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SYNOPSIS The Petrolia, California, earthquake (M_S 6.9, M_L 6.4) occurred on April 25, 1992 and was followed by numerous aftershocks including two earthquakes over magnitude 6 that occurred on April 26, 1992. The earthquakes caused structural damage in Ferndale, Petrolia, Honeydew, Rio Dell, Fortuna, and Scotia. The earthquake also produced ground failures of liquefaction, lateral spreads, and landslides in the epicentral region. Liquefaction did not appear to be widespread, and occurred in locations where it would most likely be expected to occur (low lying areas with very recent alluvial deposits and high ground water). Scattered landslides were triggered by the earthquake sequence throughout the epicentral region of the main shock and within a broad region around it. For an event of this size, the damage was limited by the sparse population, limited development, and depth of the main shock. Other than the liquefaction of a very silty sand, none of the geotechnical consequences were unexpected.

INTRODUCTION

A strong earthquake (M_S 7.0, M_L 6.4) occurred near Petrolia, California at 11:06:04 PDT on April 25, 1992. Numerous aftershocks followed including two earthquakes over magnitude 6.5 occurred during the early morning hours of April 26, 1992 (M_S 6.8 M_L 6 at 00:41:40 PDT and M_S 6.6, M_L 6 at 04:18:26 PDT). The earthquakes caused damage in the towns of Ferndale, Petrolia, Rio Dell, Honeydew, Fortuna, and Scotia and in the surrounding areas.

This paper presents the results of observations by the authors during a visit to the area on Saturday May 2 and Sunday May 3, 1992. We made an aerial reconnaissance of the epicentral area around Petrolia, along the Pacific coast, and over the lower Eel River basin aerial with Professor Gary Carver of the HSU Geology Department and graduate student David Valentine. We also observed the earthquakes effects on the ground at Ferndale, the lower Eel River basin, near Cape Mendocino, Petrolia, Honeydew, Scotia, and Rio Dell.

TECTONIC SETTING

The Petrolia earthquakes occurred along the Lost Coast of northern California, among the most seismically active and structurally complex regions in North America. The region lies near the Mendocino triple-junction, where the Pacific, North American and the much smaller Gorda plates converge. The San Andreas transform fault forms the boundary along which the Pacific and North American plates move past each other in a southeast-northwest direction (respectively). Along the Mendocino fracture zone, the Pacific plate moves west relative to the Gorda plate. The Gorda plate is the southernmost portion of the Cascadia subduction zone, which extends northward along the Oregon, Washington, and southern British Columbia coasts. The Gorda plate and the overriding North American plate are converging in a east-northeast-west-southwest direction at a rate of about 3 to 4 cm/year.

The seismic potential of the subduction zone was a matter of considerable controversy less than a decade age, largely because of a lack of recorded seismicity on the plate boundary. Since that time, significant geologic evidence has shown that large earthquakes have occurred in the past with average return periods of a few to several hundred years. There is currently some disagreement on the size of future earthquakes on the Cascadia subduction zone with the maximum estimates as large as moment magnitude 9.25 if the entire zone were to rupture in a single event. Other estimates are based on a segmented zone with individual segments capable of over magnitude 8 events.

The Gorda plate is very young (less than 10 Ma) and therefore is relatively buoyant for an oceanic plate. Because of the relative plate motions however, the plate is being actively subducted under the North American plate. As a direct consequence of this east-northeast directed convergence, the Gorda plate is internally deforming along northeast- and northwest-striking strike-slip faults and the Lost Coast is being rapidly uplifted. The main event occurred along the plate boundary, and the two large aftershocks were strike-slip events within the Gorda plate.

Direct evidence for coastal uplift during the Holocene is recorded in a remarkable sequence of emergent marine terraces, along the coast south of Cape Mendocino. The lowest platform, which is inundated during high tides, yields dates of ca 300 yr B.P. Two higher terraces date at 1700 and 3000 yr B.P. and dates from the highest terrace cluster around 5000 yr B.P. This sequence of emergent marine terraces formed by repeated, catastrophic uplift events related to movement along the Cascadia subduction zone (G. Carver, personal communication).

From the study of large earthquakes in similar tectonic settings worldwide (eg. 1964 M_w 9.2 Good Friday earthquake in Alaska), it is known that regions of subsidence often form adjacent to regions of uplift. Rapid subsidence events may be recorded by "drowned" coastal marshes and forests. Approximately 300 years ago a catastrophic event submerged and killed a mature Spruce forest along the lower reach of the Eel River.

Numerous, large earthquakes have occurred along the coast of northern California during this century. The last large event (1980 M_S 7.2, Eureka earthquake) occurred within the Gorda plate and was similar to the two large aftershocks of the Petrolia earthquake sequence. A overpass along Highway 101 near the College of the Redwoods collapsed during this event, which was centered more than 75 km to the northwest.

Table 1. Earthquakes over Magnitude 6

Event	Date	Time	N. Lat.	W. Long.	Depth	M_S	M_L
1	4/25/92	11:06:04 PDT	40.37	124.31	15 km	6.9	6.4
2	4/26/92	00:41:40 PDT	40.44	124.58	18 km	6.2	6.2
3	4/26/92	04:18:26 PDT	40.40	124.56	21 km	6.5	6.4

EARTHQUAKES

As reported by Shakal et al. (1992), the preliminary locations and magnitudes determined by the USGS and U.C. Berkeley are shown in Table 1. The epicenters of these earthquakes are near the Mendocino Triple Junction where the Pacific, North American, and Gorda plates all converge. The main event was a thrust event that according to the location, depth, strike, and dip occurred along the interface between the Gorda and North American plates. The event triggered a tsunami with a crest height of 0.2 meters in Humboldt Bay and 1.1 meters at Crescent City. The arrival times of the tsunami indicate that it originated near the epicenter. The early aftershocks were located in the North American plate above the interface. The two larger aftershocks occurred within the Gorda Plate as did most of the subsequent aftershocks.

Many of the residents of the area told us that the earthquakes early Sunday morning felt stronger than the main earthquake on Saturday, even though the later earthquakes were smaller magnitude and further away. Some of the recorded motions also showed that a few locations had higher peak accelerations from the aftershocks and many had similar peak accelerations for all three events. We can only speculate about the possible reasons for this apparently widespread feeling of larger motions from the aftershocks: 1) people were awakened during sleeping, so the motions seemed stronger; 2) the strike-slip mechanisms of the later events may have produced stronger motions in some locations; or 3) the rupture up-dip from the main event may have focused seismic energy toward the coast due to directivity.

Strong Motion Records

All information regarding the strong ground motions is from the CSMIP report by Shakal et al. (1992). Strong motion records were recovered from all three of the events with magnitudes greater than 6. The peak acceleration at the Cape Mendocino strong motion accelerograph during the main shock was beyond the measurement range of the instrument for two components. The vertical acceleration was over 1.85g and the horizontal acceleration was over 1.80g. The vertical acceleration is estimated at about 2.2g and is possibly the largest peak acceleration ever recorded. Other large peak ground accelerations were recorded at Petrolia (0.69g) and Rio Dell (0.55g) during the main shock, at Petrolia (0.60g) and Rio Dell (0.55g) during the 00:41 event, and at Petrolia (0.57g) and Rio Dell (0.25g) during the 04:18 event. The Cape Mendocino instrument ran out of film due to triggering from other smaller aftershocks before the two large aftershocks. The Cape Mendocino instrument is located on a hard sandstone site along a road cut in a steep canyon and investigators have speculated that there may be some amplification due to the topography. The instruments at Petrolia and Rio Dell are located on sites with shallow alluvium.

The Highway 101/Painter Street overpass at Rio Dell had a peak horizontal accelerations of 1.23g, 0.91g, and 0.33g on the bridge deck during the three events. The recorded peak horizontal accelerations on the roof of a one story reinforced masonry supermarket building in Fortuna were 0.46g, 0.87g, and 0.28g on the roof during the three events. Recorded accelerations on the roof of a five story reinforced masonry residential building in Eureka structures during the three larger events were 0.34g, 0.18g, and 0.17g.

Tectonic Deformation

Professor Gary Carver and David Valentine of Humboldt State University and John Foss of the U.S. Geological Survey constructed a level line and surveyed evidence of uplift along the coast in the epicentral region of the main shock. About two weeks after the Petrolia earthquakes they noticed a very pungent odor on the beach. Upon investigation they found that the upper zone of intertidal organisms was dead and decaying. This zone acts as very sensitive strain gage and is being used to document the region of uplift. Preliminary results indicate that an approximately 15 km section of the coast was uplifted, from Cape Mendocino to south of Punta Gorda. Uplift reached a maximum of slightly more than 1 meter in the middle, near the main shock, and tapered to the north and south along the coast. The maximum uplift produced during the 1992 earthquake sequence is much smaller than that required to produce emergent marine terraces like those south of Cape Mendocino. These terraces are thought to have been produced by three to four meter uplift events.

GROUND FAILURES

Quaternary faults and Tertiary shear zones in the epicentral region of the main event were closely examined from the air. No evidence of primary surface ruptures was observed. Although no surface ruptures were found, secondary slip may have occurred along a very short section of a graben-forming fault near the crest of Cape Ridge. The main shock occurred deep (15 km) and along a relatively shallow east-dipping plane that would project to the ground surface offshore. The two large aftershocks occurred even deeper and were centered offshore.

Lateral Spread

Lateral-spread failures, confined to the banks and thalweg of a lagoonal-like channel at the mouth of the Eel River, the North Bay, were observed from the air. These failures were clearly displayed as a series of anastomosing fissures that crossed the banks and thalweg of the channel. An unfavorable tide prevented observation of these features during our ground reconnaissance. Failures of this type, too small to be seen from the air, were observed in a few places elsewhere along the banks of the Eel River.

Landslides

Scattered landslides were triggered by the Petrolia earthquake sequence throughout the epicentral region of the main shock and within a broad region extending to the north, south, and east. Landslides were observed from the coast to east of Scotia and from Thompson Hill, along northern margin of the Eel River basin, to south of Petrolia. Nearly all of the landslides were reactivated pre-existing slides. The largest landslides were along the coastal bluffs from the Eel River basin to south of Punta Gorda. These slides fall into two general categories, slumps and bedding plane failures.

Several large hummocky slump failures extended from the bluffs to across the beach, a distance of about 150 meters near Guthrie Creek. One week after the earthquake a significant part of the landslide deposits had been eroded away by wave and tidal action, leaving the water near shore turbid and very muddy.

Bedding-plane failures, which include the largest earthquake-triggered landslides, were found between Guthrie Creek and Oil Creek. Along this northerly-trending coast bedding within the Wildcat Group, a thick sequence of interbedded shallow marine sandstone and shaley mudstone, was favorably oriented to fail along bedding planes; probably within shaley interbeds. Several large relatively intact blocks, each sliding on the one below in a domino-arrangement, characterized the failures of the bluffs.

The road from Ferndale to Petrolia was closed for 8 days due to landslides blocking the road. On May 3, the day the road reopened, we drove to Petrolia and on to Honeydew, then northeastward to Highway 101. A brief description of our landslide observations follows.

In about a half dozen places between Ferndale and Petrolia landslides had apparently blocked the road with debris. With few exceptions, these slides were minor and required a minimal amount of effort to remove the debris. Occasionally limited damage to the roadway was caused by sliding or settlement of probable fill materials on which the road was constructed.

Generally, landslides were found on north-facing slopes. This is particularly characteristic of the more extensive slides. This apparent distribution pattern is not unexpected, given the greater moisture content and generally thicker cover of surficial colluvium due to protective vegetation on north-facing slopes.

The largest landslide observed along the road caused significant damage to an approximately 40-50 meter section of the road between Honeydew and Highway 101. The shoulder and approximately outer third of the roadway failed in a series of elongated slide blocks that stepped downward 3 meters or more below the elevation of the remaining roadway.

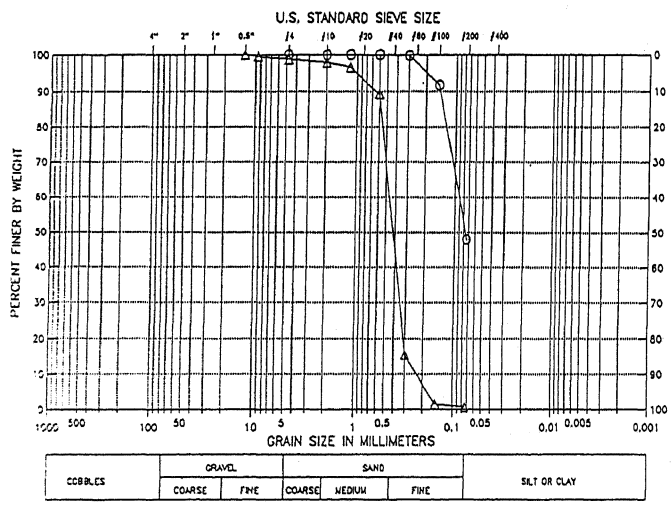
East of Highway 101 at Scotia, a large landslide was observed along the railroad tracks . A section of the Scotia Bluffs failed creating an approximately 40 meter high exposure of bedded sandstone of the Rio Dell Formation. The debris from this slide was cleared from the rail tracks within a week. Other large sections of the Scotia Bluffs have clearly failed in the past, and by analogy may have been seismically triggered. This slide, located about 25 km from the epicenter of the main shock, was among the largest slides that we observed.

Liquefaction

We observed liquefaction from the air and at two locations on the ground. One location where we observed liquefaction was along Riverside Road which runs parallel to the Salt River. The ground water table is only 30 to 60 cm below the surface at this location. The liquefaction appeared to be confined within an old channel of the river that was between the road and the river. There was damage to the road in a couple of locations where the roadway had lost support due to liquefaction of the underlying soils and the edge of the road fill moved laterally and downward. The ejected silty sand was very fine grained and produced many sand boils along a three to four mile stretch of the road. Some of the sand boils showed some slight variation in ejected material with a slightly cohesive material ejected after a cleaner sand with both soils overlain by a very thin layer of coarser sand. A sample of the ejected sand was collected for grain size analysis. The resulting gradation curve (circular symbols) shows that 48 percent of the particles passed the No. 200 (0.074 mm) sieve and only 92 percent passed the No. 100 (0.15 mm) sieve. Liquefaction of such a silty sand shows the importance of using more than just the percent fines in evaluating liquefaction susceptibility of soils.

The other location where we observed liquefaction from the ground was along a backwater (old channel still connected to the river) of the Eel River at the end of Sage Road. The eroded remnants of sand boils, observed within the tidal zone, revealed a faint structure of concentric rings. The ejected sand at this location was poorly graded and coarser than the liquefied sand along the Salt River. This was confirmed by the gradation curve (triangular symbols). This sand only has one percent passing the No. 200 sieve and a coefficient of uniformity of about 2.

In general, liquefaction did not appear to be widespread, and occurred in locations where it would most likely be expected to occur (low lying areas with very recent alluvial deposits and high ground water). The ejected materials were also the type of material most likely to liquefy (non-cohesive relatively uniform sands). A soil that was only two percent passing the No. 200 sieve from being classified as a silt liquefied.



STRUCTURAL DAMAGE

Most of the damage to structures was associated with buildings that were knocked off of their foundations. Damage to bridges and roads was also observed. We did not observe any visible damage to structures in the Eureka and Humboldt Bay areas. The PG&E Humboldt Bay Power Plant recorded about 0.25g peak acceleration and did not have any damage (Dr. William Page, personal communication). We did not observe any damage to the Samoa bridge or to the pulp mills along the spit separating the bay and ocean. From the air we observed the upper few feet of several stacks of lumber were knocked off, but did not see damage to the lumber mills.

Buildings

We observed damaged buildings in Ferndale, Petrolia, Honeydew, Scotia, Rio Dell, and nearby rural areas.

In Ferndale, the worst damage was mostly confined to old Victorian style homes that were knocked off their foundations and to the business district. The damage to the homes resulted from inadequate lateral resistance between the foundation and the first floor. The homes were supported by cripple stud columns without shear reinforcement. We noticed many toppled chimneys on otherwise undamaged homes and several brick chimneys that apparently survived without damage. Damage to the business district included broken windows, buildings off their foundations, and fallen parapet walls.

In Petrolia, homes knocked off their foundations was the most widespread damage observed, but the most complete damage was to a couple of buildings that burned down. The fire station adjacent to one of the burned buildings was severely damaged by shaking due to inadequate lateral resistance at the front of the building because of three large doors for the fire trucks.

In Scotia, we also observed wood frame homes knocked off their foundations. The cause of the damage was again due to the homes being supported on cripple stud columns without lateral resistance. Some had already been jacked up and were supported by temporary timber cribbing until more permanent repairs could be made. Scotia also had a shopping center burn down.

In Rio Dell, we again observed homes off their foundations. Many businesses along the main street were also damaged and posted with Unsafe or Limited Access tags.

Transportation Facilities

Damage to transportation facilities were the result of landslides, lateral spreading due to liquefaction, settlement of fills, damaged concrete at bridge abutments and spalled concrete at a column bent supporting a bridge. Landslides and lateral spreading were discussed above in the ground failures section of this report.

Along the roads to and from Petrolia, we observed many locations where the road had required minor patching where it crossed filled in drainages. In some locations it was obvious that some settlement had occurred as a result of the earthquake. There were also many locations where the road had older patches, so settlement of fill is not only a seismic problem. Unless associated with landsliding, the settlement was usually less than an inch, sometimes only very minor pavement cracking that was patched to avoid intrusion by water. A bridge near Petrolia showed some lateral movement in addition to settling of the approach.

At Rio Dell, we observed both abutments of a freeway bridge over the Eel River and an older bridge between Scotia and Rio Dell over the Eel River. The freeway bridge is a pair of concrete box girder bridges with a trapezoidal cross-section that are supported by three bents (one on each side of the river and one in the center of the river) in addition to the abutments). There was evidence of movement of three to four inches at the abutment. The bridge is supported on rubber bearing pads at the abutments. There was spalled concrete on the guard rails as a result of pounding between the bridge and abutment. The eastern abutment at the south end of the bridge had cracked concrete that will require sealing at the least. There was up to about 6 inches of settlement of the fill under the bridge adjacent to the southern abutment.

The older bridge is parallel to the freeway bridge and slightly to the west. The bridge is supported by several three column bents in addition to the abutments. There was a few inches of settlement that had been patched at the southern approach. There was spalling of concrete at the tops of the columns at the southernmost bent. The corner rebars were exposed at the tops of the columns. There was also damage to cable conduits running under the bridge further indicating differential movements. The bridge abutment was built in 1940 according to an impression in the concrete, but the bridge had reportedly been replaced in the 1960's after being washed out by floods. Lateral reinforcement had been subsequently placed across hinge joints in an earlier seismic retrofit. It is very possible that the retrofit of these hinges saved the bridge from collapse during this event.

CONCLUSIONS

For an event of this size, the damage was limited by the relatively sparse population, limited amount of development, and depth of the main shock. The location of the main event on the subduction zone will be of major scientific interest if confirmed by further analyses. This would represent the first recorded event on the Cascadia Subduction Zone. Clearly, the northern coast of California, Oregon and Washington should prepare for future large earthquakes.

The very large peak acceleration at the Cape Mendocino recording station has once again caused a series of potential explanations for such an extreme value. The importance of peak acceleration in characterizing ground motions has been overemphasized in the past in part because of its use in development of building code design procedures. Then when a large peak acceleration is recorded, there is an effort made to explain why the value is anomalous.

Liquefaction generally occurred where it would be most expected in non-cohesive recent alluvial deposits with high ground water. Very silty soils liquefied which shows that a high percent of fines is not sufficient to rule out liquefaction.

The need for seismic upgrades of existing older residential structures was demonstrated again in this earthquake. The cost for such upgrades is low relative to the potential damage (total loss of structure) or to the cost of earthquake insurance.

Bridges survived this earthquake with minor damage and no collapses. The retrofit of the hinge connections on the older bridge between Scotia and Rio Dell may have saved the bridge from collapse. Newer bridges also suffered damage, but all were still in operation.

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