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SYNOPSIS: A seismic risk evaluation was conducted on a site near Eureka, California. The site was subject to potential earthquake loading from a number of sources. These sources were: (1) Mendocino Fracture Zone, (2) Gorda Segment of the Cascadia Subduction Zone, (3) Little Salmon thrust fault under the site, (4) Mad River Fault Zone, and (5) Intra plate west - Gorda Plate. The geology of thrust faults in Northern California are examined along with that of the Mendocino Fracture Zone, and the southern section (Gorda Segment) of the Cascadia subduction zone. A trench log showing a splay of the Little Salmon Fault is presented. A seismic risk analysis of the site was performed using recurrence curves for the various seismic sources estimated from both trench studies and historic seismicity. Using this information the acceleration at the site due to the Maximum Credible Earthquake is estimated to be 0.85g. The corresponding acceleration due to the Maximum Probable Earthquake and assuming that the various fault zones act independently or co-seismically is estimated to be 0.5g.

INTRODUCTION

An addition to the north side of an existing building is proposed on a site south of Eureka, California. The proposed addition is predominantly one story with a small two story portion on the north side. As mapped by Woodward-Clyde Consultant (1980) and Carver and Burke (1989), this site is located within a zone of deformation and faulting associated with the Little Salmon Fault Zone (Fig. 1). The Little Salmon Fault is not presently within an Alquist-Priolo Special Studies Zone but is currently being considered by the California Division of Mines and Geology as a potentially active fault which would be included in the Alquist-Priolo Special Studies Zone Act of 1972.

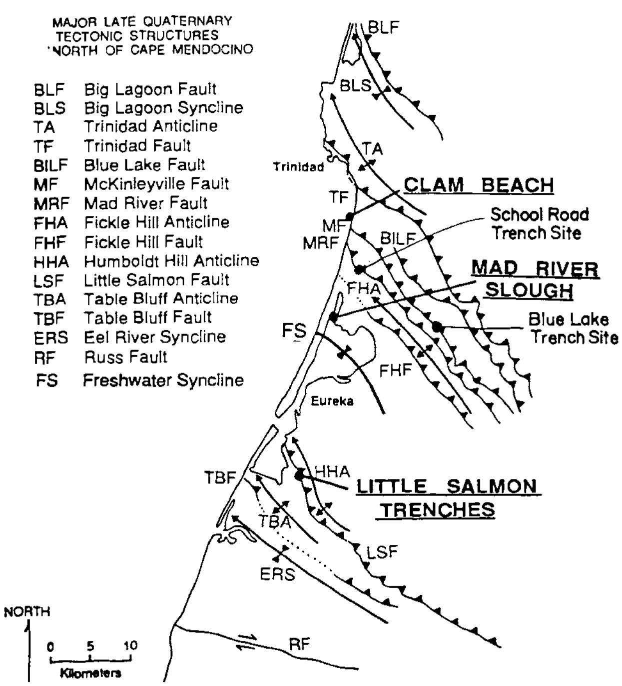


Fig. 1 - Major Onshore Late Quaternary Thrusts and Folds in Northern Coastal California.

A seismic design study was conducted to evaluate the seismic risk and to estimate the earthquake ground motion criteria for the proposed addition to the north side of an existing building at the site. The study included a review of regional geologic and tectonic data to establish the location of nearby faults; assimilation and evaluation of historical earthquake epicenter data for statistical evaluation; estimation of the seismic ground motion for design considerations; and the development of recommendations for ground accelerations and intensities for design use.

SITE CHARACTERIZATION

Regional Scale

Tectonics/Geology

The site lies about 40 km to the northeast of Cape Mendocino and the Mendocino Triple Junction (Fig. 1). Cape Mendocino marks the point of transition from the strike-slip faulting of the San Andreas system south of the triple junction to the low-angle reverse and thrust faulting associated with the Cascadia Subduction Zone north of the triple junction. In the Cascadia Subduction Zone the oceanic crust of the Gorda Plate is subducted beneath the edge of the North American continent (Heaton, 1987). A convergence rate of 20 mm/yr. has been calculated for the Gorda segment of the Cascadia Subduction Zone (Carver and Burke, 1987).

Southern coastal Humboldt County, and the site investigated in the present study, are within the fold and thrust belt associated with the deformation front of the Cascadia Subduction Zone (Fig. 1). Upper-plate deformation related to the subduction of the Gorda Plate beneath the North American plate is expressed at the surface, both on and off-shore, in a series of northwest trending folds and thrust faults. The site lies on the southwest side of one of these folds, the Humboldt Hill anticline. The site is located astride the mapped trace of a thrust fault named the Little Salmon Fault (Ogle, 1953; Woodward-Clyde Consultants, 1980; Carver and Burke, 1989).

Seismic History/Faulting

Five major active fault zones were considered to be capable of generating major earthquakes which could affect the site, namely the Northern San Andreas located 54 km SW of the site, the Mendocino Fracture zone located 40 km SW of the site , the Little Salmon located on site, the Intra Plate West and Subduction zone of the Gorda Plate beneath the North American plate (subducting plate is located directly beneath the site at 20 km depth), and the Mad River fault zone located 28 km NE of the site. An expanded view of the study area at the southern end of the Cascadia subduction zone is presented in Fig. 2. A summary of the various fault zones, fault types, maximum historic magnitudes along with maximum credible earthquake potential, recurrence intervals and estimated probability of occurrences in the next 100 years at the site are shown in Table 1. In the following sections each of the 5 fault zones will be discussed.

Mad River Fault Zone

The Mad River Fault zone consists of at least 6 thrust faults situated along the coast of northern California. These faults are the Big Lagoon, Blue Lake, Trinidad, McKinleyville, Mad River and Fickle Hill. These faults

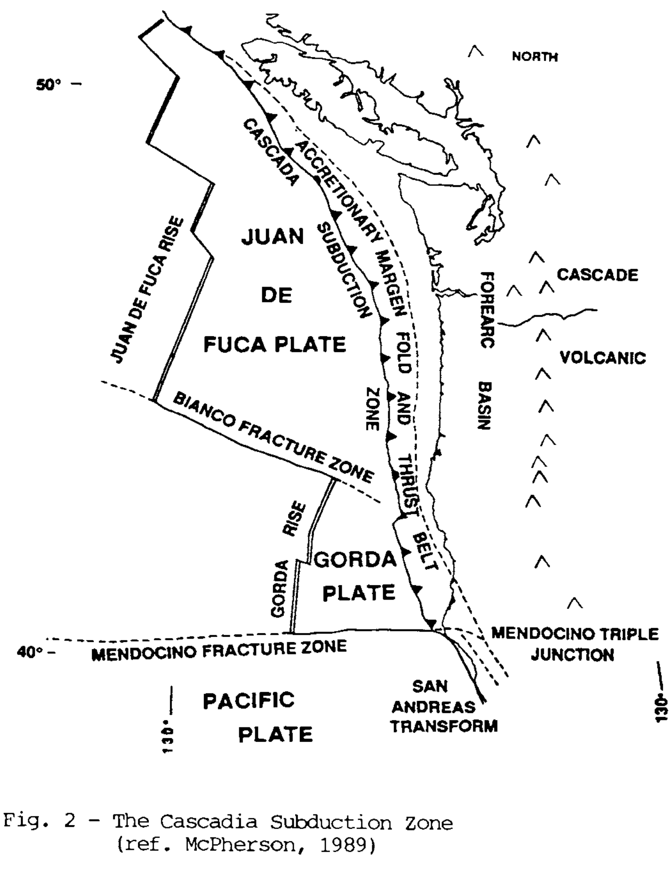


Fig. 2 - The Cascadia Subduction Zone (ref. McPherson, 1989)

are northwest trending thrust faults. The only information available on these faults is the result of trenching on the McKinleyville and Mad River Faults (Carver and Burke, 1989). The results of this trenching showed evidence that the fault is capable of producing displacements ranging from 3.2 to 3.3 m during a seismic event. The corresponding slip rate was determined to be 0.7 mm/yr. with a recurrence interval of 6500 years. Using the relationship developed by Slemmons and Depolo (1986) a maximum credible earthquake of magnitude 7.3 was determined.

Northern San Andreas Fault

The northern San Andreas fault system marks the plate boundary between the North American and Pacific plates. The San Andreas extends from northern Mexico through most of California to near Cape Mendocino and includes several distinct right lateral strike slip faults which have historically generated some of the largest earthquakes in the western United States. In northern California, the system includes the northern San Andreas fault, source of the great 1906 San Francisco earthquake (Magnitude approximately 8^+), and several branch faults which have not generated large historic earthquakes, including the Maacama-Garberville and Eatons Roughs faults (Kelsey and Carver, 1987). The 1906 earthquake resulted in fault rupture from south of the San Francisco Bay area northward along the coast and offshore to at least Point Delgado, and probably as far north as Punta Gorda, approximately 70 km, south of the Eel River basin. The fault passes along the east edge of the Pt. Arena basin. The 1906 earthquake produced strong ground motion and widespread damage in the Humboldt Bay region. Present estimates of the frequency of occurrence of great northern San Andreas earthquakes are around 300 years (Wesnousky, 1986). No data is presently available to allow assessment of the seismic potential of the principal branches of the San Andreas fault in nothern California.

Mendocino Fracture Zone

The Mendocino fracture zone is the boundary between the Pacific and the Gorda-Juan de Fuca Plates and is located at the southern edge of the Eel River basin and slightly north of the Pt. Arena basin. The Mendocino fracture zone is a right lateral strike slip fault system about 250 km long, and exhibits morphology indicative of a highly active fault. It has produced numerous small to moderate earthquakes during the historic period. The maximum credible earthquake has been determined as 7.5 (Geotechnical Consultants, 1981).

Intra Plate West and Subduction Zone - Gorda Plate

Earthquakes originating on faults in the interior of the Gorda plate in the vicinity of the Mendocino triple junction have resulted in very high levels of historic seismicity in the Eel River basin region (McPherson, 1989). These earthquakes are interpreted to result from the disintegration of the southern portion of the Gorda plate under the influence of the northward movement of the Pacific plate (Smith and Knapp, 1980; Wilson, 1989). A schematic illustration of this process is presented in Fig. 3. Most of these earthquakes occur on northeast trending left lateral strike slip faults which seem to be distributed throughout the plate offshore and in the subducting plate. The majority of the earthquakes felt in the Humboldt County region originate from this source. Since 1853 the Gorda Plate has generated about 50 earthquakes which have resulted in strong ground motion at coastal locations in northern California (Carver, 1989). Several of these earthquakes have exceeded Magnitude 7, including the November 8, 1980 Gorda basin earthquake, and have resulted in widespread damage along the Humboldt County coast (Kilborne and Saucedo, 1981). The maximum credible earthquake (MCE) for sources in the intra plate region west of the subduction zone is estimated to be 7.3±. In contrast, the MCE for the subduction zone itself is estimated as ranging from a magnitude of 8.3 (Gorda segment rupture) to 9.2 (Cascadia event - rupturing from Mendocino Fracture Zone to Vancouver Island), Carver and Burke (1989).

Little Salmon Fault

Investigation of the Little Salmon fault on land near the College of the Redwoods has shown the fault has produced at least 3, and probably 5 very large earthquakes in the last two thousand years. The three most recent events are interpreted to be 415,870 and 1730 years before present (ybp) (Carver and Burke, 1988). Each of these seismic events has resulted in displacements ranging from 5.3 - 6.3 mm/yr. The corresponding Holocene recurrence intervals for this seismic event on the fault are between 400 and 800 years. This movement appears accompanied by growth of large folds in the upper thru sheet resulting in localized uplift of anitcline crest and subsidence of syncline axes over a broad area of the coast and adjacent sea floor (Vick, 1988). Estimates of the size of the earthquakes represented in the paleoseismic record for the Little Salmon fault range from magnitude 7.6 to 7.8 (Clarke and Carver, 1989) indicated that the fault apparently does not exhibit magnitudes less than approximately 7.6 - 7.8. The consequences of movement of the Little Salmon faul based on the paleoseismic evidence, might include larg surface fault displacements, very strong ground motion of long duration, and localized changes in elevation associated with growth of folds. Such a seismic event should also be expected to generate a local tsunami.

A Summary of the estimated range of maximum credible magnitudes and the estimated range of the seismic slip rate for various faults is presented in Table 2.

Table 1 Summary of Northern California Fault Zones

Fault Zone	Individual Faults	Fault Type	Maximum Historic Magnitude	Magnitude	Maximum Credible Earthquake[1] Recurrence Interval	Probability[2] of Occurrence Next 100 Years
Mad River	Big Lagoon	Thrust	No Historic EQ	7.3	6,500yrs	1.5%
	Blue Lake	Thrust	No Historic EQ	7.3	6,500yrs	1.5%
	Trinidad	Thrust	No Historic EQ	7.3	6,500yrs	1.5%
	McKinleyville	Thrust	No Historic EQ	7.3	6,500yrs	1.5%
	Mad River	Thrust	No Historic EQ	7.3	6,500yrs	1.5%
	Fickle Hill	Thrust	No Historic EQ	7.3	6,500yrs	1.5%
Northern San Andreas		Strike/Slip	8.3, 1906	8.3	300yrs	24%
Eastern Mendocino Fracture		Strike/Slip	Not Evaluated	6.5	17yrs	100%
Gorda		Deep Seismic	7.0, 11/8/80, 20 km	7.3	50yrs	27%
Little Salmon		Thrust	No Historic EQ	7.6-7.8	440yrs	18.3%
Cascadia		Subduction	No Historic EQ	8.3[3]-9.2[4]	440yrs	18.3%

Notes: (1)Maximum credible earthquake is defined as the maximum event which may ever be expected at the building within the known geological framework (Title 24).
(2)Probabilities calculated assuming a Poisson process.
(3)Rupture of Gorda Segment, M_0=8.3.
(4)Rupture of 60% of subduction zone length, M_0=9.2.

Fault	Estimated Range of Maximum Credible Earthquake Magnitude (1)	Estimated Range of Seismic Slip Rate (2) (mm/yr.)
Little Salmon	7.6 - 7.8	5.3 - 6.3
Mad River		
Big Lagoon		
Blue Lake		
Trinidad		
McKinleyville	7 - 7.3	0.9
Mad River	7 - 7.3	1.2
Fickle Hill	7 - 7.3	0.6
Cascadia Subduction Zone		
Unsegmented	9.2	13.5
Gorda Segment	8.3 - 8.5	13.5
Intra Gorda Plate West	7.3	
Mendocino Fault Zone	7.5 - 8	
Eastern Mendocino Fault Zone	6.5	
San Andreas		
Northern	8.3	

(1) Moment Magnitude
(2) Seismic slip rate is the difference between the total slip rate and the creep rate.

Table 2 - Summary of Source Characteristics

Site Specific Scale

Surface Topography

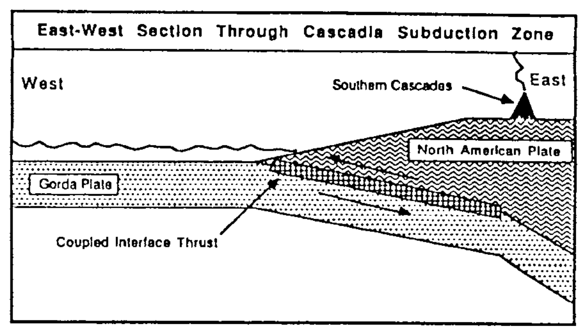
The proposed library addition site area encompasses a portion of a gently rounded grassy area whose slopes are downward in both southwest and northeast directions. Towards the southwest the ground elevation slopes downward gently towards a creek and a small pond. During construction of the campus, the topsoil (A horizon) and some undetermined amount of underlying soil (B horizon) of the original undisturbed surface was scraped off and evidently used to fill lower ground. This occurred towards the northeast in the direction of the valley of a small, northwest flowing stream along the foot of Humboldt Hill.

Soil Stratigraphy and Basement Rock

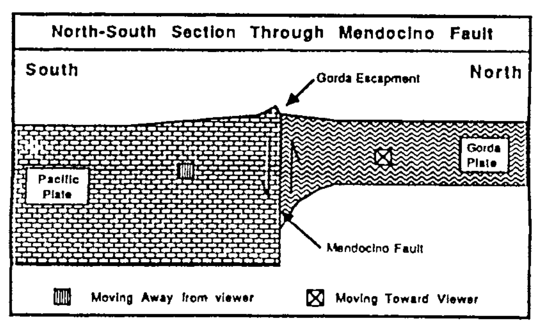
The site is underlain by marine (or bay) terrace deposits (CDMG, 1984). Marine terrace deposits at the site and in surrounding areas consist of semi-consolidated sand, silt, gravel and clay deposited on wave cut terrace platforms. The age based on other local marine terraces at similar elevations is late Pleistocene (Carver, Burke and Kelsey, 1987). The late Pleistocene marine sediments unconformably overlie Hookton marine sediments of upper Pleistocene age. Colluvium derived from the steep southwest facing slope of a hill adjacent to the site may have been reworked by wave action and deposited on the terrace surface. Some later reworking of the marine terrace deposits by fluvial processes was suggested by exposures in the trench excavated for this investigation.

Trenching

In order to ascertain whether a strand of the little Salmon Fault exists beneath the site of the proposed library addition, a series of six trenches were excavated both north and south of the existing structure as well as along its NW side. A plot plan showing the location of these trenches in relation to the existing structure and proposed addition is presented in Fig. 4.



a.



b.

Fig. 3 - Summary Cartoons of the tectonics in the southern end of the Cascadia Subduction Zone. (Ref. McPherson, 1989)

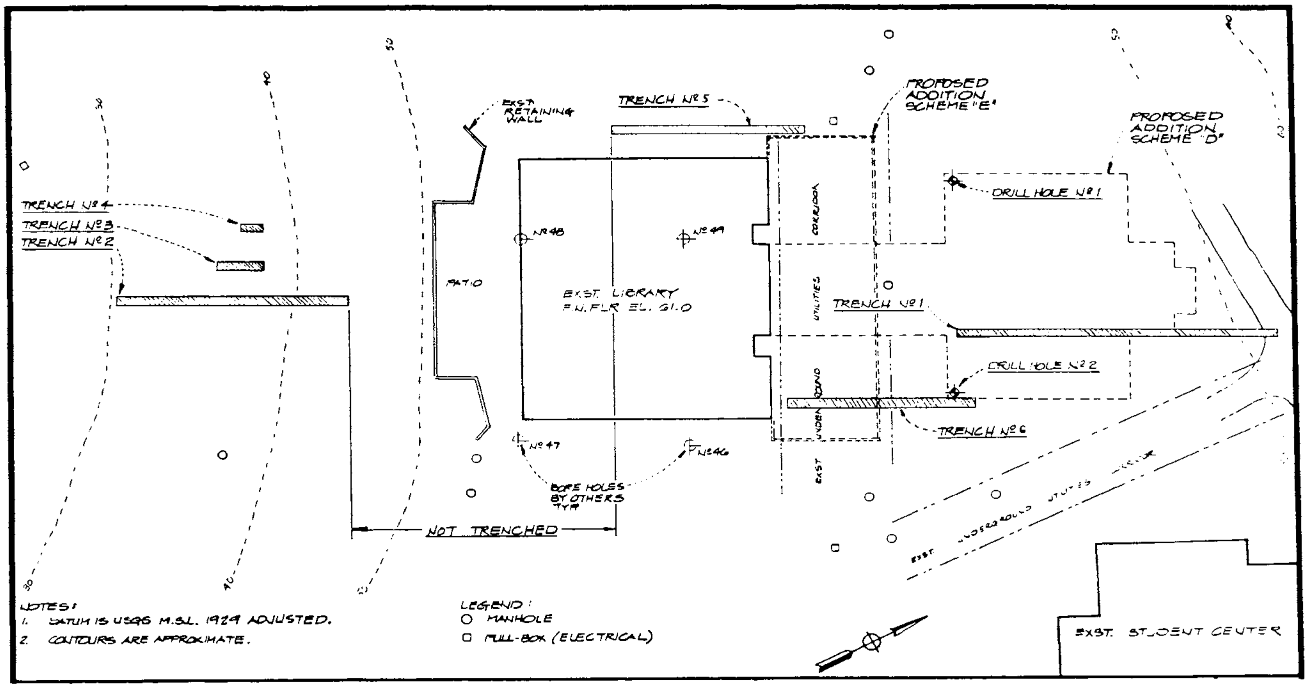


Fig. 4 - Plot Plan of Project Site Showing Location of Trenches

Two stratigraphic units were exposed within trench No. 1. The lowermost unit observed was a clay exposed beneath a prominent horizon of iron oxide staining. Groundwater percolating down to the top of the impermeable clay unit was forced to flow laterally. Laterally flowing groundwater precipitated abundant Fe and Mn oxides along the contact between the clay layer and the overlying clayey sand/silty sand layer, giving the contact a pronounced bright orange color. Beneath the orange Fe-cemented contact, a blue gray clay (unit one) was exposed in the lowermost foot to eighteen inches of the trench. In the southwest end of the trench the clay contained little sand or gravel but graded, both vertically (downward) and laterally (northwest) into sandy clay, and clayey sand containing 0.25 in. to 0.75 in. subrounded cherty gravels. The gravel content of unit one was variable but was always less than 10%.

Above the clay layer and the heavily Fe-stained contact, the upper unit consists of clayey sand and silty sand interbedded with clean fine sand. The uppermost four to six feet of the upper unit commonly shows less stratified sand and gravelly sand but commonly has fine (1 in. to 0.75 in.) subrounded to well rounded cherty gravel randomly dispersed throughout a clayey sand matrix. The lower 2 to 3 feet of the upper unit contains stringers and lenses of sand, sandy gravel and gravelly sand that were deposited by a small stream. The upper portion of the clayey sand/silty sand layer was visually estimated to contain less than 5% to 10% of the cherty gravel.

Excavation of the trench No. 1 did not expose any evidence of ground rupture. The common pattern of pervasive fracturing in the upper plate of the fault, as described by Woodward-Clyde Consultants in their nearby trenches, was not observed. Subtle folding of units exposed in the trench was observed and was interpreted as evidence of possible deformation associated with motion or a shallow, ramping thrust fault beneath the site. The change in bedding attitude between the nearly flat contacts in the southwest portion of the trench and the apparent northeast dip of contacts in the northeast portion of the trench is believed to mark the hingeline of a fault bend fold as described by Suppe (1983). A log of trench No. 5 which shows a thrust fault is presented in Fig. 5. Recurrent motion on one of the splays of the Little Salmon Fault that changes attitude (ramps up or flattens to follow a bedding plane) as it approaches the surface causes folding of originally horizontal bedding in the hanging wall of the fault (refer to Fig. 6). Topography of the site reflects the geometry of the fault bend fold in the subsurface. Similar folding of units and contacts was observed in a trench excavated across the Little Salmon Fault three miles to the south, (Carver and Burke, 1989).

Alternative models that might produce similar topography and subsurface deformation exist. One of these, the pop up model (Suppe, 1983) would require a back thrust which would come to the surface in the vicinity of the area to the north of the proposed addition. Deformation of sediments beneath the library addition and topographic expression of the structure in the area is similar to that predicted by a fault bend fold model.

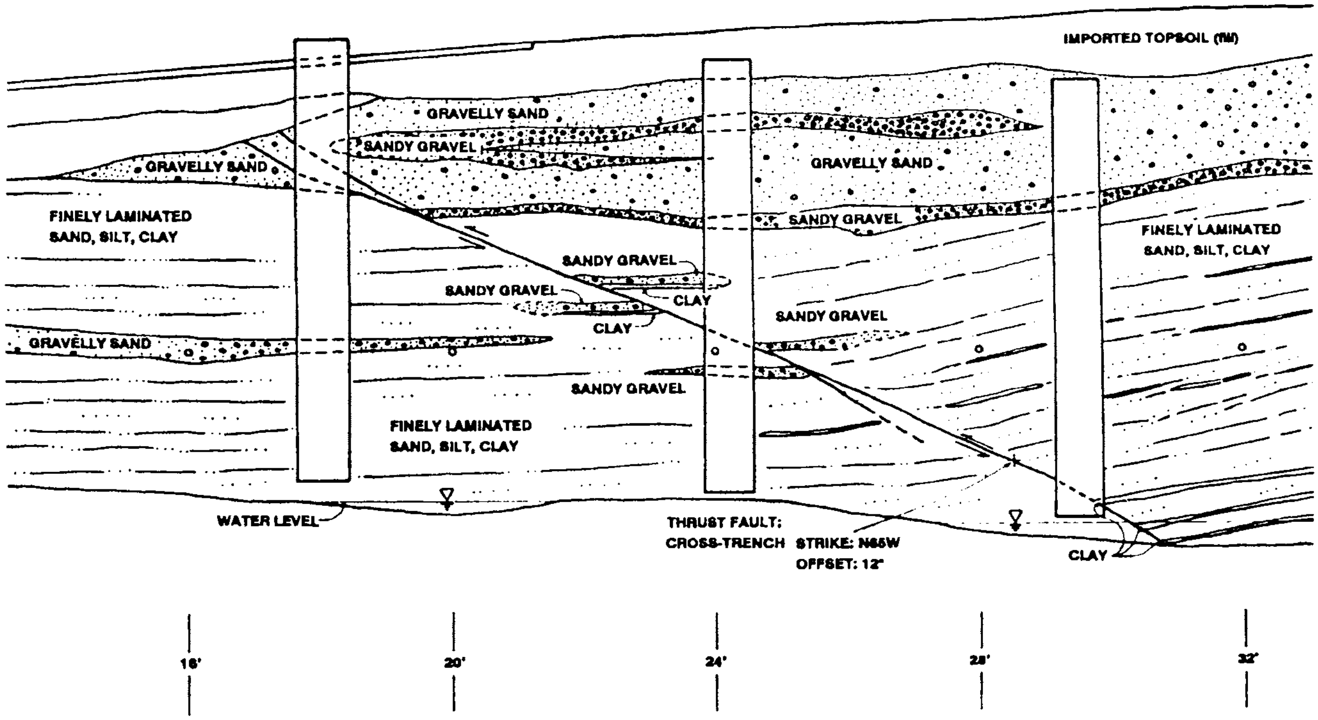


Fig. 5 - Log of Trench #5 Showing Thrust Fault

SEISMIC ANALYSIS

Earthquake Data Analyzed

Earthquake data utilized for this study was developed from various references covering a quandrant centered on the site and bounded by coordinates 41°N, 123.6°W, 40.3°N and 124.8°W. This data summarized historic earthquakes which occurred within a range of magnitudes 3.0 and greater for the period 10/23/1853 through 5/31/87.

In modeling the seismic sources, several potential scenarios were identified: (1) the Cascadia subduction zone breaks along its entire length including the Gorda plate; (2) the Gorda segment breaks independently of the other segments of the Cascadia subduction zone; (3) events occur on the Little Salmon and on reverse faults of the Mad River fault system; (4) events occur on intraplate faults with in the Gorda plate, and (5) events occur along the Mendocino fault near Cape Mendocino.

Recurrence of Earthquake Events

The recurrence curves relating the number of earthquakes per year versus magnitude for the various fault zones in the region have been determined by Woodward-Clyde (1989) as shown in Figs. 7 and 8. These curves were constructed using the general approach of Molnar (1979) and Anderson (1979) in combination with both historic seismicity data as well as geologic evidence for the long term seismic slip rate on individual faults. The recurrence model includes a relatively high likelihood that some of the seismic sources rupture with a "characteristic" magnitude. This model has been described in Aki (1983), Coppersmith and Schwartz (1983) and Schwartz and Coppersmith (1984), and has been recognized for subduction zone earthquakes by Lahr and Stephens (1982) and Singh, Rodrigues, and Estero (1983).

The recurrence relationships presented in Fig. 7 are based on the assumption that each source is 100 percent likely to be active. However, these potential sources are not necessarily independent; movement on the reverse faults may be due to events occurring on the subduction zone, or strain due to convergence along the subduction zone may be relieved by events on the reverse

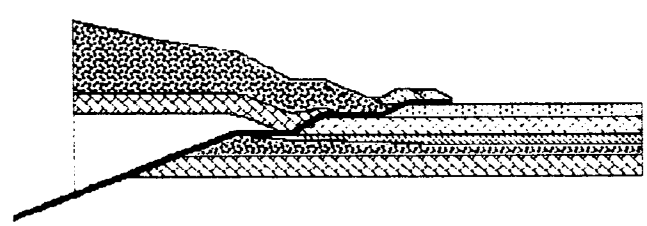


Fig. 6 - Schematic of Thrust Fault That Changes Attitude

faults. The likelihood that the entire Cascadia subduction zone ruptures in a single event was judged to be low and was assigned a probability of 5%. The remaining 95% probability was divided between the Gorda segment of the Cascadia subduction zone and the reverse faults assuming statistical weights of 60 and 40%, respectively. The weighted recurrence relationships for the faults are presented in Fig. 8. The characteristic earthquake recurrence model (Schwartz and Coppersmith, 1984) was considered to best model events that can be conclusively assigned to these faults.

The recurrences of the intraplate Gorda and Mendocino Fault events were based on the historical numbers of events in the region. Because most of the events occur in an area in the northwest of Cape Mendocino, the Seismicity was divided 70 to 30% between the Mendocino fault and Intraplate Gorda events. The Gutenberg and Richter model was considered appropriate for these sources due to the large number of smaller events and the nearly linear trend of the historical recurrence.

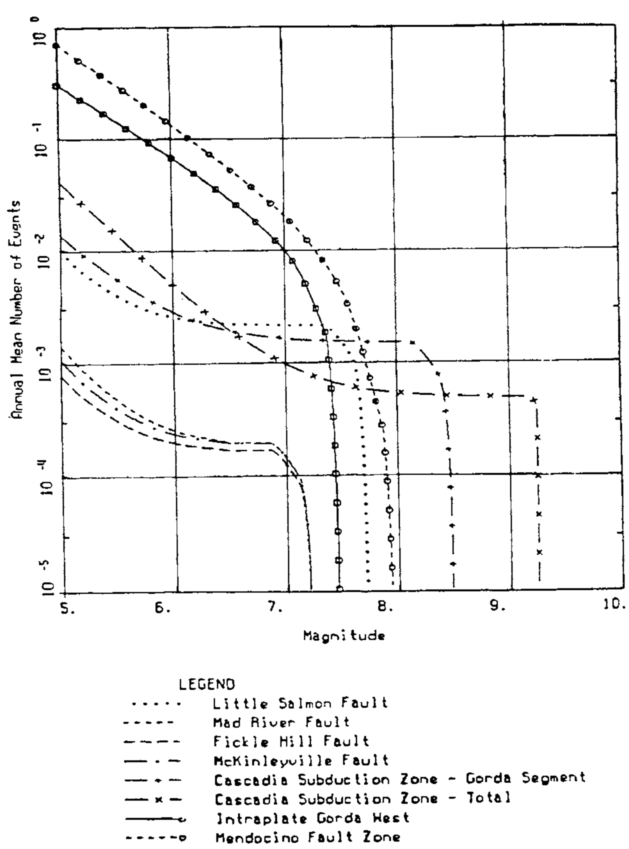


Fig. 7 - Recurrence Curves Assuming Faults Act Independently (Ref. Woodward-Clyde, 1989)

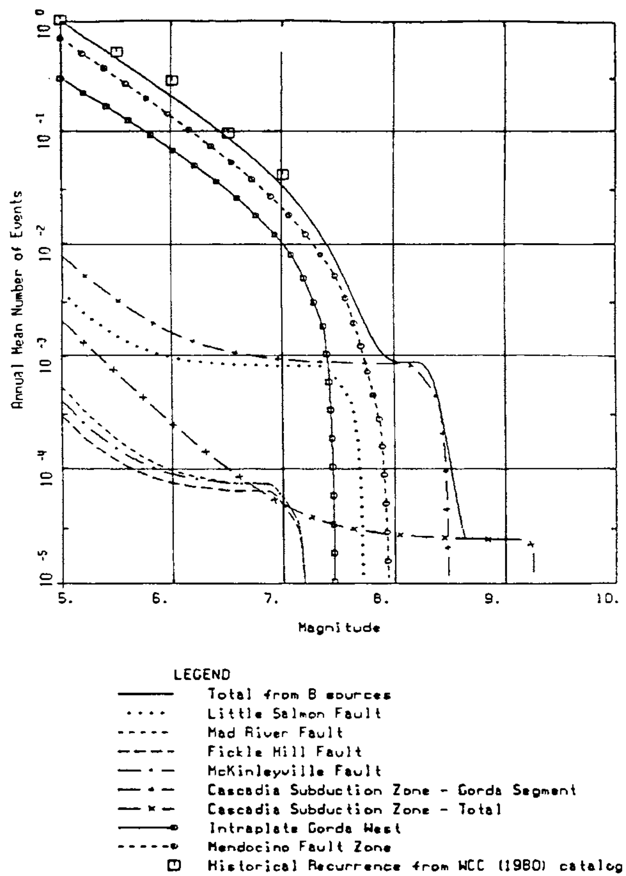


Fig. 8 - Recurrence Curves Assuming Faults Act Co-seismically (Ref. Woodward-Clyde, 1989)

Accelerations Expected at Site

Two levels of earthquake shaking were investigated. These levels are (1) the maximum credible earthquake (MCE), and (2) the maximum probable earthquake (MPE). The MCE is defined as the maximum earthquake that appears capable of occurring under the presently known tectonic framework. The MPE in contrast is defined as the maximum earthquake that is likely to occur during a 100-year interval. Estimates of the MPE are based on the criteria in CDMG Note 43 and recurrence curves presented by Woodward-Clyde Consultants (1989). The accelerations due to the MPE were calculated assuming that either the faults act independently or assuming that the faults act co-seismically.

Bedrock accelerations corresponding to these earthquake magnitude levels are presented in Table 3. A review of Table 3 shows that the maximum bedrock acceleration due to the MCE is 0.85g. In comparison the maximum bedrock acceleration due to the MPE assuming faults act independently or co-seismically is 0.5g. The fault zone causing these maximum accelerations is the Little Salmon Fault.

Table 3 Summary of Maximum Credible and Maximum Probable Earthquake Magnitudes and Accelerations

Fault Zones	Approximate Distance km(mi)	Maximum Credible Earthquake Magnitude	Maximum Credible Earthquake Bedrock Accel.	Maximum Probable Earthquake Assuming Faults Act Independently Magnitude	Maximum Probable Earthquake Assuming Faults Act Independently Bedrock Accel.	Maximum Probable Earthquake Assuming Faults Act Co-Seismically Magnitude	Maximum Probable Earthquake Assuming Faults Act Co-Seismically Bedrock Accel.
Northern San Andreas	54 (32.4)	8.3	0.24(2)	8.3	0.24(2)	8.3	0.24(2)
Mad River Fault Zone	28 (16.8)	7.3	0.23(3)	<5.0	0.04(3)	<5.0	0.04(3)
Eastern Mendocino Fracture Zone	40 (24)	6.5	0.12(2)	6.5	0.12(2)	6.5	0.12(2)
Deep Seismic	20 (12)	7.4	0.37(2)	7.0	0.35(2)	7.0	0.35(2)
Little Salmon	0 (0)	7.6-7.8	0.85(1)	5.0	0.50(3)	<5.0	0.50(3)
Cascadia Subduction Zone (Gorda Segment)	16 (9.6)	8.3	0.46(2)	5.1	0.10(2)	<5.0	0.10(1)

Note: (1) Scaled from PG&E Diablo Canyon Nuclear Power Plant Report (1988), Figures 4-19, Thrust Faults.
(2) Seed and Idriss (1982).
(3) From Sadigh (Joyner and Boore, 1988).

Discussion and Conclusions

1. The fold observed in the trench is a fault bend fold produced by changing dip on a splay of the Little Salmon Fault at a shallow depth beneath the site. While the proposed building addition would not seem to be in danger from ground rupture resulting from fault motion, the movement of the fault would cause the hanging wall (up thrown) block to slide some distance across the hinge-line, thus subjecting the building to differential vertical movement of its foundation and the resulting shearing stresses beyond those normally associated with strong ground motion.

2. Surface disruption at the site can potentially be caused by movement on the Little Salmon fault. The probability of the Little Salmon fault moving independently in the next 100 years is estimated to be 18.3%.

3. The maximum bedrock acceleration at the site due to the Maximum Credible Earthquake is 0.85g. In comparison the maximum bedrock acceleration due to the Maximum Probable Earthquake assuming faults act either independently or co-seismically is 0.5g. The fault zone causing these maximum accelerations is the Little Salmon Fault.

References

Aki, K., "Seismological Evidence in Support of the Existence of 'Characteristic Earthquakes'," Earthquake Notes, 1983, Vol. 54, No. 1, 60-61.

Anderson, J. G., "Estimating the Seismicity from Geological Structure for Seismic Risk Studies," Bulletin of the Seismological Society of America, 1979, Vol. 69, No. 1, 135-158.

Carver, G. A., "Paleoseismicity of the Southern Part of the Cascadia Subduction Zone," (abstract), Earthquake Notes, Annual Meeting Seismological Society of America, 1989.

Carver, G. A. and Burke, R. M., "Quaternary Deformation in Region of the Mendocino Triple Junction; unpublished final report, National Earthquake Hazard Reduction Program, U. S. Geological Survey, 1987.

Carver, G. A., and Burke, R. M., "Trenching investigations of Northwest California Faults, Humboldt Bay Region," unpublished final report, National Earthquake Hazards Reduction Program, U. S. Geological Survey, 1988, 53 p.

Carver, G. A., and Burke, R. M., "Final Report, Trenching Investigation of Northwestern California Faults, Humboldt Bay Region," USGS Grant 14-08-0001-G1082, 1989.

Carver, G. A., Burke, R. M., and Kelsey, H. M., "Quarternary Deformation in the Region of the Mendocino Triple Junction," unpublished final report, National Earthquake Hazards Reduction Program, U. S. Geological Survey, 1987.

Carver, personal communication, 1988.

California Division of Mines and Geology, "CDMG Note 43 - Recommended Guidelines for Determining the Maximum Credible and the Maximum Probable Earthquakes," 1975.

Clarke, S. H., and Carver, G. A., "On Shore/Offshore Characteristics and Seismic Potential of Structures Along the Gorda Segment of Cascadia Subduction Zone," abstract, Geological Society of America, Abstract With Programs, 1989, Vol. 21, (5), 66.

Coppersmith, K. J., and Schwartz, D. P., "The Characteristic Earthquake Model: Implications to Recurrence on the San Andreas Fault," Earthquake Notes, 1983, Vol. 54, No. 1, 61.

Geotechnical Consultants, "Geotechnical Reconnaissance - Proposed Greater Eureka Wastewater Treatment Plant, Elk River Site, City of Eureka," Santa Ana Office, CA, unpublished client report, 1981.

Heaton, T. H., and Hartzell, S. H., "Earthquake Hazards On The Cascadia Subduction Zone," Science, 1987, Vol. 236, 10 April 162-168.

Joyner, W. B. and Boore, D. M. (1988). "Measurement, Characterization, and Prediction of Strong Ground Motion," Speciality Conference on Earthquake Engineering and Soil Dynamics, American Society of Civil Engineers, 1988, 43-102.

Kelsey, H. M. and Carver, G. A., "Late Neogene and Quarternary Tectonics Associated with the Northward Growth of the San Andreas Transform Fault, Northern California," Journal of Geophysical Research, 1987, Vol. 93, 4797-4819.

Kilborne, R. T., and Saucedo, G. J., "Gorda Basin Earthquake, Northwestern California," California Geology, 1981, March, 53-57.

Lahr, J. C. and Stephens, C. C.,"Alaska Seismic Zone: Possible Example on Nonlinear Magnitude Distribution for Faults," Earthquake Notes, 1982, Vol. 53, 66.

McPherson, R. C., "Seismicity and Focal Mechanisms Near the Mendocino Triple Junction, Northern California," unpublished M.S. thesis, Humboldt State University, 1989, 81 p.

Molnar, P., "Earthquake Recurrence Intervals and Plate Tectonics," Bulletin of the Seismological Society of America, 1979, Vol. 69, No. 1, 115-133.

Ogle, B. A., "Geology of the Eel River Valley Area, Humboldt County, California Divisions of Mines and Geology, 1953.

Pacific Gas and Electric, "Diablo Canyon Power Plant, Long Term Seismic Program," 1988, July.

Schwartz, D. P., and Coppersmith, K. J., "Fault Behavior and Characteristic Earthquakes: Examples from the Wasatch and San Andreas Faults," Journal of Geophysical Research, 1984, Vol. 89, No. 87, 5681-5698.

Seed, H. B., and Idriss, I. M., Ground Motions and Soil Liquefaction During Earthquakes, Earthquake Engineering Research Institute, 1982.

Singh, S. K., Rodriguez, M., and Estero, L., "Statistics of Small Earthquakes and Frequency of Large Earthquakes Along the Mexico Subduction Zone," Bulletin of the Seismological Society of America, 1983, Vol. 73, No. 6, 1779-1796.

Slemmons, D. B. and Depolo, C. M., "Evaluation of Active Faulting and Associated Hazards, Active Tectonics," Studies in Geophysics, National Academy Press, Washington, D. C., 1986, 45-62.

Smith, S. W. and Knapp, J. S., "The Northern Termination of the San Andrea Fault, in Studies of the San Andreas Fault zone in Northern California," ed. by R. Steitz and R. Sherburne, California Division of Mines and Geology special report 140, 1980, 153-164.

Suppe, J., "Geometry and Kinematics of Fault-Bend Folding," American Journal of Science, 1983, Vol. 283, No. 7, 684-721.

Vick, G. S., "Late Holocene Paleoseismicity and Relative Sea Level Changes of the Mad River Slough, Northern Humboldt Bay, California," unpublished M. S. thesis, Humboldt State University, 1988, 87 p.

Wesnousky, S. G., "Earthquakes, Quaternary Faults and Seismic Hazard in California," Journal of Geophysical Research, 1986, Vol. 91, No. B12, 12587-12631.

Wilson, D. S., Deformations of the So-Called Gorda Plate," Journal of Geophysical Research, 1989, Vol. 94, B3, 3065-3075.

Woodward-Clyde Consultants, "Evaluation of the Potential for Resolving the Geologic and Seismic Issues at the Humboldt Bay Power Plant Unit Number 3," Unpublished Consulting Report for Pacific Gas and Electric Company, Summary Report, October, 1980, 74 p

Woodward-Clyde Consultants, " Geological and Geotechnical Evaluation of Founders Hall," California State University, Humboldt, Arcata, California, November 1989.