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ABSTRACT

Compressional and shear wave tests were conducted on the upper thrust sheet of the low angle Little Salmon thrust fault. The study was conducted on the campus of the College of the Redwoods. The campus is located approximately 8 miles south of Eureka and 24 miles north-northeast of Cape Mendocino and the Mendocino Triple Junction (MTJ) in Northern California. The MTJ is the point of transition from strike-slip faulting of the San Andreas transform system to low-angle reverse (thrust) faulting and folding associated with the convergent margin of the Cascadia Subduction Zone. The campus is located on the southwest limb of the Humboldt Hill anticline, one of the folds in the fold and thrust belt. The Little Salmon fault zone is a low angle thrust fault that day lights on the south side of the campus and then projects underneath striking northwest and dipping northeast. A boring was drilled down to the fault plane located at a depth of 200 ft. in the upper thrust block to develop a model of the stratification as well as the material properties. The boring also revealed the trunk of a redwood tree located at a depth of 180 feet. Results of compressional and shear wave velocities as a function of depth that were determined using an downhole geophysical technique. Results indicated two shear wave velocity units. Unit 1 was from 0 to 120 ft. with a shear wave velocity ranging from 950-1400 fps. Unit 2 ranged from 120 to 190 ft. with a shear wave velocity ranging from 2300 to 2600 fps. Compression wave velocity measurements obtained from the same test boring also depict a change in velocity in the 100 to 120 foot range. A response spectra was generated based on this in-situ model using SHAKE91 and compared against one developed using the Boore, Joyner and Fumal empirical model.

KEYWORDS

Compressional wave, Shear Wave, Spectra, Low Angle Thrust Fault, Reverse Fault, Fault Bend Fold

INTRODUCTION

The project described in this paper involved the measurement of shear and compressional wave velocities in a borehole in the upper sheet of a low angle thrust fault. This information was used to develope a response spectra for a proposed learning resource center (LRC) located on the campus of the College of the Redwoods (CR). The College of the Redwoods is located south of Eureka, California. The seismic hazards associated with this site have been discussed in a previous publication (Chaney et al., 1991). The response spectra was developed using two different approaches: (1) conducting a 1D dynamic response analysis using SHAKE91 incorporating physical properties of the various soil layers, and (2) using the empirical relation given by Boore et al. (1997). In the following sections the geologic and seismic setting, field program and spectral analysis will be discussed.

GEOLOGIC AND SEISMIC SETTING

CR is located about 40 kilometers north-northeast of Cape Mendocino and the Mendocino Triple Junction (MTJ). The MTJ is the point of transition from strike-slip faulting of the San Andreas transform system to low-angle reverse (thrust) faulting and folding associated with the convergent margin of the Cascadia Subduction Zone. The MTJ is the most seismically active region in the lower 48 states.

The regional tectonic framework north of the MTJ is controlled by the Cascadia Subduction Zone wherein the Gorda plate is subducted beneath the North American plate. Convergence along the subduction zone occurs at a rate of 30-40 mm/year (Heaton & Kanamori, 1984). Deformation associated with the subduction zone is expressed as a roughly 90-100 kilometers-wide fold and thrust belt along the plate margin.

Deformation in the region is expressed as a system of northwest-striking, northeast-dipping thrust faults and fault-related folds. Thrust faults are thought to extend into or near the interface between the Gorda and North American plates (Clarke, 1992). Cumulative slip greater than 15 kilometers has been estimated across the fold and thrust belt (Carver, 1987; Kelsey and Carver, 1988). The fold and thrust belt is accommodating about 2 centimeters per year of northeast-southwest horizontal contraction (Clarke and Carver, 1992).

The direction of shortening nearly parallels the Gorda and North American plate convergence vector, and accounts for more than half of the overall convergence rate. Convergence is accommodated by growth of the fold and thrust belt (Carver and McCalpin, 1996). The apparent youthfulness of these structures indicates that the subduction zone is strongly coupled and compressive deformation within the North American plate margin is active (Clarke and Carver, 1992).

CR is located on a bluff at the base of the Humboldt Hill anticline, a major fault-bend fold produced by repeated movement along the east trace of the Little Salmon fault. The Little Salmon fault is designated by the State of California as an active fault. No earthquakes have occurred on the Little Salmon fault since at least 1850, the period for which records have been kept. The California Division of Mines and Geology has assigned a maximum moment magnitude (Mw) of 7.3 and a recurrence interval of 268 years to earthquake events on the onshore segment of the Little Salmon fault (Petersen *et al*, 1996).

CR is underlain by the Pleistocene Hookton Formation (Ogle, 1953), late Pleistocene marine terrace deposits, and late Pleistocene to Holocene fluvial, alluvial and colluvial sediments. The Hookton Formation is composed of sands, silts, clays and gravel, deposited in a near-shore, shallow-water marine to coastal plain and fluvial environment. Late Pleistocene marine terrace and late Pleistocene-Holocene Hookton-derived fluvial-deltaic and alluvial deposits cap much of Hookton Formation on the hanging wall block of the thrust. Field investigation has shown that the College is built on a fault-bend fold generated by repeated movement of the Little Salmon fault underlying the campus. The fold is expressed as a broad northwest-trending anticline with a steeply dipping forelimb, flat lying crest, and shallow dipping backlimb.

Little Salmon Fault

The Little Salmon fault is a major northwest-striking, northeast-dipping thrust fault in the Cascadia Subduction Zone fold and thrust belt. The Little Salmon fault, including its offshore segment, is about 80 kilometers long (Petersen *et al*, 1996). The fault can be traced from east of Carlotta, northwest to the coast at Humboldt Bay (Ogle, 1953). Offshore, where the Little Salmon fault was mapped by acoustic-reflection profiling, it terminates along a major structural discordance (Clarke, 1992).

Strike of the onshore portion of the Little Salmon fault varies from N60W in the southeast near Carlotta, to N35W at CR. In map view the surface trace is sinuous and broadly convex to the southwest. Where it underlies CR, the fault plane is postulated to dip 10-15 degrees to the northeast, based on field investigation and modeling (LACO Associates, 1998). Petroleum industry well-log data suggest the fault plane steepens down-dip reaching about 29 degrees where it underlies Humboldt Hill. The Little Salmon fault was assigned a dip of 30 degrees by the Division of Mines and Geology (Petersen *et al*, 1996). A schematic profile of the site showing the low angle thrust fault is shown in Fig. 1.

FIELD PROGRAM

Seismic velocity measurements were taken from a two hundred foot deep test boring that was drilled for this study. The boring log along with shear and compressional wave velocities as a function of depth is presented in Fig. 2. A review of the boring shows interbedded gravels/sands /silts/clays. In addition, the boring log also shows the remains of a tree that was carried down in the lower sheet of the low angle thrust fault. These remains.are now located at a depth of approximately 180 feet. To measure seismic waves ten sensors spaced 10 feet apart were lowered down the boring. The sensors were oriented so that the direction of movement was horizontal and were coupled to one side of the wall of the cased boring by elastic arms which formed "bridges" across the hole at the sensor sites. Thus by initiating the shear wave in opposite directions, but in a plane parallel to the horizontal axes of the seismic sensors, the difference in polarity of the waves could be observed and used as the primary criterion for discerning shear waves. The data obtained in this program was fairly noisy. This resulted in several of the traces in a given record being unreadable. To confront this problem, a six-to ten-fold redundancy of velocity measurement was obtained. The shear wave source was located thirty feet to the side of the boring. The boring was surrounded by blacktop pavement and the source was located on the nearest natural ground. This results in difficulty in accurately depicting the shear wave velocity near the surface. This is because as one approaches zero depth, the horizontal component of the distance traveled becomes greater and the vertical component diminishes. Regardless of the above condition, the velocity data derived in this program appears to be diagnostic and coherent. The interpreted velocity distribution versus depth is presented in Table 1.

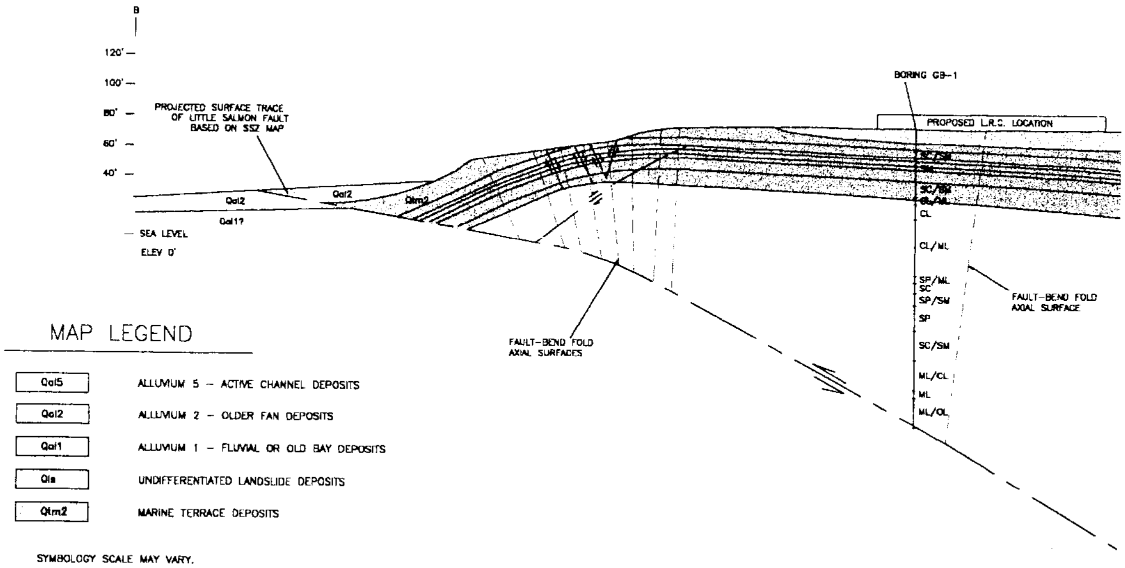

Fig. 1 Schematic Illustration of Low Angle Thrust Fault and Deep Boring

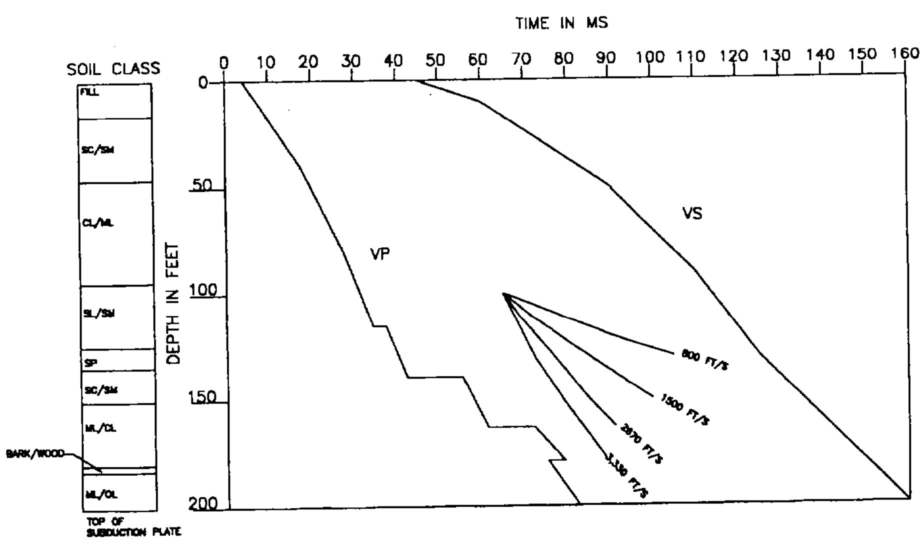

Fig. 2 Variation of Compressional and Shear Wave Velocities as a Function of Depth

Depth (ft.)	Shear Velocity Unit (ft./ms)
0-120	0.950 to 1.400
120-190	2.300 to 2.600

Table 1 – Interpreted Velocity Distribution

Where velocity were measured with the 1.4 and 2.3 fpms range, the ninety foot log seismic sensor configuration straddled the contact zone between the two velocity units. P-wave velocity measurements obtained from the same test boring also depict a change in velocity in the 100 to 120 foot range.

SPECTRAL ANALYSIS

The program SHAKE91 requires an input acceleration time history, peak acceleration, material type, total unit weight and shear wave velocities of the various layers. The program EZ-FRISK was used to calculate the seismic hazard curve at the CR-LRC site. All currently recognized active faults in the north coast region of California were included in our analysis. The active faults utilized in this investigation, and their estimated maximum moment magnitude and distance from the CR Eureka campus are presented in Table 2. All fault parameters, with two exceptions, were based on information presented in Peterson et al. (1996). The exceptions were combining the onshore and offshore segments of the Little Salmon fault, and increasing the upper-bound maximum moment magnitude for the Little Salmon fault (on shore plus off shore) from 7.1 to 7.3 (Carver, 1997).

These faults, their locations relative to the site and their seismic parameters, were included in the computer analysis with an attenuation equation developed by Campbell (1993, hard rock). Results of the maximum amplitude of acceleration as a function of the probability of occurrence are presented in Table 3 (LACO Associates, 1997). These values of acceleration were used to scale the earthquake acceleration time history that was input into the base of the soil model.

A dynamic response analysis was conducted for the site using the program SHAKE91, boring log (Fig. 2), laboratory analysis of soil samples and shear wave velocities (Fig. 2). The total unit weight of soil samples from the boring varied from 120 to 141pcf. An acceleration time history from the 1972 Sitka Earthquake (7.6 Ms, N090E, 49 km epicentral distance, graywacke) was scaled for peak accelerations associated with the earthquakes indicated in Table 3.

Fault Name	Maximum Moment Mag. (Mw)	Closest Epicentral Distance (km)
Cascadia Subduction Zone (entire)	9.0	17.54
Fickle Hill	6.9	20.53
Mad River	7.1	19.21
McKinleyville	7.0	23.85
Little Salmon (entire)	7.3	0.08
Mendocino	7.4	53.74
Big Lagoon-Bald Mtn.	7.3	48.36
Table Bluff	7.0	3.17
Trinidad	7.3	30.99
San Andreas – North Coast Segment	7.6	53.39
Garberville - Briceland	6.9	51.79

Table 2 – Faults and Distances from College of Redwoods

Earthquake Type	Return Interval (years)	PGA (a/g)
Occasional	72	0.11
Design Basis 10% in 50 years	475	0.71
Upper Bound 10% in 100 years	949	1.2

Table 3 – Peak Acceleration as a Function of Probability of Occurrence at Site

CONCLUSIONS

1. The geometry of the low angle thrust fault generates a series of fault bend fold axial surfaces that can cause surface disruptions in the upper sheet.

2. Shear and compressional wave velocities increase with depth in the upper thrust sheet down to the surface of the fault plane.

3. Response spectra generated by SHAKE91 utilizing one earthquake record for the case studied is greater than that predicted by Boore et al. (1997) for frequencies less than 0.4 Hz. For frequencies greater than 0.4 Hz Boore et al. (1997) predictes a response spectra greater than that from SHAKE91.

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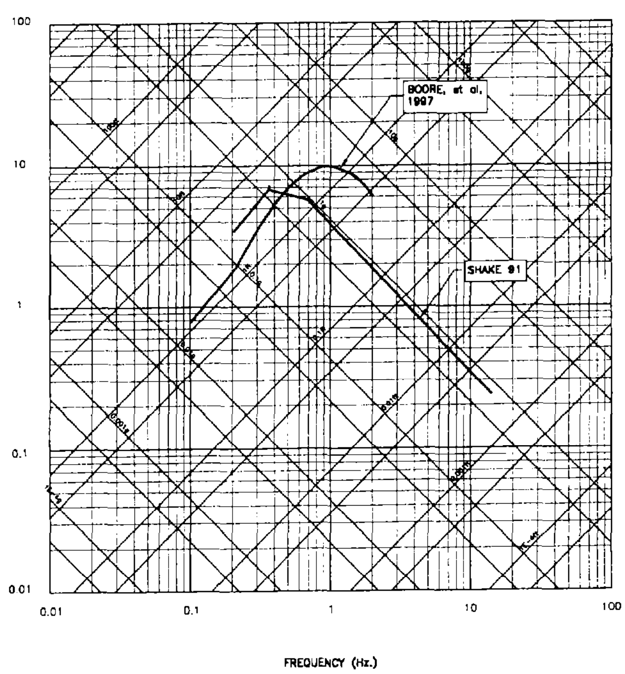

Fig. 3 Response Spectra Comparing Results From SHAKE91 and Boore et al. 1997 Analysis