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INTRODUCTION

A unique aspect of the October 17, 1989 Loma Prieta earthquake was the extensive structural damage and irregular ground response observed in the greater Oakland-East Bay Area, approximately 95-105 km north of epicenter. Strong motion recorders on Yerba Buena and Treasure Islands registered motions with 250% variance over a distance of 900 meters. Three-thousand m east of Buena Island, the center portion of the Oakland Container Wharf received shaking levels of 0.27g to 0.29g (horizontal) with up to 0.084g vertical motion.

Twenty-one-hundred m east of the Wharf, the northern half of the double-decked I-880 Cypress Street Viaduct experienced an extensive partial collapse. Portable seismograph arrays placed adjacent to remaining and collapsed portions of the Cypress Viaduct recorded variances of strong motion arrivals (up to M 4.4 aftershocks) on the order of 400% to 900% between stations (at 2 to 6 Hz frequencies, the main shock being closer to a 1 Hz frequency).

Ground enhancement effects appear to be ascribable to site geology. An extensive subsurface exploration data acquisition program has been implemented in an attempt to explain the variances in strong motion enhancement. To date, 9 borings have been made, with two penetrating the Franciscan bedrock basement at depths of -154 to -168 m below sea level. Another 15 boring logs, extending to the basement rock in the greater Oakland area, have been retrieved. Both structural and stratigraphic relationships suggest a far different interpretation of Pleistocene depositional patterns than previously appreciated. Major tributary drainages have been shifted from the east to the westerly side of San Francisco Bay, apparently between the Sangamon and Wisconsin glacial stages. This shift appears to have been preceded by a flow reversal, apparently accompanying truncation or blockage of an ancient outlet of San Francisco Bay, south of and much deeper than the present-day Golden Gate channel.

Compilation of historical data suggests that most of downtown Oakland was originally founded upon aeolian blow sands of the Merritt formation, a shallow, freshwater aquifer. Brackish sloughs and backwater areas were infilled beginning in the 1890's, culminating with a rash of infilling in 1941-42. It was over such a "made ground," or "soft soil sites," that the northern half of the I-880 Cypress Viaduct collapsed. Historical research shows that this same area reacted poorly during the 1906 San Francisco earthquake, destroying the Key System power plant at Cypress Street and MacArthur Boulevard. Major stream channels of Wisconsin glacial age (which pre-date recent Bay Muds) were discovered; one just north of the Bay Bridge toll plaza, one through Oakland Outer Harbor, another passing through the center of Alameda Naval Air Station and still another crossing the northern third of Oakland International Airport. All of these areas experienced noticeable liquefaction during the brief dynamic loading of the Loma Prieta earthquake.

These recent studies point to the critical need for developing both historical and geologic data bases capable of correlating large bodies of information in a three-dimensional, user-friendly format. The relative paucity of any deep boring data and appurtenant geophysical profiling (such as shear wave velocity data), as well as historically indiscriminate stratigraphic nomenclature usage, has made the compilation of such a data base an extensive cooperative undertaking, which is likely to extend throughout the coming decade.

Brief History of the Bay Bridge, Port of Oakland and the Cypress Structure

The San Francisco East Bay-Oakland area was initially settled in 1820 when Rancho San Antonio was granted to Luis Maria Peralta, who split the land amongst his four sons. His son, Antonio, built the first residence in 1821. Residents of the Rancho and all parts of the East Bay were rocked by a strong earthquake in June 1836, which was felt to be centered in the northeast Oakland-El Cerrito area (on the north Hayward Fault; Alameda Co. Gazette, 1868). This quake is thought to have been of Richter-magnitude (M) 6.8.

Oakland became an established American settlement beginning in 1852, when the town was named and incorporated as a hamlet of about 75 people. Later that year, the Town's Founder, Horace Carpentier, constructed three small wharves to provide for shipment of redwood lumber cut from the East Bay hills and purchased by a rapidly building San Francisco. The first map of Oakland was made in 1853, and it shows the town clustered about Broadway Avenue, west of Lake Merritt and east of what is now the I-980 freeway connector. The community was constructed almost entirely upon the Merritt Sand, a late Wisconsin-age aeolian blow sand deposited by prevailing onshore winds when sea level was approximately 105m (350') lower than today. Potable ground water was plentiful in shallow backyard wells excavated 4.5 m to 6 m into the Merritt Sands.

By 1860, the community numbered over 1500 and growth of the downtown area was beginning to exhaust the shallow water wells by 1865. New sources of water in the Oakland Hills began to be tapped and Temescal Dam, located along Temescal Creek on the Hayward Fault Zone, was initially constructed by Anthony Chabot in 1866-67. It was subsequently raised in 1886, then lowered again in 1936. The October 8, 1865 earthquake (a M 6.3 event) from the Loma Prieta/Santa Cruz Mountains area badly damaged many structures in San Francisco, but did no damage to those in Oakland (Holley, 1876). This quake had been preceded by a large precursor shock on May 24th (Holley, 1876). On October 21, 1868, the southern half of the Hayward Fault ruptured, in what is believed to have been a M 6.8 event (Toppozada, 1981). A large precursor quake had occurred on March 24th. Surface fault rupture was well exposed in the Hayward area, hence the fault being named the "Hayward's Rift" (Buwalda, 1929). Masonry structures in the Hayward-San Leandro area fared poorly, and the Alameda County Courthouse in San Leandro was destroyed (Figure 1). Damage to multi-story masonry structures in San Francisco was also extensive, but of a differing character and direction that was experienced three years earlier in the Santa Cruz Mountains quake (Huber, 1929). Although the shaking was intense in Oakland, area residents who had lived through the 1836 North Hayward quake believed the earlier quake had been felt more intensely in the Oakland area (Alameda County Gazette, 1868). Most of the structures in Oakland at that time were of wood frame construction situated on the Merritt Sand, although some structures, such as the Wilcox building constructed in 1865, shown in Figure 2, have survived all Bay area earthquakes.

Figure 1 - *Remains of Alameda County Courthouse in San Leandro following the M 6.8 Hayward Earthquake on October 21, 1868. The Courthouse was then moved to Oakland because its structures fared much better in both the 1865 and 1868 earthquakes (Oakland Public Library).*

Figure 2 - *The Wilcox Building on the northwest corner of 9th and Broadway in downtown Oakland. Originally built in 1865 on the Merritt Sands, it has withstood every earthquake since that time.*

Oakland continued its commercial development in the late 1800's because it was the western terminus for four transcontinental railroads: the Western Pacific/Central Pacific which arrived in 1869; the Southern Pacific Line in 1884; the Santa Fe which came in 1899; and the Western Pacific Mainline, completed in 1911. Nineteenth century land speculator Horace Carpentier attempted to monopolize the Oakland waterfront during this period, which was then clustered along San Antonio slough between 10th Avenue (Brooklyn Basin) and Adeline Street. Limited fill was placed in this area during development of the waterfront, but the heavy silt load of San Antonio Creek filled the Oakland Estuary with mud, thereby negating its use by sea-going clipper ships.

The Central Pacific Railroad built a 1.3 mile Oakland Long Wharf in 1879-81 using rock quarried from Niles Canyon, 26 miles away. The Long Wharf provided Oakland with deep water berthing for up to six ships as well as railroad ferries to San Francisco. In the late 1870's, a group of local businessmen set about excavating a tidal-level channel between the Brooklyn-Fruitvale area and Alameda, in order to enhance tidal draw which would, hopefully, "pull" the silt-laden waters of San Antonio slough out into the Bay, and thereby, better open the channel to sea-going shipping. The project was a major engineering undertaking for that era (Figure 3), and was eventually completed in 1893. The City's original port improvements in the 1890's focused on the Brooklyn Basin area in between what is now Laney College and Government Island (Figure 4).

During the 1906 earthquake, many parts of Oakland were badly damaged, but only one person was killed. Many unreinforced masonry buildings experienced failures at the upper wall-roof connections, and several tall church spires were badly damaged (First Baptist and St. Francis churches). Near Cypress and MacArthur Streets, the newly constructed Key System Power Plant lost its 90' (27.4 m) high brick chimney at the 62' (18.9 m) level (Figure 5, Left). This partially-destroyed chimney remained standing until 1988, when it was demolished. Originally at the shoreline, the Key System viaduct and the Southern Pacific mainline now lie beneath the Oakland distribution structure, the largest freeway interchange in the East Bay (Figure 5, Right).

PORT OF OAKLAND

Between 1905 and 1915, Oakland greatly expanded its Port facilities in an ambitious building program. In 1910-12, the Port constructed a 2000' long pile-supported concrete Inner Harbor Quay Wall, while Western Pacific Railroad built its Oakland terminal yards and Oakland Estuary Mole, west of Adeline Street (Figure 6). By World War I (1917-18), Oakland had become the largest shipbuilding facility on the West Coast, with all activity emanating from either side of the Inner Harbor area along the Oakland Estuary.

From about 1912 onward, the ship building companies and the railroads began to push development further into the Bay, working off of the San Francisco-Oakland Great Wharf, now taken over by the City (Figure 6). Most of

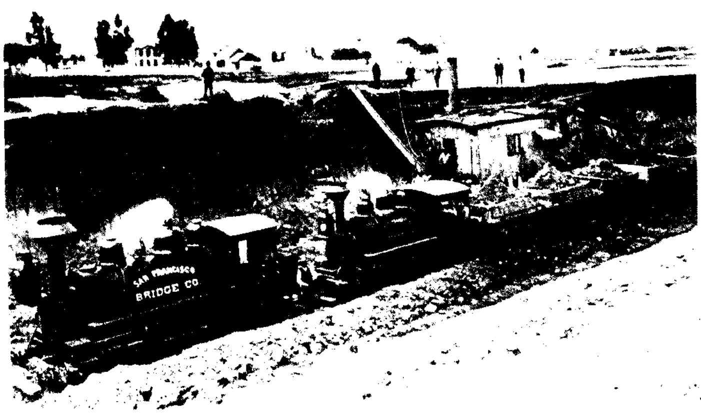


Figure 3 - *Excavation of the Merritt Sands in the Oakland estuary tidal canal between Fruitvale and Alameda, circa 1890. This canal was built between 1878-93 to enhance tidal fluctuation out of the San Antonio Slough. Its completion made Alameda an island (Oakland Public Library).*

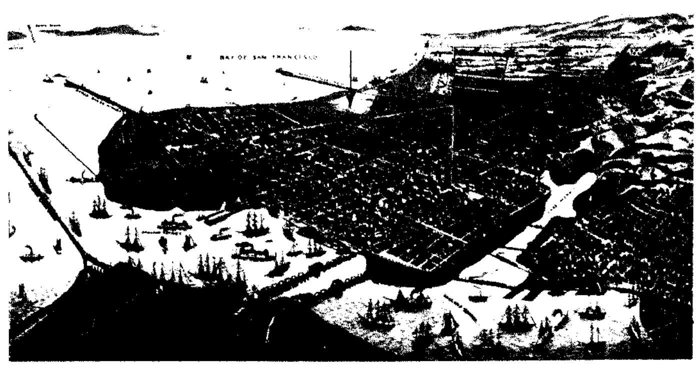


Figure 4 - *Lithograph overview of the Oakland central business district as it appeared in 1892. Arrow indicates the location of a brackish Holocene marsh where the north end of the I-880 Cypress Structure collapsed in October, 1989 (Oakland Public Library).*

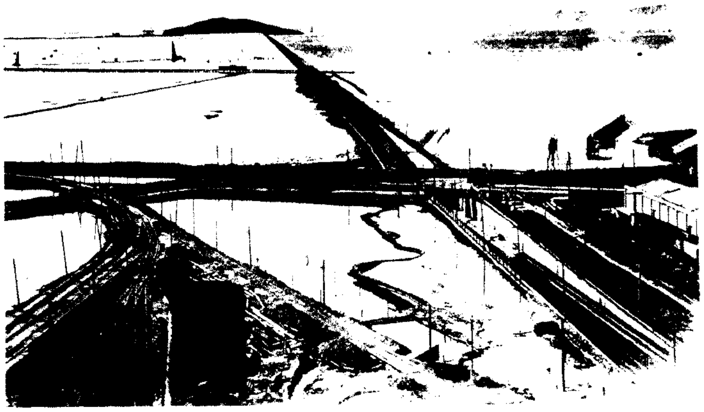


Figure 5 Left - *Oblique view of the Key System undercrossing beneath the Southern Pacific Railroad mainline, looking towards the newly-completed Key mole and Yerba Buena Island in 1905. The 27.5 m high chimney at left foreground was toppled in the 1906 San Francisco earthquake (Oakland Public Library).*

Figure 5 Right - *Approximately the same view as seen in 1990. The old concrete undercrossing (right foreground) now serves the EBMUD filtration plant. The Oakland Distribution Structure, connecting Interstates 80, 880, 580, and State Route 24 converge on the old shoreline. Filling has pushed the Bay shoreline out 3 km to the west.*

Figure 6 - *Portion of the 1915 U.S.G.S. Richmond 15' quadrangle showing the Oakland-Alameda area. The greater part of Bay infilling was accomplished adjacent to the railroad moles which were originally constructed to accommodate deep water ship berthing.*

the infilling used hydraulic fill techniques utilizing Merritt sands dredged from nearby channels. A substantive fill was made over one mile into the Bay to accommodate the San Francisco-Oakland Bay Bridge Toll Plaza in 1934-35. Additional filling "spilled" off this to the south, a few years later (Figure 7). Between January of 1941 and June of 1942, an unprecedented building program ensued as more than six million cubic yards of fill was placed out to the limits of the Old Great Wharf in an 18 month period! Much of the fill was trucked in from local quarries, carried in diesel trucks at the rate of one truck per minute--day and night (Oakland Library, 1952). This was part of the Country's gearing up for World War II. The Army Corps of Engineers took over jurisdiction after the Pearl Harbor attack in December, 1941, and constructed the Oakland terminal of the San Francisco Port of Embarkation, later called the Oakland Outer Harbor (Hamilton and Bolce, 1946). This massive fill allowed the construction of Port Wharves, warehouses, Oakland Naval Supply Center and Oakland Army Base, all constructed seaward of the Southern Pacific rail yards (also built on Bay fill; Figure 8). Additional filling had begun in the late 1920's to construct a municipal airport as an appendage to Bay Farm Island. Surplus World War I four-stack destroyers were sunk around Bay Farm Island in 1937-38 to create an artificial seawall to contain dredge sand infilling. Filling continued on Bay Farm Island into the late 1960's.

Alameda Naval Air Station was also constructed on shallow estuarine muds west of Webster Street in 1939-40. The infilled area involved a little under two square miles behind a hand-stacked rockfill sea wall built on the old Oakland Railroad and Ferry Company narrow gage mole (originally built in 1875, later obtained by Southern Pacific and shown as the S.P. mole in Figure 6). What had been shallow mud flats a few years before was now a bustling industrial metropolis rapidly constructed on "made" ground.

In his authoritative treatise on the damaging effects of the great 1906 earthquake, Wood (1908, p.241) had concluded: *"This investigation has clearly demonstrated that the amount of damage produced by the earthquake of April 18 in different parts of the City and County of San Francisco depended chiefly upon the geological character of the ground. Where the surface was of solid rock, the shock produced little damage; whereas upon made land (fill) great violence was manifested."*

THE I-880 CYPRESS STRUCTURE

In the late 1940's, east bay infrastructure rapidly expanded during the post-World War II boom period. State Route 17 was conceived by the State Division of Highways in the late 1940's as the Eastshore Freeway. The highway's northern terminus was in the Oakland Distribution Structure, a complex interchange connecting four freeways/expressways with the San Francisco-Oakland Bay Bridge. The southern terminus of the highway was at its juncture with the Bayshore Freeway (U.S. 101, in San Jose). Actual construction of the route began in 1949 and was completed in 1958, whereupon it was renamed the "Nimitz Freeway," after Fleet Admiral Chester W. Nimitz, whose family had lived in nearby Berkeley since the mid-1920's. The Nimitz retained its nomenclature as State Route 17 until 1987 when it was redesignated as Interstate Route 880, or I-880.

A structural kingpin of the Nimitz was the Cypress double-deck viaduct at the freeway's terminal juncture with the Oakland Distribution Structure. Design by the Division of Highway's Bridge Department in Sacramento began in 1951, with the final plans being issued in late 1954. In the early 1950's, commuter and commercial traffic traveling up the East Bay toward the Bay Bridge or points north, swung around the congestion of downtown Oakland, along a broad, 6-lane boulevard named Cypress Street. This was renamed the Eastshore Highway and carried approximately 50,000 vehicles per day in the early 1950's (on a 24 hour basis during weekdays).

Design concepts for a modern freeway, running through what was then (1951) an expensive, heavy industrial area, were extremely complicated. Over a 1.3 mile distance, the proposed route had to cross 24 existing city streets, three railroad spurs serving industry, miss the Oakland Army Base railroad yard, access to the Southern Pacific Railroad Depot, and just skirt the largest sewage treatment plant in the East Bay, with dozens of incoming sewer trunk lines. In addition, the six existing lanes of the Eastshore Highway (Cypress Street) must necessarily remain open during freeway construction so as not to create intolerable (not to mention politically unacceptable) congestion.

The compromise reached by the bridge design team was to create an extended double-deck structure, not too unlike those emanating from the San Francisco anchorage of the Bay Bridge (built in 1934-37). A doubly-supported deck structure possessed a number of important advantages:

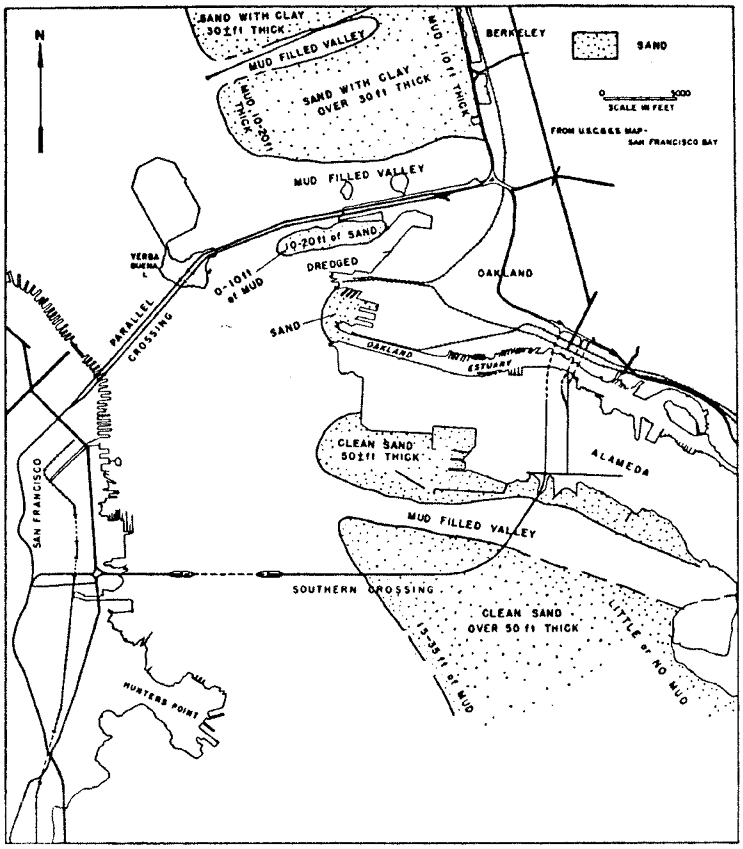


Figure 7 - *Distribution of borrow sand used to infill large margins of central San Francisco Bay from 1900 to 1942. Thickness of mud refers to overburden above the sand (taken from Trask and Rolston, 1951).*

A. It required the least amount of right-of-way, thereby saving the State land acquisition money. At this time, the heavy industrial properties in that area, such as steel fabricating plants, would have been very expensive to condemn and relocate.

B. An elevated freeway would create the least disruption to the neighborhood's well-established infrastructure (railroads, commuter rail lines, streets, trolley lines, buried utilities).

C. A double-deck structure could be built with a minimum of disruption to the existing commuter corridor by buying only enough land (some 75') to create two three-lane streets on either side of the freeway while it was under construction (a 2-1/2 year process). In this way, Cypress Avenue was split, with the north-bound lanes paralleling the east side of the freeway and the south-bound lanes on the west side. These streets were left in place to improve traffic mobility in the affected area, and the contractor could stage his work in the 75'/22.9 m strip of land between the two streets.

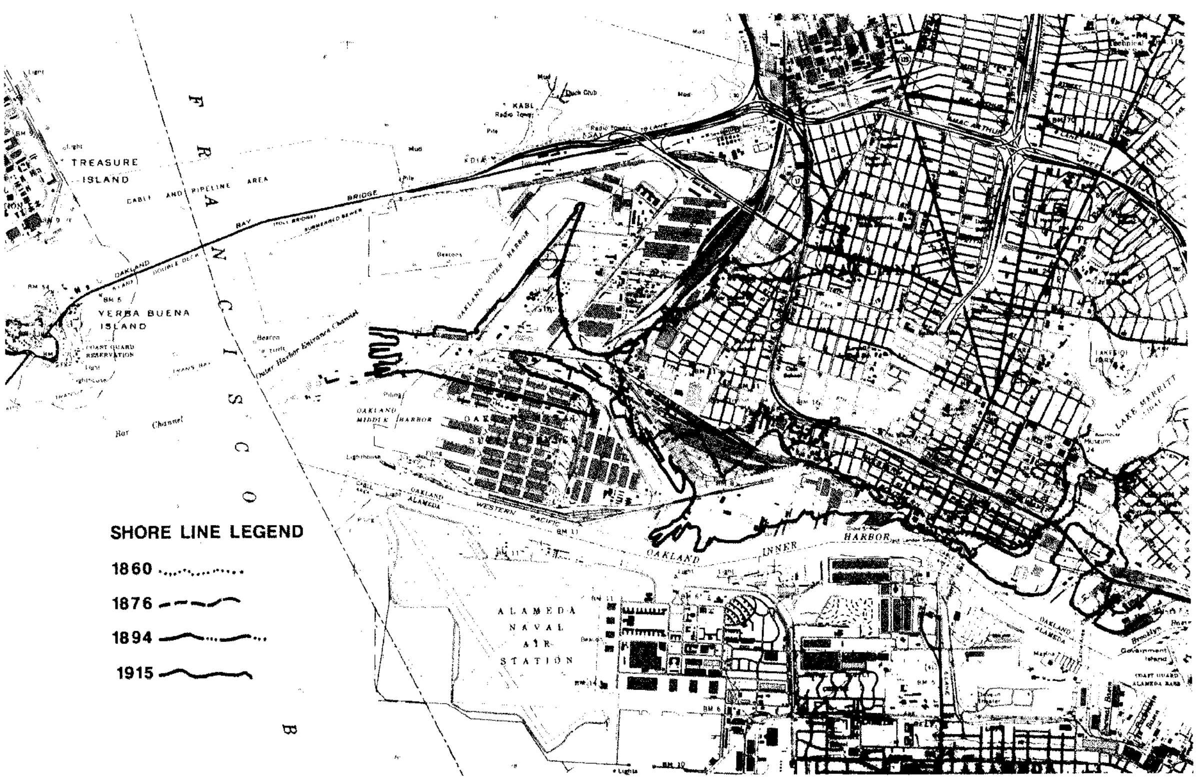


Figure 8 - *Overlay of historic Oakland waterfront shorelines from 1860 through present-day. Much of the infilling extends more than 3 km into the Bay. Six million cubic meters of fill was placed in an 18 month period in 1941-42.*

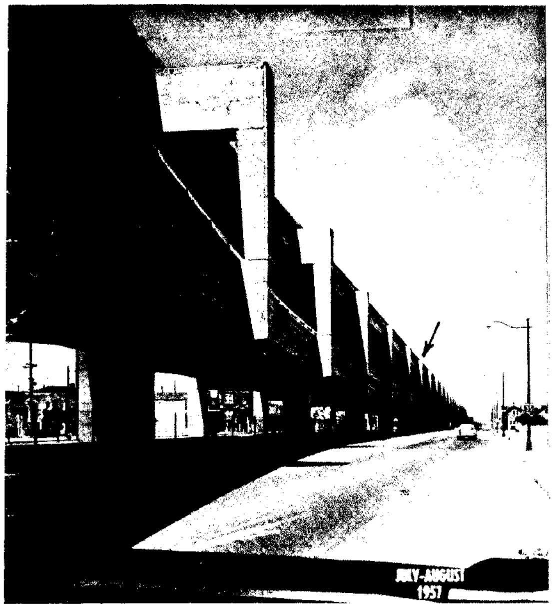


Figure 9 - *View looking north at the east side of the newly-completed double-deck Cypress Viaduct from Sixteenth Street in June, 1957. The Fourteenth Street on-ramp is cantilevered from the main support bents at left foreground. The October 1989 collapse preceded south to Bent 62, indicated by arrow (Calif. Highways & Public Works).*

The double-decked freeway section would be a little over 6,800' long (2072 m) and was to be California's first (Figure 9). The two 52 ' (16 m) wide roadways were to be of the concrete box girder type, supported on multiple column reinforced-concrete bents. Bents were spaced from 70' to 80' (21.3 to 24.4 m) apart, with 124 bents in all. The upper deck would be supported some 50' (15.3 m) above the ground, and many of the upper supporting cross spans, or girders, were reinforced with post-tensioned rods, an early form of the pre-stress concrete method routinely employed in concrete structures today. The finished structure would be able to handle 200,000 vehicles per day, which easily met the 20 year projections routinely applied to such projects at that time (1951-54).

The bridge engineers of that period were aware of earthquakes and the need for incorporating lateral pseudostatic loads to a structure so as to provide structural redundancy and hopefully, to prevent its collapse. Following the M 6.3 Long Beach earthquake of March, 1933, a number of major building code changes were made in California. A minimum of 2% of vertical loads applied as a lateral force as mandated by the statewide Riley Act, while the City of Los Angeles adopted a 13% vertical load standard (Anderson and others, 1952). Housner (1987) relates that most codes adopted a 0.08g pseudostatic loading factor following the Long Beach quake. In January of 1943, the Bridge Department of the Division of Highways adopted a 0.06g pseudostatic horizontal acceleration load factor that was universally applied by that agency into the late 1960's. Interviews with surviving engineers of this period indicated that the 0.06g factor came from strong motion data supposedly collected in the M 6.3, 1933 Long Beach earthquake. The author believes that this value is based on the strong motion record as the Los Angeles subway terminal during the 1933 Long Beach earthquake (Anderson and others, 1952; Neumann, 1935). Accelographs close to the 1940 El Centro quake had recorded peak horizontal accelerations of 0.33g, but were apparently thought too severe for the wide-spread application to engineered designs. The recognition that much greater accelerations were likely became appreciated after the M 7 Parkfield quake of 1967 when 0.50g lateral accelerations were recorded. Predicted and observed ground enhancement effects in the March, 1957 Lake Merced quake were first discussed by Seed and Idriss in 1969.

Just as the last concrete was being poured on the Cypress Viaduct construction, it was loaded by the M 5.3 Lake Merced earthquake of March 22, 1957, whose epicenter was 13-1/2 miles (21.6 km) to the west (CDMG S.R. 57, 1959). The Lake Merced earthquake had caused noticeable damage to the west San Francisco area, and exerted Modified Mercalli scale intensities of at least VII on The Cypress Structure. This intensity would likely have corresponded to a maximum horizontal acceleration on the order of 0.10g on the Cypress Structure (Murphy and O'Brien, 1977). No deleterious effect of the quake was noted by the resident engineers, who inspected the structure afterward.

OBSERVED LEVELS OF SHAKING DURING THE LOMA PRIETA QUAKE

The Loma Prieta Earthquake occurred at 5:05 p.m. on Tuesday, October 17, 1989, just as the third game of a San Francisco Bay World Series was getting underway at Candlestick Park. Initial reports pegged the quake at Richter magnitude of 7.0. This was downgraded to a 6.9 several days later, then recast at an official magnitude of 7.1 some ten days later, based on energy release data recorded by far-away stations. Strong motion (source) shaking was recorded for approximately six seconds, with site response shaking averaging 12 to 15 seconds. Some of the taller structures in San Francisco continued some level of response motion for upwards of 30 to 35 seconds.

The quake came as no surprise to those familiar with California seismicity. In 1984, the Division of Mines and Geology (Real, 1984) had predicted *"odds better than 1 in 2 (>50% probability) that a major earthquake would occur on the San Andreas Fault between San Jose and San Juan Bautista within the next 20 years"* (Real, p. 28). The quake was forecast to be a magnitude 6.5 to 7+ event (Real, 1984, p. 3). The next most likely quakes had odds of only 1:10 and 1:20 over the next twenty years, suggesting that the Loma Prieta event was the most likely expectable earthquake in the Bay Region.

The Loma Prieta Quake was the most well-instrumented quake in the United States' history. Over the past twenty-five years, the U.S. Geological Survey and California Division of Mines & Geology had emplaced an extensive network of recording stations (over 150) which were within 200 km of the epicenter. The style of slippage was unusual however, even for the San Andreas. The quake's focal depth was quite deep, 16 to 19 km, instead of the usual 9.5 to 13 k. The Pacific Plate (Santa Cruz side) *rose* 5.6' (1.7 m) on an inclination of 70 degrees from the horizontal, suggesting mostly dip-slip movement in lieu of the San Andreas' more usual strike-slip motion (with the western plate heading north). The rupture energy petered out about 4 km below ground surface. The theoretical surface rupture would be 1.6 m vertical and 0.58 m horizontal, if the offset had propagated all of the way to the ground surface. Geologists have found no such break, only a ridgetop zone "sackung," or ridge-spreading structures, with soil-filled grabbens suggesting that such phenomena had a long history of occurrence (Cotton, 1990). The largest of the ground scarps associated with such ridge spreading was about 0.70 m high and exhibited left-lateral motion, suggesting clockwise rotation and ridge spreading. Geologists are now postulating that the fault rupture is disseminated over a broad zone, 1/2 to 1 miles (0.8 to 1.6 km) wide with "ridge spreading" actually serving to lower the ridge level in several locations.

One of the benefits to come out of the 1971 San Fernando earthquake was the creation of the C.D.M.G.'s Office of Strong Motion Studies which manages the California Strong Motion Instrumentation Program (CSMIP). At the current time, several hundred strong-motion records are generated for any sizeable earthquake. In this manner, localized *ground amplification effects* can better be appreciated and MCE's and planning-level documents annotated to reflect areas of increased concern. It is only by having an adequate number of records that site-specific seismic analyses can be generated and evaluated to test their validity (the acid test of any analytical procedure is to see if it will accurately predict previously-recorded or observed behavior).

The Cypress Structure was located almost exactly 62 miles (100 km) from the quake's epicenter. A preliminary evaluation of the CSMIP data suggests a marked component of so-called *ground enhancement* effects, seen in the recorded acceleration arrivals. Simply put, Oakland got hammered much worse (0.18 to 0.29g) than any other area close in range to the quake (and on the north side of the fault, Figure 10). San Francisco averaged 0.10g over 8 CSMIP reporting stations, with the Praised records skewing that average with a 0.21g reading. These strong-motion data (for peak horizontal accelerations) are presented graphically in Figure 10.

Ground amplification effects are very apparent in some adjacent stations. For instance, the recorder on Yerba Buena Island, situated near bedrock on colluvial sands, measured only 0.06g peak, while the station on Treasure Island, a man-made appendage to Yerba Buena, registered 0.16g, or more than 2-1/2 times the peak horizontal acceleration! In nearby Oakland, *vertical accelerations* of between 0.04 and 0.16g were measured, also suggestive of ground amplification. In the downtown Oakland area, a cover of young (Pleistocene and Holocene-age) alluvial and marine sediments is 120 to 185 m thick, lying upon the much older Franciscan Assemblage bedrock (Jurassic-Cretaceous-age).

The disparity between traditional, deterministic predictions of peak ground acceleration with epicentral distance and those observed in the Oakland-Alameda area are presented graphically in Figure 11, taken from Shakel (1989). Those instruments 1500 to 2300 m from the collapsed Cypress structure plot more than two standard deviations from the published mean relationship. Unfortunately, the ground enhancement effect on Young Bay Mud deposits was observed, but went largely unrecorded. The downhole instrumentation array at U.C. Berkeley's Richmond Field Station was pulled for servicing, batteries in the Komatsu/Levine-Fricke building at Emeryville had not been replaced, and no downhole device had been placed at the CSMIP Oakland Container Wharf (and Bay Muds adjacent to this structure had been dredged). The

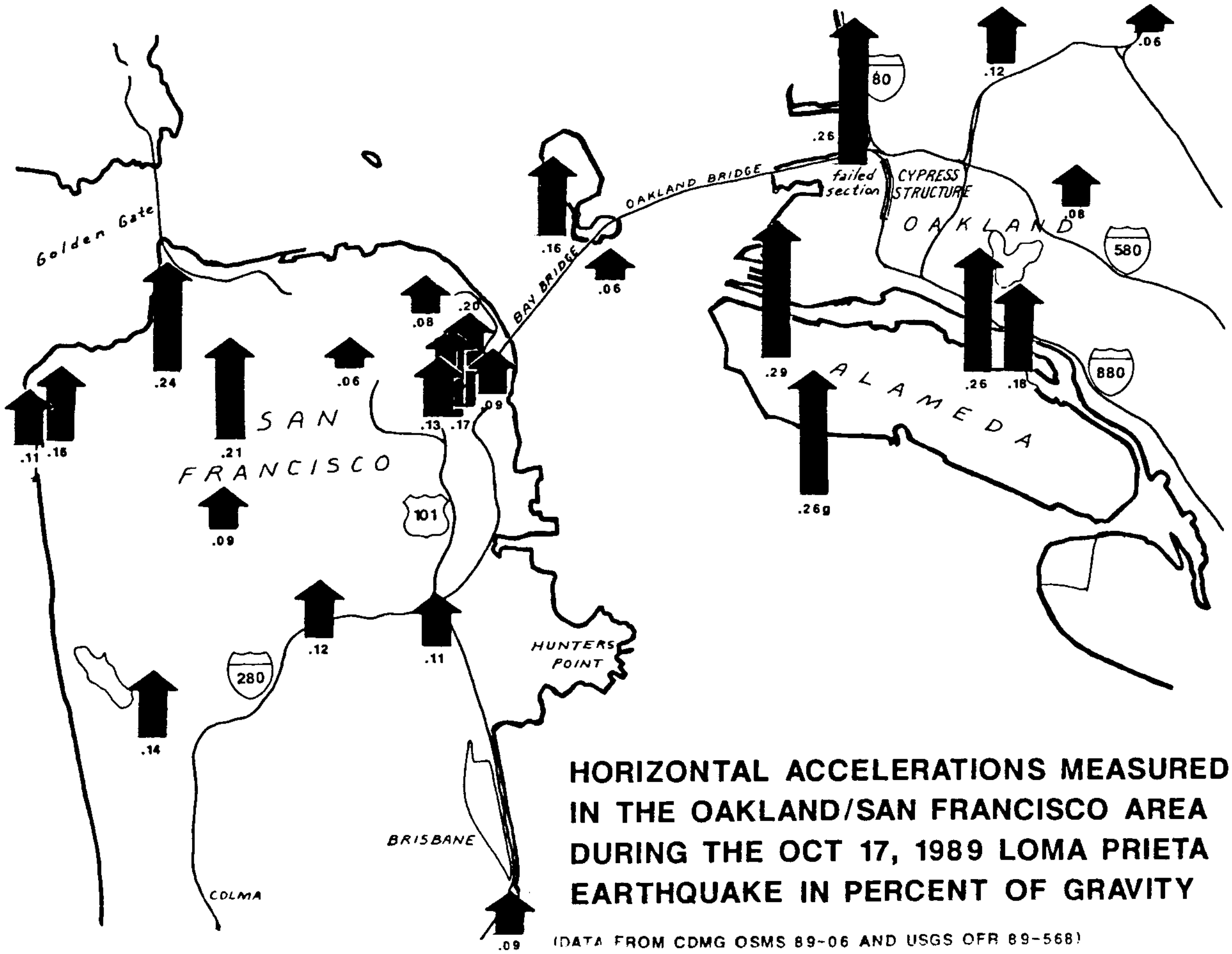


Figure 10 - *Weighted vectors depicting peak horizontal accelerations from raw data recorded on State and Federally-owned strong motion sensors in the Oakland-San Francisco area during the Loma Prieta earthquake. The tip of the arrows delineates the position of each sensor.*

one strong record recovered on an East Bay Bay Mud site was at an Alameda Naval Station hangar, and it recorded a peak base acceleration of 0.26g.

FAILURE OF THE I-880 CYPRESS STRUCTURE

The Cypress Structure was unusually empty at the time of the earthquake (5:04 p.m. PDT). Traffic speeds on the upper, southbound deck were unlimited (averaging 58 mph). Traffic on the lower deck was similarly unencumbered, but somewhat slower (reported at 53 mph; CHP, 1990).

On the structure, 96 to 97% of the drivers experienced some noticeable driving difficulty, expressed as a lateral motion or flat tire effect. Drivers and passengers of some vehicles on the upper deck described seeing intermittent puffs of concrete dust at the supporting bents, indicative of explosive crushing spalling and flexure at those supports. According to the CHP (1990) report, collapse of the upper deck may have occurred early in the earthquake loading sequence, maybe 5 to 8 seconds following the initial shock wave arrivals. It would appear that all of the vehicles on the structure were still in motion when the structure collapsed.

The upper, southbound deck of the structure collapsed onto the lower deck along the northern half of the structure, between Eighteenth and Thirty-fourth streets (Figures 12 and 13). The failure sequence appears to have been a chain reaction, set in motion by shear failure of the upper supporting column bases in a few discrete locations (Figure 16).

Twenty-eight of the one-hundred-twenty-four supporting bents on the Cypress viaduct were of the design cross section shown in Figure 14. These bents were massive, comprised of conventional steel reinforcement with shear

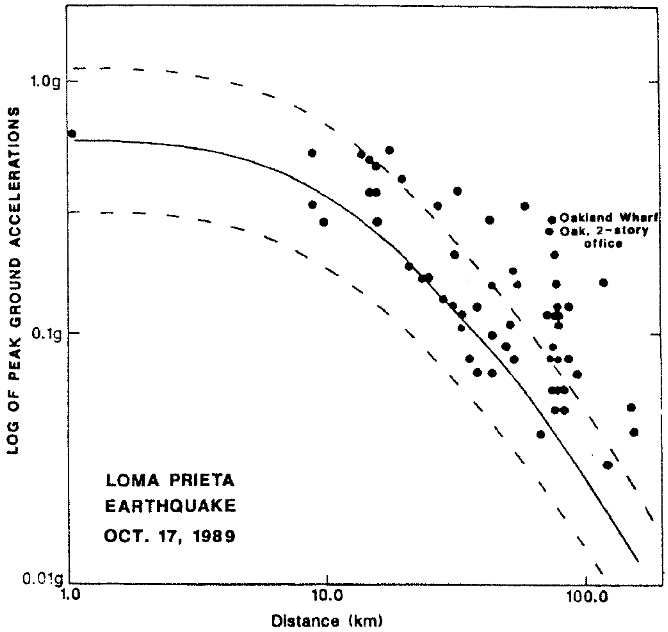


Figure 11 - *Peak horizontal acceleration values versus distance to causative fault surface trace for the Loma Prieta earthquake on the Joyner-Boore (1988) attenuation relationship. The solid and dashed curves are the median and one standard deviation curves, respectively (taken form Shakel, 1989).*

Figure 12 - *Overview of Cypress Viaduct collapse looking southerly, towards the unfailed portion, at Bent 62 (arrow). The northern half of the double-decked structure experienced a partial collapse of the upper deck onto the lower deck.*

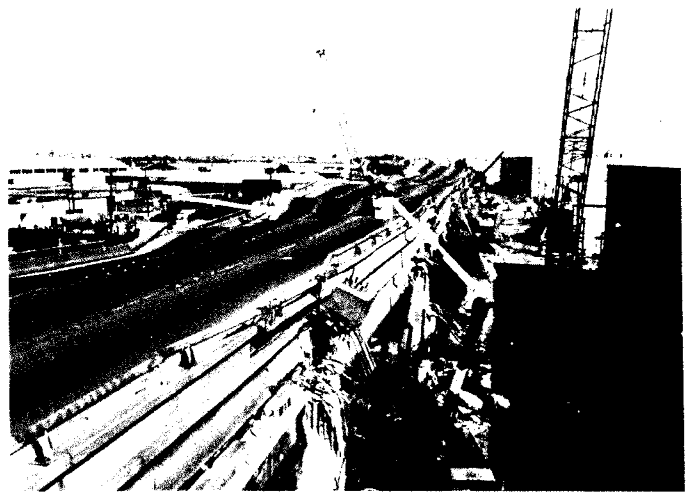


Figure 13 - *Overview of Cypress Viaduct collapse looking north from the vicinity of Bent 66, just north of Eighteenth Street. Foundation conditions change in this vicinity and pile depths suddenly increase three-fold at Bent 72 (arrow).*

keys at the base of the upper supporting columns. The keys appear to have been a convenient mechanism by which the engineers of the late 1940's could resolve the design stresses in such a complicated, multi-column structure, which otherwise was, statically indeterminate. Other designers of that era assumed that bending moments would be transferred across the shear key boundary, but we have no knowledge that this was indeed the designer's intent. The supports beneath the shear keys were provided with discontinuous reinforcement, an area loosely dubbed "the pedestal" by the U.C. Berkeley professors studying the collapse (Nims and others, 1989).

Horizontal accelerations, transverse to the structure's axis, likely loaded the structure as depicted schematically in Figure 15. The upper supporting columns were supporting over 272,400 kgs (600,000 lbs) tributary load. In transverse loading analyses, Professor Bertero of U.C. Berkeley, calculated that these bents would fail in shear under a horizontal acceleration of between 0.18g and 0.19g, or more than three times the design seismic load of 0.06g (Bertero, 1990). Factoring in the actual concrete strength, found to be in excess of 41.2 MPa (6000 psi), would raise this failure threshold value even higher. Additional shear loading of the upper column pedestals could have come about through vertical seismic accelerations, measured at 0.15g on the nearest Oakland office building. This level of loading would increase the total loads by 15%, also exacerbating the pedestal area shear capacity.

The failure of the 28 bents with basal upper column shear keys likely proceeded as sketched in Figures 15 through 17 with the upper columns deflecting outward after shear failure across the pedestals. This extreme outward deflection during the collapse sequence ruptured the now-failed column's upper attachments with explosive force typical of overly-reinforced, high-strength con-

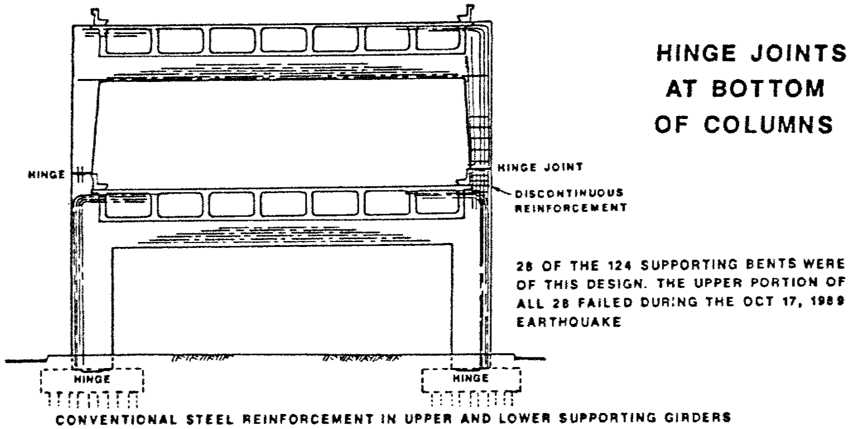


Figure 14 - *The most implemented supporting bent layout for the Cypress Viaduct consisted of this conventionally reinforced structure with shear keys, or hinges, at the bottoms of both the upper and lower supporting columns.*

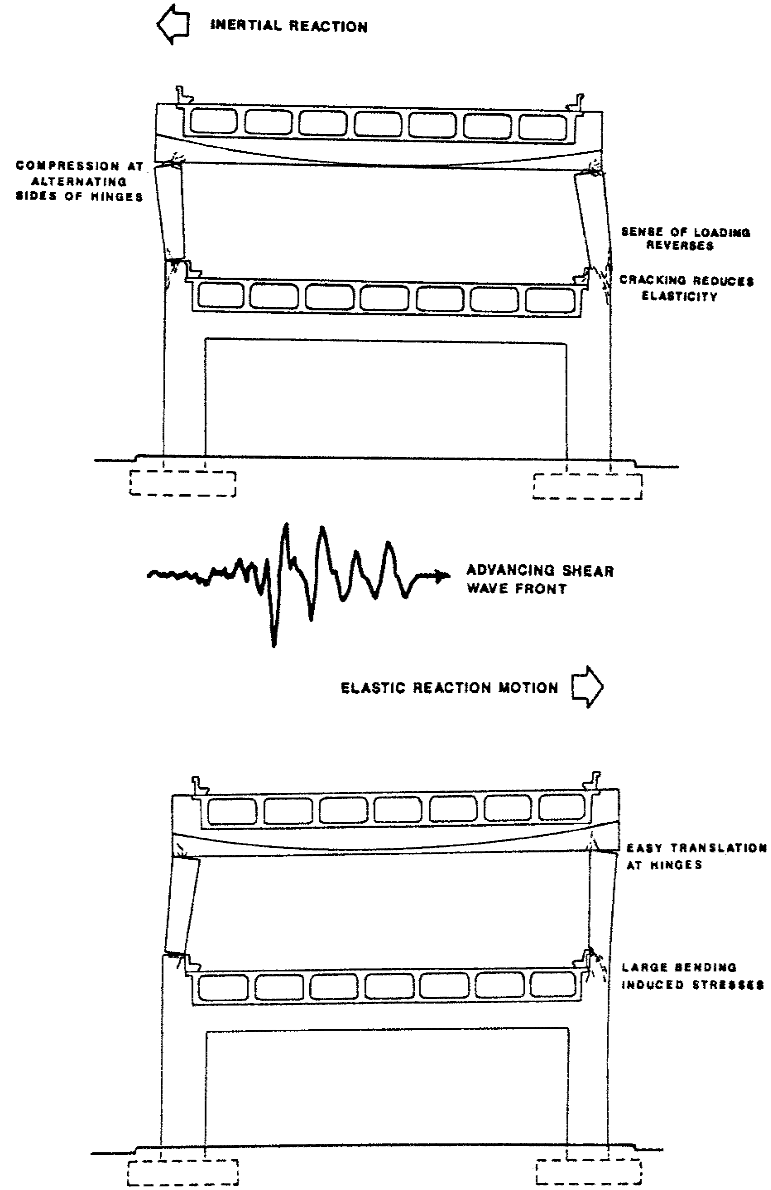


Figure 15 - *Predicted reaction of doubly-hinged supporting bents under transverse cyclic loading. U.C. Berkeley Professors Bertero and Mahin estimated that the structure would fail in this mode under a load of 0.17 to 0.18g.*

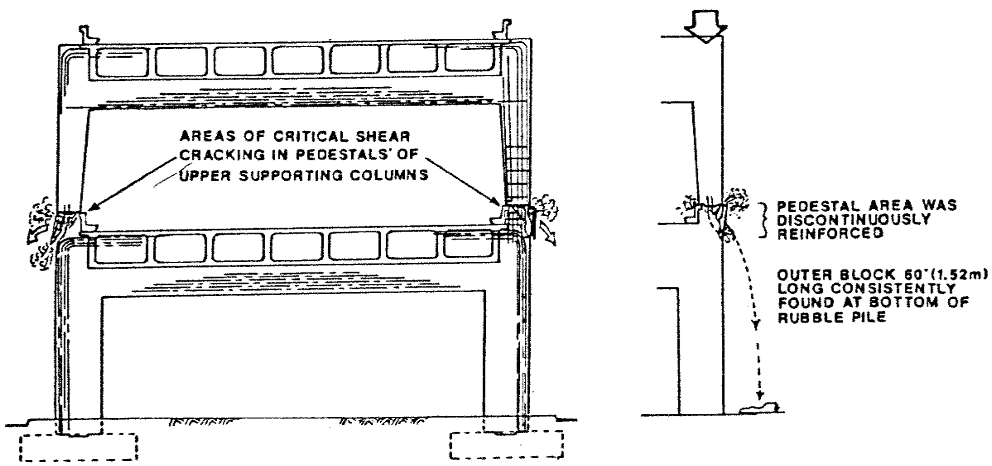


Figure 16 - *After-failure observations shown a preferred tendency towards shear failure of a discontinuously-reinforced zone about 1.5 meter high, dubbed the "pedestal." In this area, 1.5 meter long No. 11 bars were lapped with curved No. 18 negative moment reinforcement.*

Figure 17 Upper - *Area in upper column pedestal called the "critical crack" by U.C. Professor Jack Moehle (1989), as seen at the first surviving Bent #62. In this view, the pedestal area is continuously reinforced.*

Figure 17 Lower - *Outside block of a failed bent "pedestal," showing 1.5 meter long No. 11 reinforcing bars. Note spalling at upper shear key, indicative of extreme cyclic oscillation before failure (arrow).*

crete. A representative sketch and site photograph of this mode is presented in Figure 18.

Other failure modes were noted at supporting bents with differing structural details. A number of bents were constructed with shear keys at the top of both supporting columns, as sketched in Figure 19. The keys were apparently emplaced to provide bending stress relief, or "bond break," between the upper post-tensioned supporting girder, and the conventionally-reinforced section beneath it. This is because the post-tensioned girder

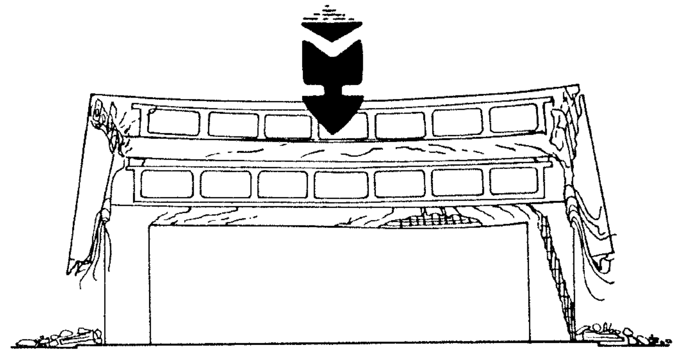


Figure 18 Upper - *Sketch of most common failure mode, manifested at bents with hinges at bottoms of upper supporting columns (Figure 20). Column heads were deflected outward by lower supporting columns, which remained standing.*

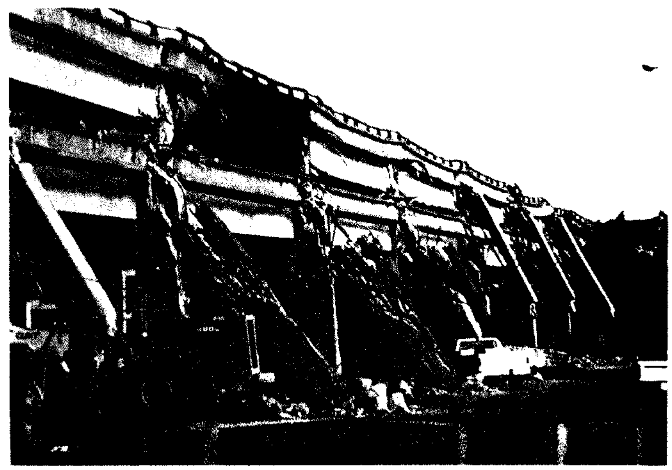


Figure 18 Lower - *Photograph of the dominant failure mode sketched above. Dark area is from diesel fire which broke out shortly following the collapse.*

would shorten under the imposed pre-stress loads (this structure was designed in 1951-53, in the infancy of pre-stress technology).

On other supporting bents, shear keys were emplaced at both the top and bottom of the upper supporting column on one side of the bent, and only on the top or bottom of the opposing upper column. One of these bent sections are sketched in Figure 20. The rationale for constructing top and bottom shear keys appears to have been anticipated additions to the western side of the structure which were never subsequently built. In these cases, the top and bottom shear keys acted like plastic hinges, yielding with scant lateral capacity. The lateral bending capacity of these bents was controlled by the opposing, continuously-reinforced column. Repeated loading cycles would concentrate bending loads

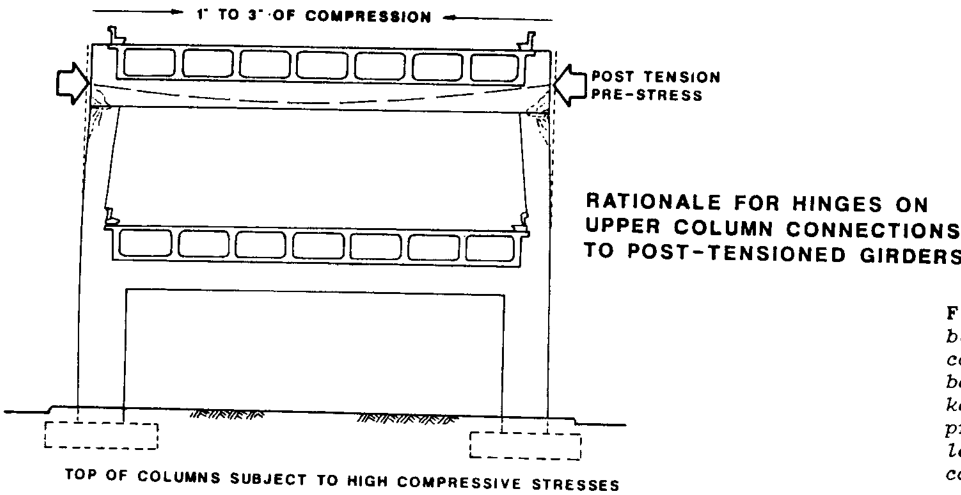


Figure 19 - *Some of the Cypress bents combined pre-stressed with conventionally-reinforced supporting beams. In these bents, hinges/shear keys were placed just beneath the pre-stressed member in order to alleviate moment transfer to the upper columns.*

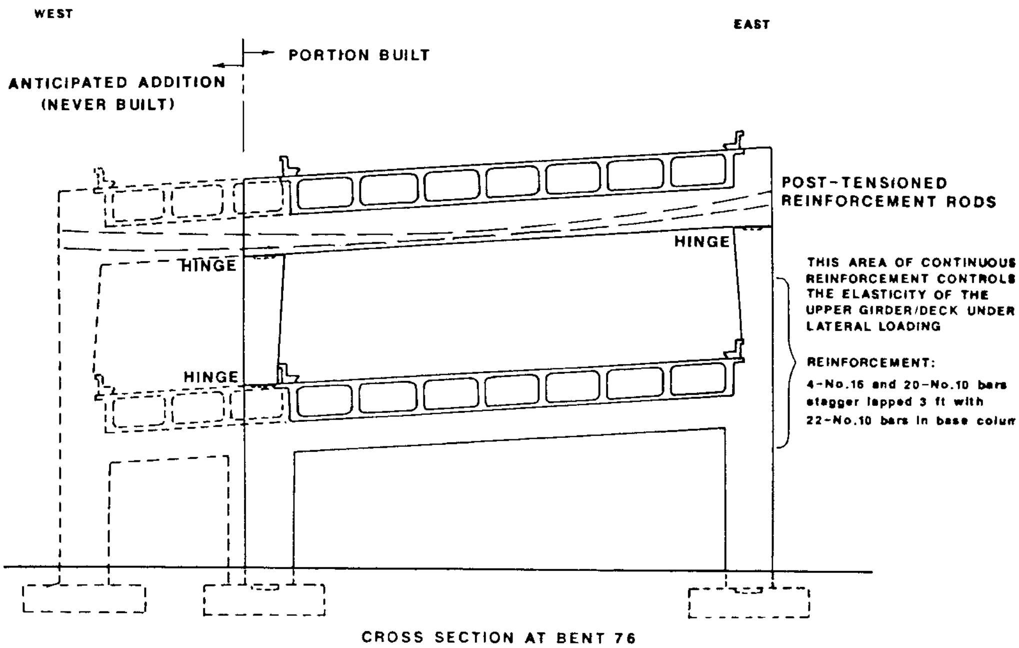


Figure 20 - *Near the Grand Avenue overcrossing doubly-hinged upper supporting columns were utilized on the west side of the viaduct in anticipation of structural additions which were never made.*

in the pedestal area of the continuously-reinforced column, causing it to crack, and thereby initiate a progressively degrading section modulus and damping of structural period, as the column cracks. This process could occur rapidly in a stiff structure like the Cypress, as the bending loads would reserve with each cycle of loading. The main shock shear waves arrived on about a 0.80 Hz frequency. Four or five cycles (4 or 5 seconds) could then have caused failure of one or more of the columns, which would then collapse and initiate a chain reaction, either up or down, the axis of the structure.

Failure modes of the viaduct in areas with top-and-bottom shear keys were of two distinct styles. In Figures 21 and 22, the partial collapse of the super-elevated section over the Grand Avenue under-crossing is shown. In this case, the top-and-bottom shear keys on the west side of the structure simply acted as plastic hinges, while the continuously reinforced column, providing virtually all lateral stiffness, became over-stressed and collapsed.

A short distance to the south, the failure sequence appears to have been more catastrophic, and the top-and-bottom shear keyed columns were simply "blown off" their supports, consistently landing on their upper ends on south-bound Cypress Street. This mode is sketched in Figure 23 and depicted visually in Figure 24.

A skewed railroad crossing over Thirty-second Street remained standing, while the viaduct north and south of it collapsed. A ground view of this section at Bents 96 and 97, is shown in Figure 25. The three column-base

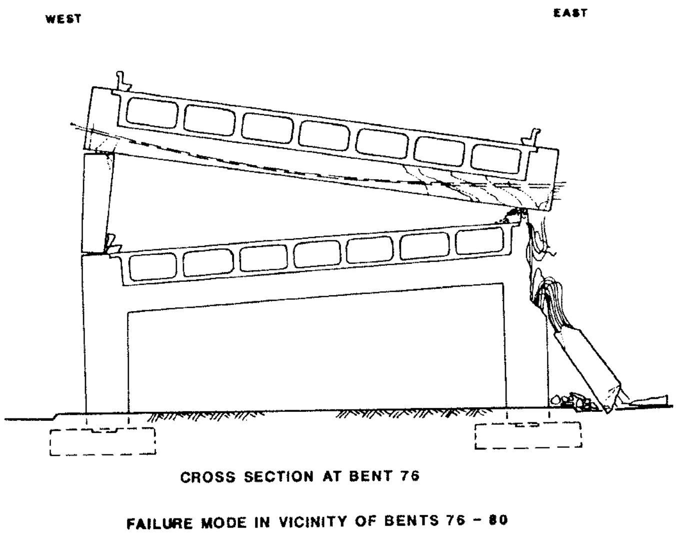
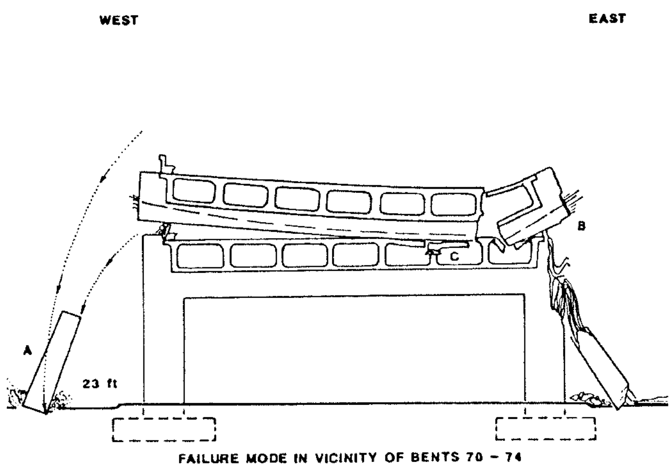


Figure 21 - *Sketch of partial collapse mode observed at super-elevated turn in viaduct at Grand Avenue overcrossing. Upper deck fell to the continuously-reinforced side.*



A COLUMNS WITH UPPER AND LOWER HINGE JOINTS BLOWN OUT INTACT

B POST-TENSIONED RODS SNAPPED AND POPPED OUT OF BROKEN UPPER SUPPORTING GIRDERS

C SUPPORTING GIRDERS COMPRISED OF SOLID CONCRETE. CONCRETE BOX DECK ONLY BROKEN IN AREAS WHERE UPPER GIRDER FELL PARTIALLY ONTO LOWER DECK

Figure 23 - *Sketch of catastrophic failure of doubly-hinged upper supporting columns along west side of Bents 70 through 74.*

bents were necessary in order to accommodate greater clear spans due to on-ramps or skewed overcrossings. In the case of Bents 96 and 97, the skew was 27-1/2° from normal. These bents possessed inherently superior-lateral stiffness, thereby distributing stress concentrations to a third support point. In the case of Bents 96 and 97, the skew also created a larger pedestal area, thereby engendering increased shear capacity. The sketch in Figure 25 shows the 3-column base bent section

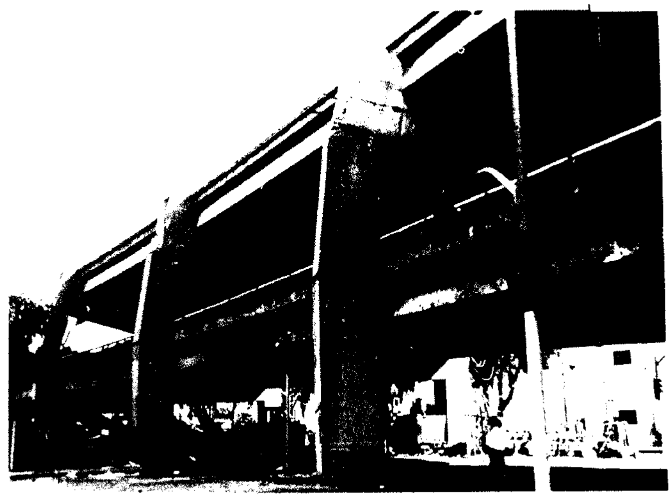


Figure 22 - *Ground view of Grand Avenue overcrossing partial collapse, as seen from the west side of the viaduct. Note how the doubly hinged upper columns simply rotated at their hinges.*

at Bent 62 where the failure sequence arrested as it progressed south (also shown in Figure 12).

Only one area of the Cypress experienced total collapse, that being in the vicinity of Bents 105 and 106, near Thirty-fourth Street (Figure 26). Although situated on old Holocene slough (Figure 29), subsequent demolition and excavation of the pile cap showed that the basal supporting columns had rotated outward at their respective basal shear keys, due to asymmetric collapse, as the viaduct was super-elevated in this area. As the upper deck collapsed eastward, the west basal column hinged at its basal shear key, allowing it to rotate outward, and thereby, bring both decks to the ground.

FOUNDATION SYSTEM OF THE CYPRESS STRUCTURE

Each of the Cypress Structure's supporting bents were founded on either two or three large spread footings, or pile caps, in-turn supported by 12" (30.48 cm) diameter, concrete-filled pipe piles. Piles were driven in the conventional manner, then augured, and filled with concrete. No less than nine different sizes of pile cap footings were utilized in the structure. Their average size was 12' x 15' (3.7 m x 4.6 m) in plan and 3-1/2' (1.1 m) thick, with an average of 20 supporting piles (see Figure 27). The pile caps were intended to distribute the structures' heavy, concentrated loads onto the underlying piles, which convey this distributed load to the underlying soils through skin friction.

Depending on the frictional strength characteristics of the underlying soils, some pile groups were driven much

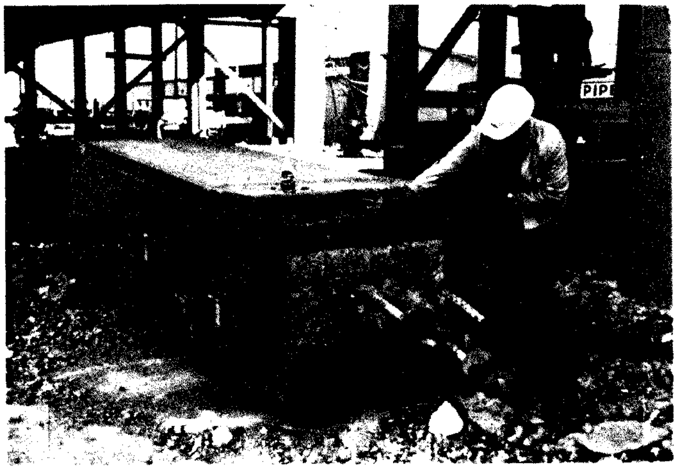


Figure 24 Upper - *End view of exposed lower hinge joint (shear key) on one of the doubly hinged columns that were thrown clear of the structure. Note the four No. 11 dowels, each extending 60 cm into either side of the key.*

Figure 24 Lower - *Street view of impact crater left by doubly-hinged column thrown 7 meters from the Cypress structure. These columns all landed on their upper hinges, suggesting a very rapid, chain-reaction failure sequence.*

deeper than another, adjacent group. In the vicinity of the Eighteenth Street over-crossing, a major geologic contact exists between stiff Wisconsin-age aeolian Merritt Sands, and a shallow Holocene estuarine fill, comprised of inter-tongues of Young Bay Mud and Temescal alluvium (Figure 28).

During construction, the contractor experienced some problems with driving the pipe piles through the partially saturated Merritt Sands south of Eighteenth Street, as these materials were found to be quite stiff (today, piles driven into sands are jetted to assist placement). From Bents 57 through 61, piles were only

Figure 25 Upper - *View of lone surviving section of the Cypress Viaduct, a skewed railroad crossing at Thirty-second Street. One truck (arrow) and two cars found sanctuary here. The crossing was supported on a 3-column base bent with a large pedestal area due to the skew.*

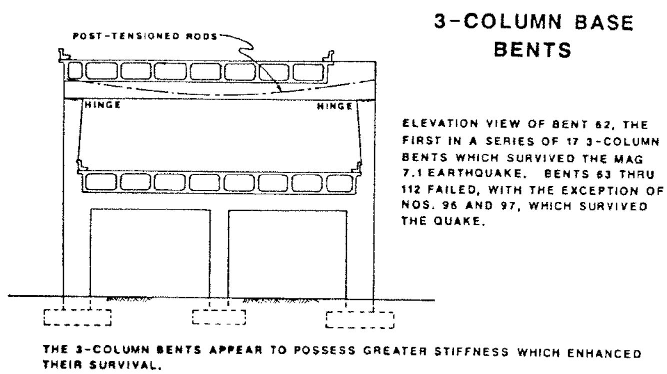


Figure 25 Lower - *Elevation view of 3-column base bent used to support longer spans, like the Fourteenth Street ramp between Bents 56 through 62.*

13' (4 m) to 15' (4.6 m) deep. From Bents 66 through 71, they were a maximum of 23' (7 m) deep (the failure sequence stopped at Bent 62). At Bent 72, the Merritt Sands suddenly pinch out in the Holocene estuary, and pile depths of greater than 59' (18 m) were necessary to carry loads down below the compressible clays of the estuary (Figure 28 Lower). This sudden change in the depth of the supporting structure essentially put a 73' (22.3 m) high structure in direct contact with an adjacent 109' (33 m) high structure, a variance of one-third. This difference in height, and thereby, structural stiffness, could be expected to create different damping characteristics of either section, engendering different natural periods of vibration. As the decks

Figure 26 - *Between Bents 104 and 106, both decks of the Cypress fell to the ground, the only location where total collapse occurred. In this area the decks collapsed asymmetrically, with the upper deck falling to the east of the lower. This suggests different parts of the appurtant supporting bents failed in differing manners, or at slightly different times (and motion phases would not be aligned). In this area, the lower supporting columns rotated outward, about their respective basal hinges.*

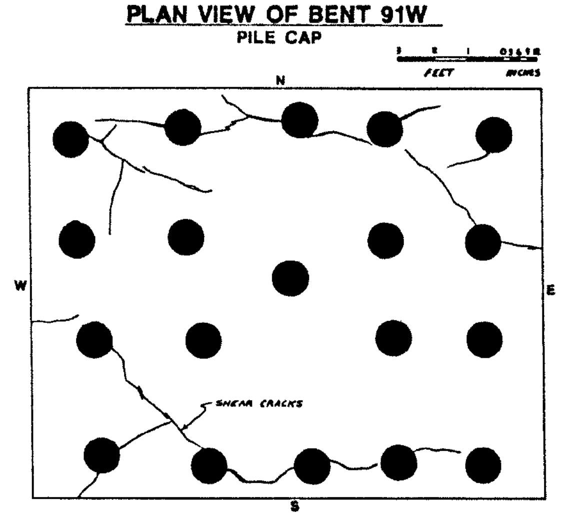


Figure 27 - *Pattern of macro shear cracking observed on bottom of pile cap 91W. These cracks extended well through 0.91 meters of reinforced concrete and are suggestive of high impact loads. No shear cracks were found in the opposing footing (91E) of this same bent.*

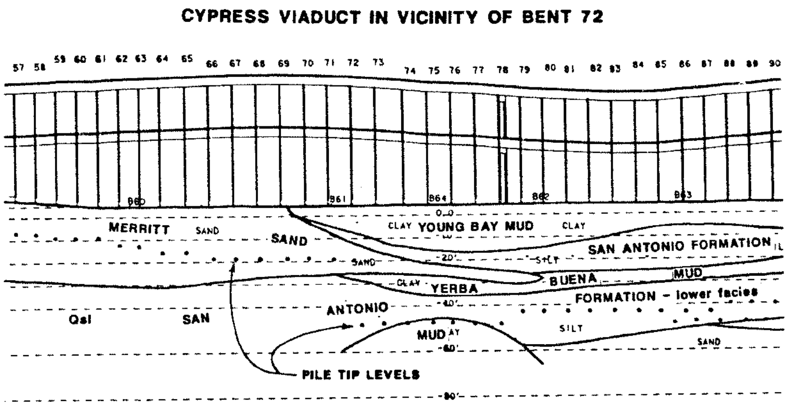


Figure 28 Upper (shown to the left) - *Detail geologic cross section through the Cypress Viaduct in the vicinity of contact between Merritt Sands and Holocene-age estuarine muds around Bent 69. Geology is inferred from original 1951 borings. Dots beneath structure indicate recorded pile depths.*

Figure 29 (shown below) - *Map showing Lamont-Doherty aftershock recording locations and near-surface geology inferred by Borchardt and others, (1976). The six seismographs were distributed upon bedrock, sand, young mud/fill and key structures to measure site effects on response during Loma Prieta aftershocks (taken from Hough and others, 1990).*

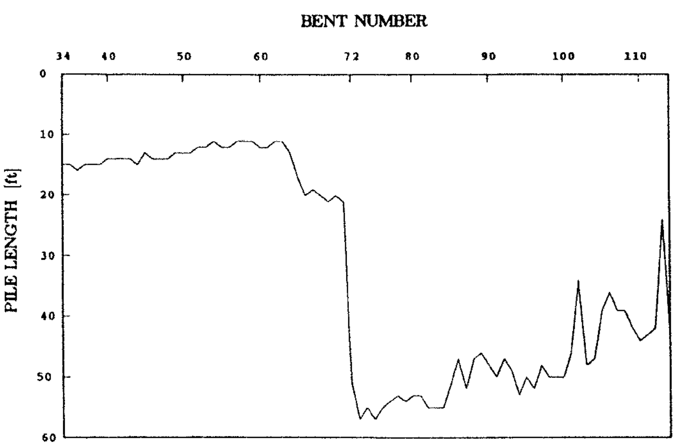
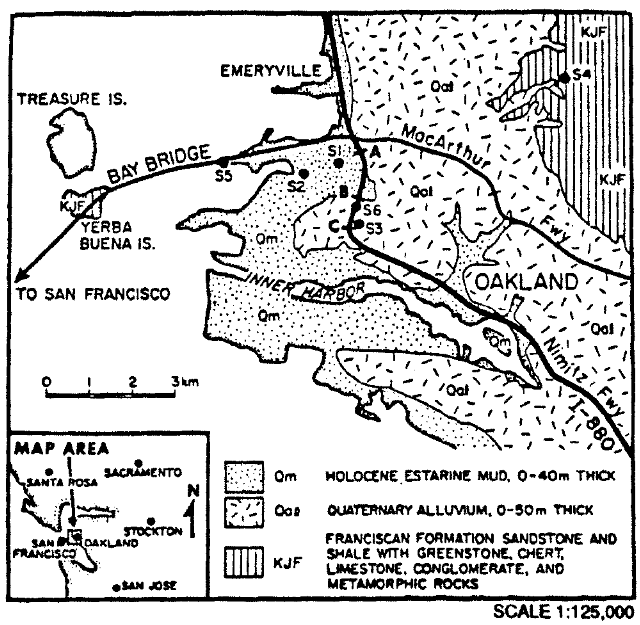


Figure 28 Lower - *Chart of pile lengths with respective supporting bent numbers for the Cypress viaduct, as-built. Note the dramatic change in pile length at Bent 72 due to the sudden absence of Merritt Sands. These deeper piles are founded in Old Bay Muds and impure San Antonio formation alluvial sands and silts (taken from Nims and others, 1989).*



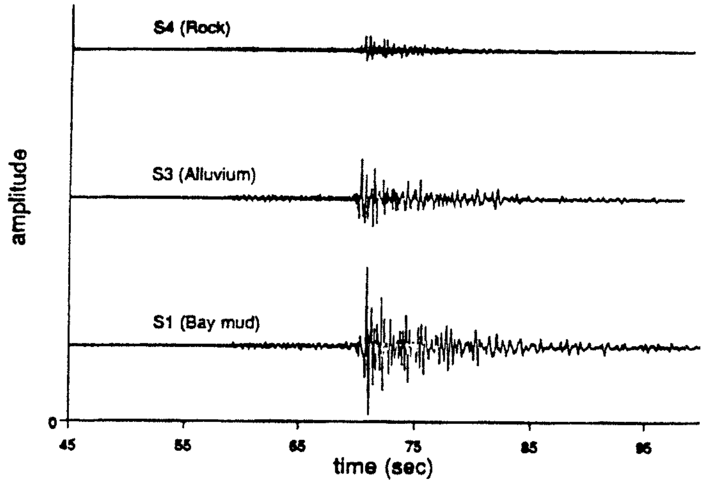


Figure 30 - *Measured north-south horizontal components of recorded motion for a M 4 aftershock. Site amplification on alluvium and Bay Mud is apparent (taken from Hough and others, 1990).*

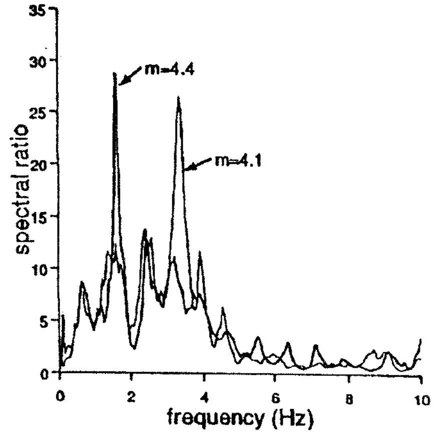


Figure 31 - *Spectral ratio versus frequency for adjacent Bay Mud and Franciscan greywake sites during M 4 and M 4.4 Loma Prieta aftershocks. Note how the ratios drop with increasing and decreasing frequencies (taken from Hough and others, 1990).*

were attached together above ground (with CALTRANS Phase 1 restrainer cable retrofits from the late 1970's), some manner of deleterious behavior could be expected in this region when subjected to traveling seismic wave trains propagating up the axis of this long continuous structure.

Bertero (1990) focused his failure analyses on shear reinforcement details at Bent 73, and for those reasons, feels the collapse may have emanated from this location. But, the dramatic change in geology and the foundation system at this same location may also have played a role in initiating collapse in this reach of the viaduct.

GROUND ENHANCEMENT EFFECTS

In the aftermath of the Loma Prieta Earthquake, there is little doubt that opposing ends of the Oakland Bay Bridge and the nearby I-880 Cypress Structure were subjected to dramatically different seismic loads due to sediment-induced amplification of their respective foundations. Recognition of this effect had been pioneered by Seed and Idriss (1969, 1971) in attempting to deconvolute response spectra generated in San Francisco and Oakland from the March 1957 M 5.3 Lake Merced quake. At about that same time, Borcherdt (1970) had discovered dramatic variances in site response on the Bay margins while recording arrivals from underground nuclear tests in Nevada. The premise had been reiterated more recently in assessing the damage to Mexico City during the 1985 Michoacan earthquake, 300 km away (Seed and Sun, 1989). Topographic and basinal effects on acceleration had previously been explored by others (Goodman, 1967; Rimer 1973; Chang 1976; Krinitzsky and Chang, 1988).

As discussed previously, strong motion records in the Oakland area displayed highly anomalous peak ground accelerations, when compared to expected norms (Figure 13). Shortly after the quake, a group of Lamont-Doherty seismologists working under the auspices of the National Center for Earthquake Engineering Research (NCEER) and the Incorporated Research Institution of Seismology (IRIS), placed six portable seismographs in the vicinity of the Cypress Structure to measure variability of ground motion in Loma Prieta aftershocks. These locations are shown in Figure 29, overlain by a map showing the surficial geology of the area. Five of the six sites were occupied for six to eight days in areas felt to be representative of differing site characteristics; a bedrock site 3 km away, an alluvium site 250 m east of the freeway, and a Bay Mud site approximately 600 m west of the northern, collapsed section of freeway.

Figure 30 shows the recorded ground motion by the Lamont-Doherty Scientists from a M 4.1 aftershock recorded on the North-South horizontal component for three adjacent sites on Franciscan bedrock, alluvium and recent fill on Bay Mud. Computed spectral ratios for mud versus rock from this aftershock and a larger M 4.4 event, are shown on Figure 31. The dramatic variance in amplification between adjacent rock and mud sites can be readily appreciated. In analyzing this record, the Lamont-Doherty scientists felt that the complicated na-

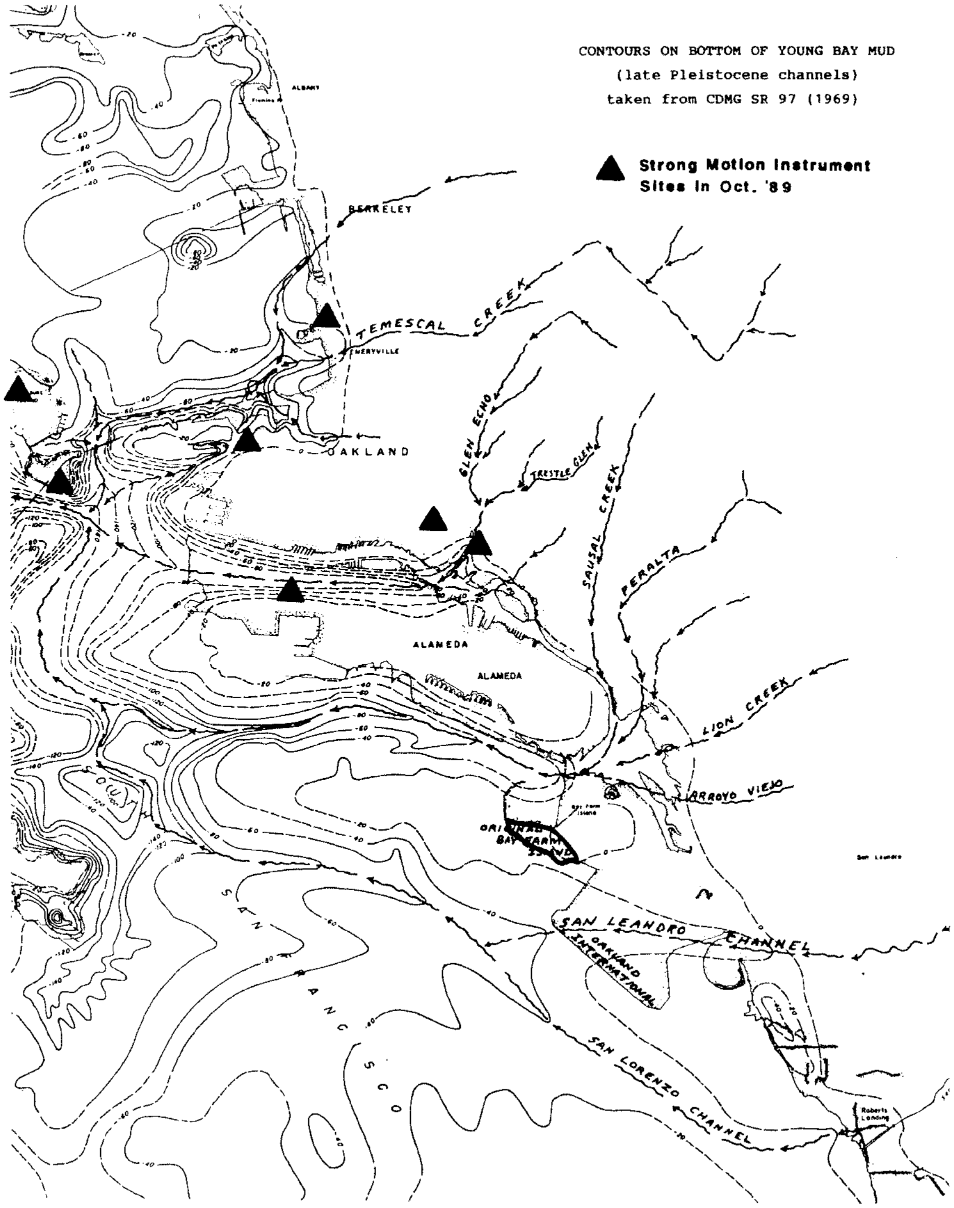


Figure 32 - ***Contours on bottom of Young Bay Mud (on 20 ft intervals), taken from Goldman (1969). Late Wisconsin age streams have been drawn onto inferred channel bottoms as squiggled arrows. Some of the mud filled channels are more than 30m deep. Black triangles indicate locations of strong motion records from the Loma Prieta earthquake.***

ture of the ratios were probably *"due to a complex resonance of both mud and underlying alluvium layers"* (Hough and others, 1990).

Indeed, the estuarine covering of Young Bay Mud could not be the only culprit in promulgating ground-induced amplification. If we overlay the 1989 main shock strong motion record stations on a map showing contours on the bottom of Young Bay Muds (Figure 32), we can see that only one of the anomalously-high strong motion records was on *Young Bay Mud*. The two story office building in downtown Oakland which received 0.26g acceleration was founded on the relatively stiff Merritt Sands. Only the 0.26g reading at the Alameda NAS hangar was situated atop any significant amount of Young Bay Mud. Backanalyses of the Oakland Bay Bridge anchor bolt failures suggest it received at least a 0.33g level of shaking. We are left to conclude, therefore, like the Lamont-Doherty scientists, that other units, underlying the Young Bay Muds, are also exerting a powerful influence on site response.

FRANCISCAN BASEMENT

In order to fully appreciate the effects that "soil cover" have on amplification of traveling seismic waves, it is necessary to know the depth, density, and wave propagation properties of the respective geologic units mantling higher density "bedrock." In San Francisco Bay, a thick sequence of unconsolidated late-Pleistocene sediments overlay dense Jurassic-Cretaceous age bedrock of the Franciscan assemblage. The velocity boundary created by this disconformity is well-recognized by geophysicists in the petroleum industry, and the depth of this contact varies from several hundred m above sea level on the East Bay hills to over 760 m below sea level beneath Daly City (Bonilla, 1964).

Before the Loma Prieta earthquake, very little was known of the Quaternary stratigraphy east of Yerba Buena Island (Trask and Rolston, 1951; Radbruch, 1957; Atwater, et al., 1977; Atwater, 1979). Early borings for the San Francisco-Oakland Bay Bridge (Hoover-Young, 1930) extended to depths over 320' (97 m) below sea level at the Key System mole, but failed to penetrate the Franciscan basement (although erroneously reported to do so in Louderback, 1951). Later, borings for the final alignment of the San Francisco-Oakland Bay Bridge penetrated

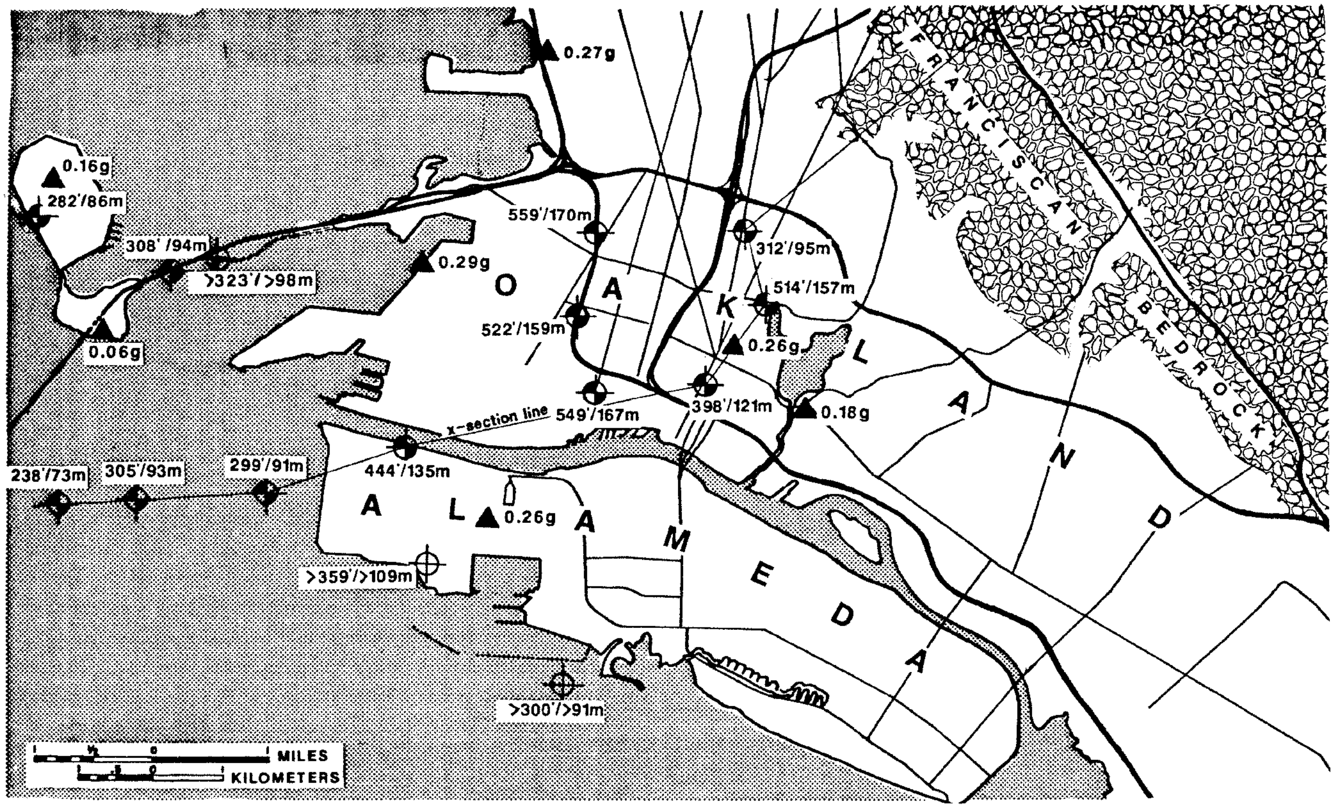


Figure 33 - *Locations of borings and indicated depths to the Franciscan basement (depth below sea level) for the Oakland Alameda area. Strong motion record sites are also shown with their respective peak accelerations. The line of section for Figure 34 is as indicated by "X-section line."*

Franciscan Sandstone at a depth of -307' (-93.6 m) on Pier E-3, just off the eastern shore of Yerba Buena (Trask and Rolston, 1951). Borings east of E-3 failed to penetrate the basement, even though in excess of -324' (-98.5 m).

Between 1941-56, a number of southern, parallel crossings to the San Francisco-Oakland Bay Bridge were contemplated. One of these encountered Franciscan bedrock at -72.5 m, 2400 m south of Yerba Buena Island. A boring made on Treasure Island in 1966, north of Yerba Buena Island, also encountered Franciscan sandstone at -86 m (Basore and Boitano, 1969), suggesting that a bedrock ridge trends north-south, splitting the Bay, with Yerba Buena as it's highest point.

Old water wells have also provided insight to the deepening of the East Bay basement. A water well on the north breakwater of NAS Alameda is reported by Weaver and Radbruch (1960) to have hit shale bedrock at 437' (133 m) below sea level, while another, across the Oakland estuary, at the foot of Adeline Street, reportedly went -542' (-165 m) before penetrating bedrock. A well on Bay Farm Island, 3-1/2 miles (5.6 km) south of downtown Oakland, extended 1050' (320 m) before hitting bedrock (Radbruch, 1957; Goldman and others, 1969).

In the 1970's and 1980's, several other deep borings were made as part of Geotechnical studies. The included -156.6 m (-514') at Kaiser Center Tower #1 by Woodward-Clyde (1982), -123 m (-404') at 9th and Broadway by Woodward-Clyde (1980) and (1980) and -95 m (-312') at Peralta Hospital, also by Woodward-Clyde (1975).

As part of the geotechnical study made by the California Department of Transportation (CALTRANS) following the Cypress Structure collapse, a series of 9 exploratory borings were made along the former axis of that structure in December, 1989 and January 1990. These included two borings which penetrated the Franciscan basement on the Merritt Sands at Bent 43 and the Young Bay Muds at Bent 91. These penetrated Franciscan Greywacke at -522' (-159 m below grade) on the southern hole (Bent 43) and -569' (-173 m below grade) on the northern hole (at Bent 91).

An overlay of the known basement depths (relative to sea level) and locations are presented in Figure 33. A preliminary cross section through the Oakland area, based on the existing data, is sketched in Figure 34.

It can be appreciated that several asymmetrically-concave bedrock basins underlay Oakland and that a broader, bedrock slope extends southwestward. This bedrock topography, in and of itself, could be expected to create topographic basinal effects, as deeper soil covering usually engenders lengthened site periods. As seismic energy is directed up a basement slope, the natural site periods will generally decrease and higher frequency energy is damped-out with increasing distance from the source. Based upon preliminary data, the bedrock depression would appear to be greatest southwest of Oakland International Airport, where the San Francisco Bay is widest (near the Hayward-San Mateo Bridge Crossing). According to Hazelwood (1976), the Franciscan basement raises to a natural divide at around -183 m (600') in the vicinity of the Dumbarton Bridge (coincidentally, where the Bay narrows adjacent to the Coyote Hills).

QUATERNARY STRATIGRAPHY

The bedrock basins and canyons are not the only culprits which likely shape seismic wave amplification. The density and consistency of overlying Pleistocene sediment can be of equal or greater importance in modifying seismic wave energy. In order to evaluate the potential for ground amplification, unraveling the Quaternary depositional history of San Francisco Bay depression sediments, of both continental and marine origin, must be accomplished. What follows is a brief recount of that depositional history, given what limited data is available at the present.

Around 13 million years before present (13 Ma), regional uplift began in the tectonically-bounded block between the San Andreas and Hayward faults, here-after referred to as the "Bay Block" (Graham and others, 1984). Around 10 Ma, initial rupture of the Hayward fault zone occurred following the uplift. Between 10 and 7 Ma, there was localized volcanism along the Hayward fault zone. Sometime later, between 8 and 6 Ma, a similar pattern of uplift and drainage began to occur along what is now the Calaveras fault zone, extending south to Hollister, where it joins the San Andreas. Individual land-locked basins were created between these progressively younger strike-slip fault segments, side-stepping to the east of the San Andreas. During Pliocene time (5.3 to 1.6 Ma), uplift on the Hayward rift supplied Franciscan detritus to nearby subsiding areas, like the Contra Costa Basin. In the Pleistocene epoch (1.6 Ma to 11,000 years before present or 11 ka), faults bounding the eroded Franciscan

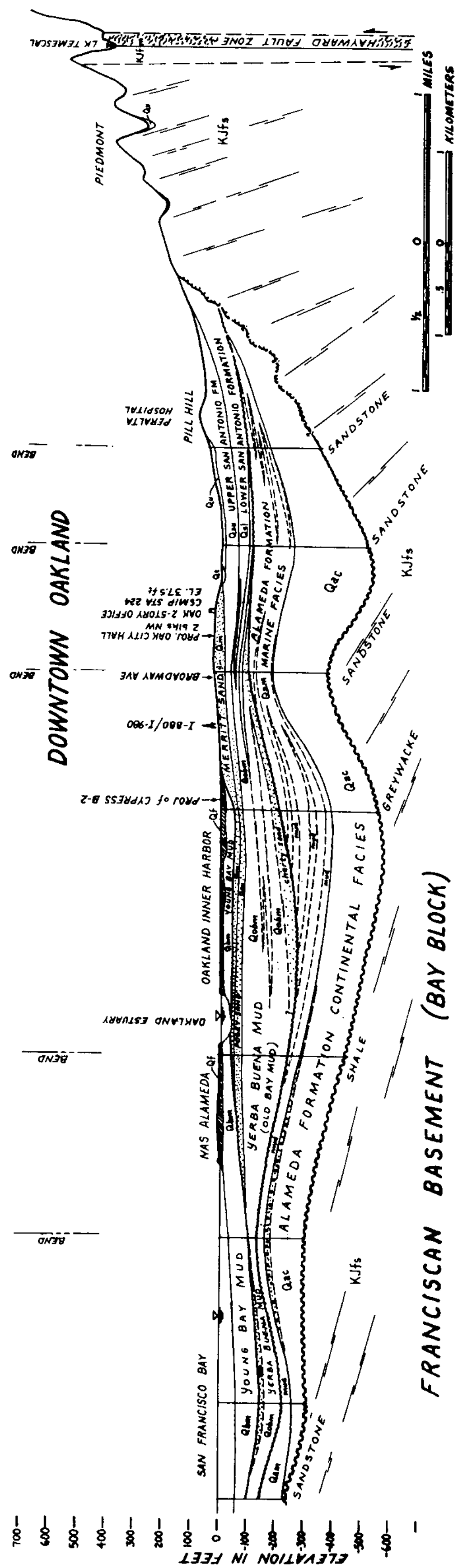


Figure 34 - *Geologic cross section across Piedmont-Oakland-Alameda and central S.F. Bay, as inferred from data in 9 borings extending to the Franciscan basement. A complex interfingering of alluvial and estuarine sediments has repeatedly occurred, with basinal troughs or channels changing position with seemingly randomness from one stage to another. Note the extensive accumulation of Sangamon-age Yerba Buena Muds (formerly called Old Bay Mud) extending inland of the relatively thinner covering of Young Bay Mud. Much more work is needed in order to develop transverse sections so that three-dimensional effects can be better appreciated.*

bedrock highlands of the Bay block reversed direction, and the block between the San Andreas and Hayward faults began to subside.

It is likely that the lowering of the Bay depression is ascribable to both tectonic subsidence and drag-induced uplift along the San Andreas. Atwater (1979) has suggested that ancillary uplift along the San Andreas is approximately 0.5 to 1.1 m per millennium. This 0.05 to 0.11 cm/year value would be about 1/30th to 1/70th of the concurrent strike-slip motion of the San Andreas. This ancillary uplift could be partly responsible for land-locking the subsiding Bay block. This would help to explain why relatively-young marine sediments of the Colma formation (Bonilla, 1971) lie as much as 100 m above modern sea level (Clifton, 1990). Alternatively, crustal subsidence of the Bay block could be likened to the formation of a *tectograben*, or inter-fault block caught in a regional tensile stress field created by continuous motion on two adjacent, right-stepping, right-lateral strike-slip fault zones (see Figure 35).

Land-locked continental sediments began to fill in the newly-created Bay depression, beginning about 1 Ma. Drainage in California's great Sacramento-San Joaquin Valley was internal, being comprised of an enormous lake up until at least 620,000 years ago (Sarna-Wojcicki, 1985).

In a bedrock depression between the San Andreas and San Bruno faults, lies a 1740 m thick wedge of sediment known as the Merced Formation (Figure 36). The lower two-thirds of the formation consists of alternating series of prograding shore and shelf deposits, lain within ocean depths of less than 100 m, much like the continental shelf off the San Francisco Peninsula today (Clifton and Hunter, 1988). Sometime between 400 ka and 620 ka, the Merced strata recorded a dramatic facies change wherein sediments derived from the Sierra Nevada Mountains suddenly appear, suggesting a seaward connection was established between the Great Central Valley, the Bay depression and the open ocean. Around 400 ka, the Rockland ash bed was deposited on the shelf. This was followed by the first of four marine incursions into the San Francisco Bay (Clifton, 1990). In the upper third of the formation, The Merced sediments records a prograding shoreline sequence, usually including a surf zone deposited in water 1 to 5 m deep, then shoal of deeper water, aeolian dunes, dissected erosion of the near-shore land surface, fluvial deposition, then back into surf zone and shoal sediments (Clifton, 1990).

The earliest marine incursion recorded along this ancient shoreline was around 400 ka according to Clifton (1990), which was previously estimated as 550 ka by Atwater (1979). Repeated landward transgressions by rising seas are again recorded approximately 300 ka and 200 ka (Clifton, 1990). These older estuarine clays are correlable with similar age clays found in Bay borings and dated by Atwater (1979).

The base of the Merced beds abuts the San Andreas fault. Progressive distortion of these beds approaching the fault suggests that it has become most active in the past 200,000 years (Clifton, 1990). The Merced formation may be an erosional remnant of the continental side of what was periodically a drowned valley that accommodated seaward intrusion into ancient San Francisco Bay (Figures 35 and 37). The author has tentatively called this the *San Bruno Channel* during the period covering 100 ka to approximately 500 ka. Known depths to the Franciscan basement pierced within the San Bruno depression show levels ranging from greater than 500' (150 m) to 2500' (760 m) below sea level, considerably deeper than the -330' (-100 m) opening through the Golden Gate.

A thick sequence of non-marine continental alluvial and fluvial sediments belonging to the Alameda formation appears to lie atop the Franciscan basement in the greater Oakland area, reaching thicknesses of 250' (76 m) under the Cypress Structure. This would be in keeping with the observations of the Merced formation, suggesting that there was no seaward outlet of the Bay depression until 400 ka to 500 ka. Near the top of the lower Alameda is the Rockland Ash (Trask and Rolston, 1951), the same material as seen in the upper third of the Merced formation and dated at 400 ka.

The upper Alameda formation appears to be a mixture of marine estuarine and continental alluvial sediments, somewhat thinner than the underlying continental facies. At the Cypress Structure, this unit is tentatively identified to be 49 m to 53 m thick. This upper marine facies may be correlative with the upper third of the Merced formation, which contains similarly mixed assemblages of marine and continental deposition (Clifton and Hunter, 1988).

Atwater (1979) reports age dates of approximately 350 ka on the next youngest series of old marine clays encountered in the Southern Crossing Borings of 1948, made west of Alameda. These clays may be correlable with Clifton's third marine incursion at around 300 ka and

Figure 35

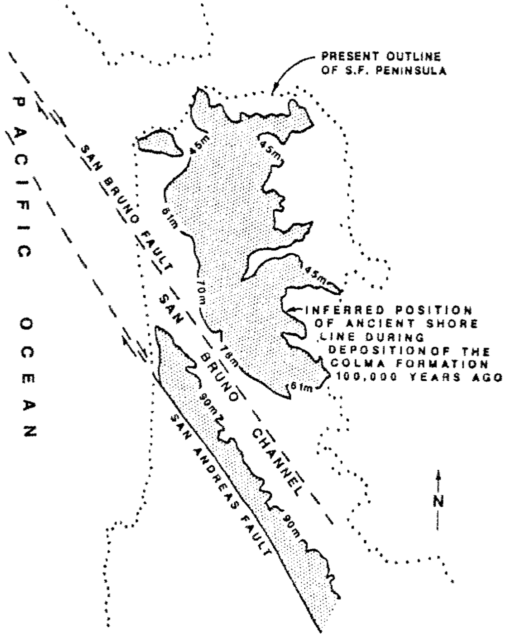


Figure 35 - *Scrutiny of well logs in the Daly City/San Bruno area suggest that a downdropped structural trough exists between the San Andreas fault and the inferred San Bruno fault, offset approximately 2.4 km to the northeast. In this trough, Franciscan basement rocks lie 180 to 760 m below sea level, the deepest eroded surface in the Bay Area. Between approximately 1 Ma and 100 ka shallow oceanic shelf deposits filed the trough to a depth in excess of 1740 m (Clifton & Hunter, 1987). Between 400 ka and 500 ka, a drainage connection formed in or close to the trough that initially brought Sierra Nevada sediments to the sea (Hall, 1965).*

Today, shallow near-shore Colma formation sediments thought to have been deposited 100 ka are lifted up as much as 90m in vicinity of the San Andreas fault. By assuming a diminishing rate of uplift with increasing distance from the San Andreas (90m within 1.5km; 76m within 3.2km; 61m within 4.8km and 45m within 6.4 to 10km); a theoretical shoreline in vicinity of the San Bruno Channel was constructed as it may have appeared during Colma deposition 100 ka. The likely 6m higher shoreline of the Sangamon interglacial has been ignored in this estimate, its inclusion would enlarge the area of inundation, possibly helping to open up a channel between Daly City and India/China basins.

Figure 36

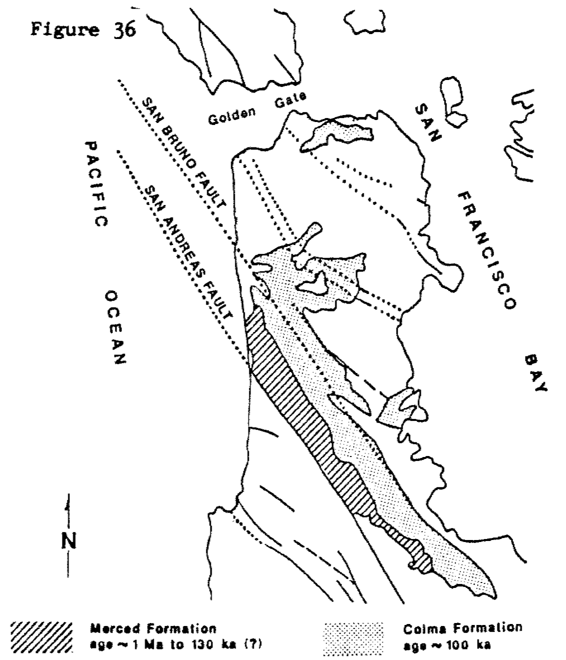


Figure 36 - *Outcrop patterns of the Merced and overlying Colma formations adjacent to the San Andreas fault on the S.F. peninsula (from Clifton and Hunter, 1987). Reasonable correlation can be made between the Colma outcrop pattern and that predicted in Figure 35. The Golden Gate channel is only 100m deep. It is not known when it was initially pierced, or if it has been raised slightly by ancillary uplift along the San Andreas fault.*

Oakland is underlain by -200 m sediment-filled basins cut upon the Franciscan basement while the deepest portion of the Golden Gate is only -100 m deep. This dichotomy raises two possibilities: the Bay Block is rapidly subsiding; and/or there was once another, deeper outlet to the sea. Evidence exists to support both of these theories.

Figure 37

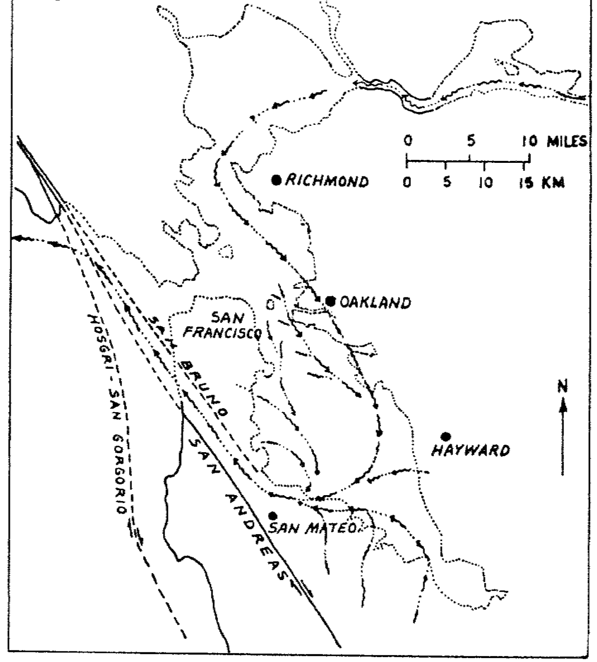


Figure 37 - *Possible channel axes with seaward outlet through the San Bruno Channel during pre-Sangamon time (before 300,000 years ago). During deposition of the lower Alameda formation there does not appear to have been an oceanic transgression of the Bay, but internal drainage may have built up to a level sufficient to pass flows out to the continental shelf via the San Bruno Channel. The San Bruno Channel may have persisted for a very long time if the two parallel faults were active, for a tectono-depression would form between them (Borchardt and Rogers, 1991). The channel may have been sufficiently wide and deep so as to mask out high energy channel deposits. Sometime between 500 ka and 400 ka drainage broke through the channel from the Sierra Nevada Mountains, 300 km to the east. Since that time four sustained estuarine intrusions were recorded in marine clays left in the channel. Post-Alameda erosion (Figure 38) in the Oakland area appears to have been directed northward, away from the San Bruno Channel.*

the Upper Alameda marine facies.

In the first attempts to unravel the Quaternary history of the Bay, Louderback (1951) and Trask and Rolston (1951), utilized boring logs from the San Francisco-Oakland-Bay Bridge and proposed Southern Crossings to reconstruct structural contours at the top of the Alameda formation. The age of this interval is unknown, but it may represent the Illinoian interglacial stage, approximately 200 ka. The erosional surface etched upon the Alameda sediments suggests that the thalweg of the main trunk stream ran east of Yerba Buena Island, and sloped northerly, presumably towards Angel Island. It is not known if this slope represents an outlet to the sea during the Sangamon glacial stage (130 ka to 200 ka). The relatively low energy sedimentary deposits left in the San Bruno channel during this interval suggests that although it was open to the sea, it may not have accommodated a high-energy channel carrying large rivers from the interior of California.

During the Sangamon interglacial period, approximately 130 ka to 95 ka, sea level slowly rose to a level 6 m higher than today (Sloan, 1981). Once again, the rising seas of this interglacial period caused a thick covering of estuarine marine clays to fill in the Sangamon topography. This unit is widely recognized as the so-called "Old Bay Muds" (Treasher, 1963) or more recently, as the Yerba Buena Mud (Sloan, 1990). Sloan's research indicates that the Yerba Buena Muds became progressively more saline, suggesting increasing oceanic transfer, as the interglacial period progressed. In addition, examination of benthic foraminifera suggests a cooling and saline trend towards the San Bruno channel, compelling evidence for it's existence as a seaward connection at this time, similar to Tomales Bay, a drowned valley 50 km northwest along California's coastline. Sloan's (1990) most recent research indicates that the Yerba Buena Mud is correlative with Isotope stage 5e, or about 123 ka. It would appear, therefore, that from 400 ka until at least 126 ka, the San Bruno channel likely represented at least one seaway connection to San Francisco Bay. The Golden Gate channel may have been cut by the end of Alameda time, thereby accommodating another outlet for the Bay (Figure 38). It may have subsequently been lifted as much as 45 m by ancillary compressional rise adjacent to the San Andreas (Figure 35). Such "scientific adjustment" would allow the Golden Gate to be a pre-Sangamon outlet, although speculative at best.

As a consequence of the seaward intrusion during the San-

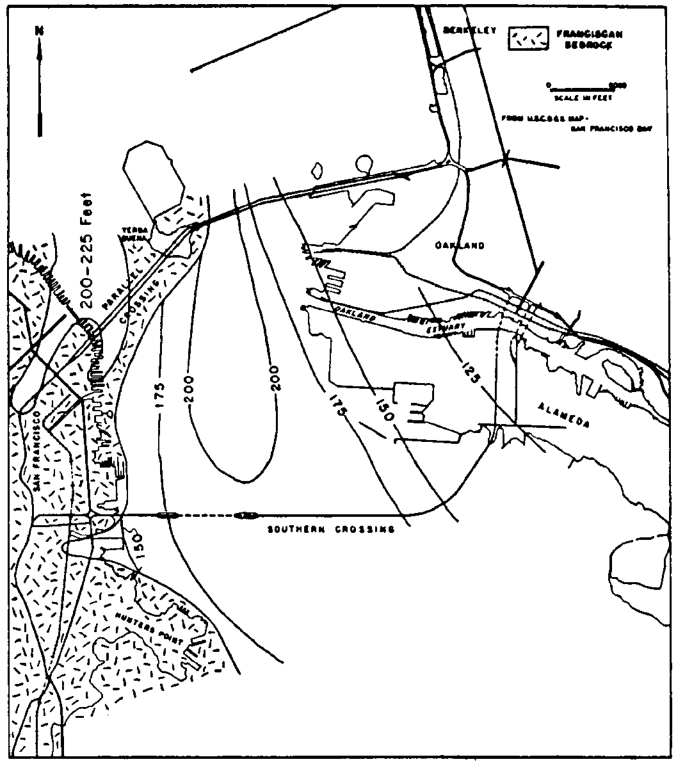


Figure 38 - *Depth contours on top of the Alameda Formation in Central San Francisco Bay (taken from Trask and Rolston, 1951). Sometime late in the Sangamon glacial stage (125,000 to 150,000 years ago) the dominantly-marine upper facies of the Alameda formation was subaerially eroded. The thalweg of the main trunk channel appears to have been northerly directed, east of Yerba Buena Island. Other tributaries in the San Francisco financial district also appear to be north directed. At the levels indicated (in feet), seaward drainage could have been effected through the Golden Gate channel (max depth of 100m or -330 feet).*

gamon interglacial period, Yerba Buena Muds were deposited over an extensive area, extending well-inland of the present shoreline along the East Bay (Figure 34). However, out in the Bay depression, much of this older mud was subsequently subaerially exposed and eroded during the Wisconsin glacial stage (95 ka to 11 ka) where those streams were deepest. Early Wisconsin Channels, carved into Yerba Buena Muds, were well-exposed in all of the borings made for trans-bay bridge crossings between Dumbarton and Point Richmond (Treasher, 1963). But, comparative structural correlation of the erosion surface incised upon the Yerba Buena Muds has been accomplished (as it has been on the Young Bay Muds), so the relative position of Bay outlet(s) is not known.

After the deposition of the Yerba Buena Muds at the beginning of the Sangamon/Wisconsin interglacial, another seaward transgression appears to have occurred along the general trend of the San Bruno depression. After the last Merced units were deposited, they were tilted and exposed to erosion. A bench appears to have been cut across the Merced beds during the Sangamon interglacial (95 ka to 128 ka). Over this surface was deposited a series of foreset beds, typical of a prograding sedimentary wedge that records one last sea transgression during a relatively high sea stage. The foreset beds were subsequently eroded away, leaving a basal layer of lag gravels with overlying sands. The Colma formation appears to have been deposited in two, or possibly three channels, one parallel to the San Bruno channel, another between Daly City and India Basin, and possibly a third in the Golden Gate channel, opposite the Presidio and Marine area of San Francisco (Figures 35 and 36). The Colma beds exposed near Lake Merced are not indicative of a high-energy channel or outlet to the ocean like today's Golden Gate (Clifton, 1990). Other workers have estimated the Colma's age as 70 ka to 80 ka. Clifton (1990) suggests an age of about 100 ka, which is more in line with indications for high sea stands from sea level Isotope studies.

In the past 100,000 years, the Colma beds appear to have been elevated by ancillary uplift during compressional drag along the San Andreas fault. This uplift and distortion appears greatest in proximity to the Fault, as the Colma rises to over 100 m at Thorton Beach, but dips below sea level at Lake Merced. In continuous exposures along the San Bruno depression, the unit rises to 45 meters. By superposing 100 m to 46 m of post-Colma uplift to a map of the northern San Francisco peninsula, some crude estimate of the 100,000 year shoreline is appreciated (Figure 35).

As North America entered the Wisconsin glacial stage (around 95 ka), the Sangamon interglacial sea retreated from the Bay, eventually to a position some 106 m lower than present. At that time, the continental shelf retreated to a position approximately 59 km west of the Golden Gate, slightly beyond the Farallon Islands. As sea level dropped, the emerging Bay uplands began to adjust to the retreating base level. Stream systems incised themselves, cutting through both the Colma beds and the estuarine Yerba Buena Muds. Subaerial erosion of the surrounding upland brought alluvial sediments down onto the Yerba Buena Muds, covering them with a contemporaneous-age alluvial unit called the San Antonio formation (Trask and Rolston, 1951; Radbruch, 1957) and "Qpha, Alluvial Sediments" by Atwater and others (1977).

Trask and Rolston (1951) included the Yerba Buena Muds as the basal unit of the San Antonio formation. The alluvial facies of the San Antonio reached thickness of between 6 and 18 m along the San Francisco-Oakland-Bay Bridge alignment. Margason (1990) identified 11 to 18 m of San Antonio sediments beneath downtown Oakland and 35.5 m beneath Peralta Hospital on Pill Hill (near 30th Ave and Telegraph).

Within the uppermost portion of the San Antonio is a sandy unit called the Posey Formation, because it was well-developed near the Posey Tube, between Oakland and Alameda. The Posey sands are well recognized on both sides of the Bay as a unit containing shells and sand. It is locally missing in subaerially-eroded Wisconsin-age stream channels.

Sometime in very late Wisconsin or early Holocene time, the weather became somewhat drier, and aeolian blow sands accumulated along offshore wind corridors adjacent to the Golden Gate, East Bay and Oakley. In the San Francisco area, these sands have loosely been called the Merritt Sands (Trask and Rolston, 1951). The Merritt Sands accumulated as thick deposits blanketing most of the Bay shoreline where prevailing onshore winds existed.

In very late Wisconsin time, the Merritt Sands were themselves excavated by an apparently rejuvenated stream system (Figure 32), which cut down some 45 m into the underlying San Antonio formation. As the Wisconsin glaciers began to retreat approximately 11 ka, the Bay's stream system connected to a main trunk stream located between Yerba Buena Island and San Francisco. East Bay tributaries had to flow further to reach this main stream, which was their controlling base level. The Temescal stream system made a sharp turn, south and around Yerba Buena, crossing over the southern flank of Yerba Buena (Figure 32). The main trunk stream likely carried what is today known as the Coyote, Guadalupe, San Tomas Aquino, Alameda, San Leandro and San Antonio stream systems; emanating from the South Bay.

North of Yerba Buena, the trunk stream made it's confluence with the ancient Sacramento-San Joaquin River just northwest of Angel Island (Atwater and others, 1977). The combined rivers then flowed out through Raccoon Straits between Tiburon and Angel Island, hugging the Marin coastline before exiting through the Golden Gate and the 59 additional km to the continental shelf (Figure 39).

According to Atwater and others, (1977), between 11 ka

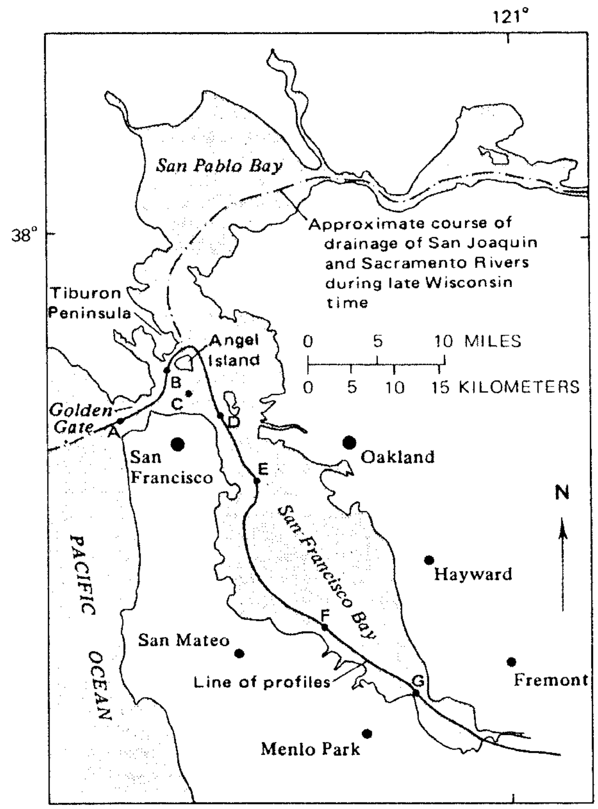


Figure 39 Upper - *Atwater and others' (1977) reconstruction of the late-Wisconsin age drainage patterns in San Francisco Bay, based on evaluation of borings for Bay toll crossings. The late-Wisconsin (11,000 years ago) trunk stream ran down the western side of the Bay, possibly due to increased subsidence as the Hayward and San Andreas faults approach each other towards the South Bay.*

Figure 39 Lower - ***The late-Wisconsin main trunk stream emanating from the south bay joined up with the ancestral Sacramento-San Joaquin river system just northeast of Angel Island, and flowed out to sea through Raccoon Straits, hugging the Marin shore (see dotted paths). At that time, the continental shoreline lay 59 km west of the Golden Gate.***

and 8 ka, sea level rose sharply, at an average rate of 24 mm/year. Since 8 ka, there has been a somewhat slower rate of sea level rise, averaging about 1 mm/year to it's present level. The incised stream valleys, cut through the Merritt, Posey and San Antonio formations were soon filled with estuarine mud, known as the Young Bay Mud (Trask and Rolston, 1951; Treasher, 1963) or ("Qpha" by Atwater and others, 1977).

These recent, unconsolidated muds were initially deposited in quiet water with high initial void ratios and low unit density. The Young Bay Muds are divisible into three units, low, middle and upper, each more saline than it's predecessor. The Bay Mud reaches a maximum thickness of 120' in the main trunk stream channel, off China Basin and south of Hunter's Point in San Francisco. The Bay Muds infilled the drowned valleys much like a policeman would use plaster to make a cast of a footprint. The "footprint" of late Pleistocene stream valleys is easily seen by viewing Goldman's (1969) 1:70,000 scale map entitled: "Contours on Base of Bay Mud," a portion of which was presented in Figure 32.

In the East Bay, a distinctive, younger alluvial unit known as the Temescal Formation (Radbruch, 1957, 1969) overlies the San Antonio alluvium and infills the existing network of incised streams. The Temescal Formation is more fine-grained than the underlying San Antonio Formation, comprised almost wholly of silt and clay, the latter which contains noticeable amounts of the swelling clay mineral montmorillonite. This smectite clay is likely derived from the weathering of nearby late-Pliocene-age volcanics, like the Leona Rhyolitic, which had previously upwelled along the Hayward fault zone. The Temescal Formation is also readily identifiable by it's mottled, variegated color, intermixing a yellowish-ochre color (oxidized) with it's original olive-grey (unoxidized) color. The Temescal Formation likely represents cooler, wetter periods of early Holocene time, when abundant colluvial production and stream carrying capacity were available to bring these materials down within channels excavated into the San Antonio Formation.

In the past 6800 years, there has occurred a progressive drying out of the weather, thereby promoting a period of renewed stream retrenchment. The old East Bay Channels, recently filled with soft Temescal sediments, were re-excavated to their current levels.

In the latest **stream system readjustment**, San Antonio-

Glen Echo-Trestle Glen creek system joined at Lake Merritt and cut a new channel through the Merritt Sands, called San Antonio Slough, approximately 630 m north of the former Pleistocene channel, which runs parallel to it beneath Alameda Naval Air Station (Figure 32). Part of this shift appears to have been due to piracy of nearby Sausal Creek to a new San Leandro channel, between Alameda and Bay Farm Island. From Figure 32, it can be appreciated that Pleistocene San Leandro creek channel ran through what is now Oakland airport, 3 km south of the current channel.

CYPRESS STRATIGRAPHY AND WAVE PROPAGATION PROPERTIES

Significant subsurface exploration and assessment of the foundation materials underlying the Cypress Structure and San Francisco-Oakland Bay Bridge were carried out by the CALTRANS Transportation Laboratory and their respective consultants following the Loma Prieta earthquake. As mentioned previously, Borings B-2 and B-8 at the Cypress Structure were carried through the Pleistocene sediments, and approximately 15 m into the Franciscan basement, a dense grey-green colored greywacke. Boring logs of these holes, remarked by the author to include tentative stratigraphic assignments, are shown in Figures 40 and 41.

In the summer of 1990, Redpath Geophysics (1990) was retained by CALTRANS to perform a series of shear wave propagation profiles for the 600' (182.9 m) deep Cypress borings depicted in Figures 40 and 41. Both of these holes had been cased with PVC pipe when drilled the previous December. Redpath utilized two separate and independent methods to acquire shear-wave velocities. The first was the conventional 'downhole' technique in which pulses from CALTRAN's compressed-air-operated shear wave generator provided a ground-level energy source which was repeatedly fired, then detected by downhole geophones positioned at various depths in the hole. Redpath also utilized an OYO-PS suspension logging sonde, a Japanese built device which incorporates the energy source with the downhole sensor assembly.

Redpath was unable to test the impure estuarine muds (Young Bay Muds) encountered at shallow depth in Borehole B-8 at the northern end of the Cypress Structure. The upper Yerba Buena Mud Possessed shear wave velocities between 183 and 244 m/sec. The middle member of this unit recorded values of 178 to 244 m/sec beneath the Cypress and 180 to 225 m/sec at the San Francisco Embarcadero (Figure 40). This increase in shear modulus would be expected due to overconsolidation and burial, as well as induration of the older muds.

Younger alluvial sediments of the lower San Antonio formation had average shear wave velocities of 280 to 323 m/sec. The upper, mixed marine facies of the Alameda formation averaged 410 to 490 m/sec. What appears to be a soft estuarine clay was encountered at a depth of -110 to -116 m in Boring B-8, and it exhibited an unusually low velocity of approximately 137 m/sec. This clay lies at the boundary between the lower continental, and upper marine facies of the Alameda formation. The lower Alameda formation shown alternating velocities in the range of 460 to 730 m/sec, with an average value of 540 m/sec.

The author's interpretation of site stratigraphy is overlain on Redpath's summary shear wave velocity data logs in Figures 40 and 41.

CONCLUSIONS

The site response of the Oakland area to the October, 1989 Loma Prieta earthquake was much more severe than other areas at a similar epicentral distance (96 km) from the quake (with the exception of San Francisco's Marina District). The reason for the abnormal severity of shaking appears to have been site-induced amplification, due to the variable depth and consistency of unconsolidated Pleistocene and Holocene-age sediments mantling the Franciscan bedrock. Site response on Franciscan-age and younger, consolidated bedrock units was less, and in keeping with accepted *peak ground acceleration versus distance from causative fault* relationships published by Joyner-Boore through EERI (1989) and Krinitzsky and Chang (1988). Shaking levels on upland alluvial sites were more severe, but also in keeping with predictable ranges for soil sites at such range (88 to 105 km).

Site response recorded on late Pleistocene-age lowland alluvial, estuarine muds and recent fill deposits was abnormally high. Five recording stations in the Oakland lowlands recorded base accelerations between 0.26g and 0.29g. Only one of these, at NAS Alameda, was situated upon any meaningful amount of Young Bay Mud. Back analyses of anchor bolt failures on the Oakland Bay Bridge indicated a force level of at least 0.33g (Astaneh, 1990). Detailed aftershock comparisons by scientists from Lamont-Doherty and the U.S.G.S. showed

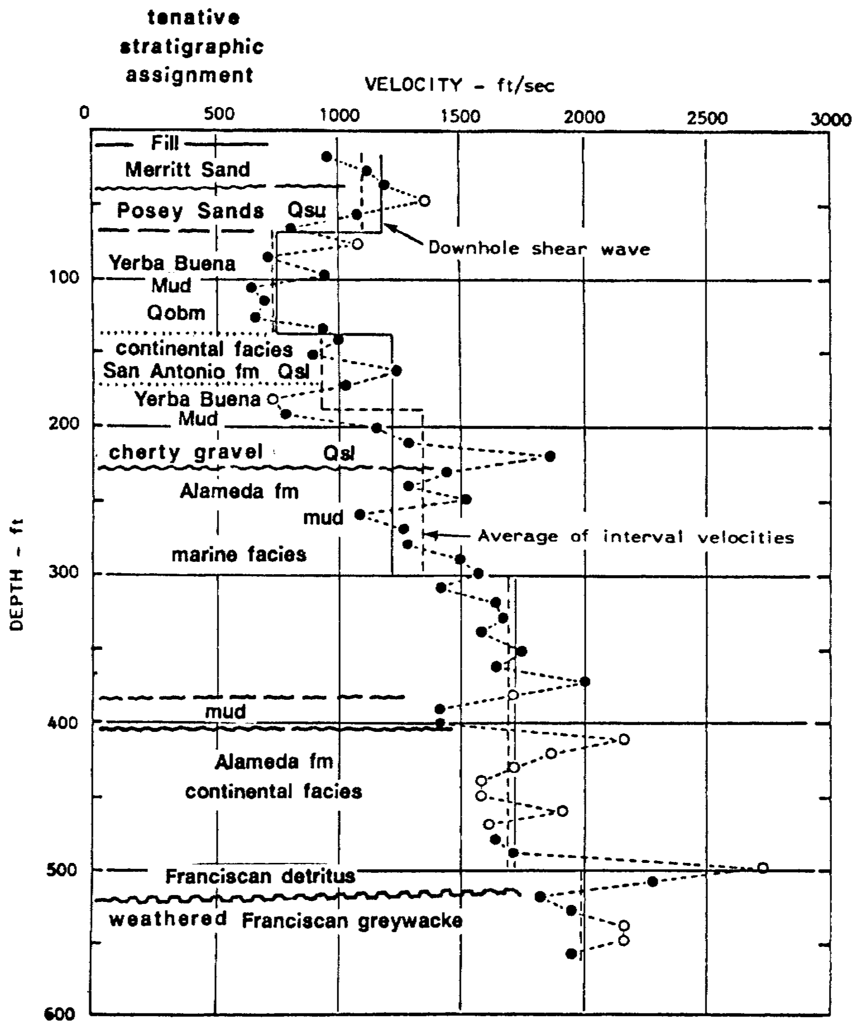


Figure 40 - *Comparison of Quaternary stratigraphy beneath the southern end of the Cypress viaduct with average shear wave propagation velocities gathered by using downhole interval velocities and above-ground shear wave energy sources (velocities taken from Redpath, 1990). The influence of geologic material types on velocity propagation can be readily appreciated.*

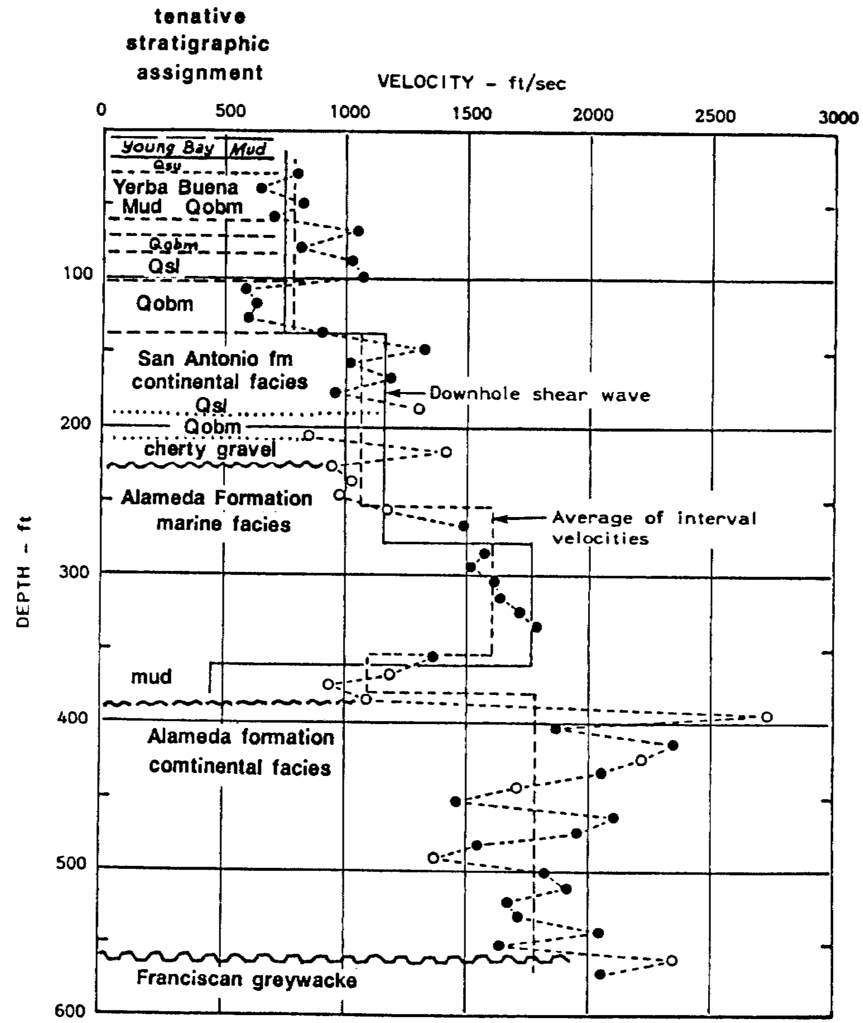


Figure 41 - *Comparison of Quaternary stratigraphy with shear wave velocities beneath the northern, collapsed end of the ill-fated Cypress viaduct in west Oakland. No velocity data was garnered for Young Bay Muds because of their close proximity to the surface and related ambient noise interference. Along the San Francisco embarcadero shear wave velocities in Young Bay Muds are generally in the range of 300 to 570 fps (91 to 174 m/sec). Velocity data taken from Redpath (1990).*

that spectral ratios of between 6 and 9 could be expected between Young Bay Mud sites and those on alluvium, and up to 30X when compared to nearby bedrock basement (for M 4 to 4.6 aftershocks). These scientists concluded that the Young Bay Muds are not the only factor contributing to ground amplification, but that the underlying assemblage of materials must also contribute (Hough and others, 1990).
By evaluating the known data taken from exploratory borings which pierce the Franciscan bedrock in the greater Oakland area, we have demonstrated that a significant Pleistocene-age assemblage of predominately continental sediments mantles the Franciscan basement with considerably variable thickness. The basement surface itself exhibits ample evidence of being highly dissected, with a broad, conically-shaped basin lying beneath western Oakland, opening to the southwest. The dissected bedrock surface appears to contain sharp hummocks and valleys up to 45 m high, all of which are buried beneath the Alameda Formation, a thick expanse of continental and marine sediments.

Between 1 Ma and 500 ka, the San Francisco Bay block appears to have been self-contained, and occasionally filled with freshwater lakes. Between 400 ka and 500 ka, waters entrained within the Bay depression appeared to have found an outlet to the sea, through the San Bruno/Colma channel, located between San Bruno Mountain and the San Andreas Fault. The earliest of the four estuarine muds deposited in the Bay dates from 400 ka, and may comprise the soft clay found in Boring B-8 under the collapsed section of the Cypress Structure at a depth of 110 to 119 m.

Four distinct sequences of marine clay were deposited during the past four respective interglacial periods. These include Atwater's (1979) clay units N-O and Q-R, which probably lie within the Alameda formation with dates of 300-350 ka and 550 ka, respectively. The Yerba Buena Mud, which could have reached 6 m above sea level, was deposited during the Sangamon interglacial (123 ka) and the Young Bay Muds, deposited in the current interglacial period, between 11 ka and the present time. These latter two units are the most recognized estuarine units in the San Francisco Bay.

Ground amplification effects on site response in the greater Oakland area are likely ascribable to the following engineering geologic and stratigraphic controls:

1) presence of underlying Holocene-age Young Bay Mud it's respective thickness;

2) presence of underlying late Sangamon interglacial-age Yerba Buena Mud and it's respective thickness;

3) the presence of either or combinations of the above units within incised valleys up to 50 m deep, or two older estuarine units with low shear wave velocity propagation properties, within ancient filled channels or depressions, so as to create thick accumulations that pinch out to either side of such channels;

4) depth and consistency of other continetally-derived, but geologically young, unconsolidated sediments lying above the bedrock basement;

5) the three-dimensional character of the regional slope of the dissected bedrock basement; and

6) steep-sided bedrock depressions or bedrock inselbergs protruding from the Franciscan Basement.

All of these factors may collectively influence control on the natural period of vibration of any particular site with respect to the direction of propagation of the energized seismic wave train(s).

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