	0.5	0.2	0.5	
	58	60	n	0.3	0.2	0.3	
	60	60	n	0.3	0.2	0.3	
	65	60	n	0.5	0.3	0.4	
	70	65	n	0.4	0.2	0.4	
	77	64	n	0.5	0.2	0.4	
	79	64	n	0.2	0.1	0.2	
	84	65	n	0.4	0.2	0.4	

	88	64	n	0.3	0.1	0.3
	98	74	n	0.3	0.1	0.3
	101	64	n	0.3	0.1	0.3
	102	75	n	0.2	0.1	0.2
8-2-C HBG	372	67	n	2.2	0.9	2.0