A PROBABILISTIC LIQUEFACTION EVALUATION OF A RIVERFRONT SITE

by

Alan L. Kropp, Principal Engineer
Alan Kropp & Associates, Berkeley, California

ABSTRACT

A 17-acre site along a major Northern California river was being considered for development, and geotechnical studies were performed. Exploratory borings on the parcel indicated that the site was underlain by silts and sands which might liquefy if a moderate earthquake occurred when the materials were saturated. Therefore, a probabilistic evaluation of the liquefaction potential of the site was performed. The soil densities, the variations in groundwater depth, and predicted seismicity levels for the area were combined in this probabilistic liquefaction analysis. The results of the analysis were combined with estimates of settlement which might be produced by the liquefaction of each soil layer in order to obtain values of ground surface settlement. Based on these analyses, two plots were prepared. These graphs present the estimated areal ground surface settlement versus return period if site soils were characterized by the mean standard penetration resistance values and if the soils were represented by the mean minus average deviation resistance values.

SEISMIC SETTING

The project under study was a condominium, office, and hotel development located in Sonoma County. This county, along with most other coastal areas of California, is recognized by geologists and seismologists to be located in the most active seismic region in the United States. The significant earthquakes which occur in this area are typically associated with crustal movements along well-defined active fault zones which trend in a northwesterly direction. Two such faults pass very close to the property; these faults are the San Andreas fault (passing about 9 miles southwest of the site) and the Rodgers Creek-Healdsburg fault (passing about 12 miles northeast of the site). The San Andreas fault is the dominant fault along the California coastline and produced the great San Francisco Earthquake of 1906, which had a Richter magnitude of 8.25 (1). It is believed that this earthquake represented the largest earthquake which could occur on the section of the San Andreas fault adjacent to the site (2). The Rodgers Creek-Healdsburg fault is one of the number of active faults that lies east of the San Andreas fault movement. This fault is believed to be capable of generating earthquakes with a maximum magnitude of 7.0 (2). Two moderate earthquakes occurred in 1969 on this fault, with the epicenters located about 15 miles east of the site; these earthquakes had magnitudes of 5.6 and 5.7 (1).

SITE CONDITIONS

The site is irregular in shape and includes about 16.7 acres. The majority of the site consists of a river terrace within the Russian River canyon. This terrace is relatively flat and generally lies at an elevation of about 50 feet. In contrast to the majority of the property, the south side of the parcel slopes down into the Russian River channel, and includes a sandy beach area. The slope separating the Russian River portion from the main body of the site is typically about 30 to 40 feet high, and has inclinations on the order of 2:1 (horizontal to vertical).

The subsurface investigation of the site included the drilling of 12 exploratory borings which were extended to depths of 15 to 50 feet. Below scattered fill materials across portions of the site, the soils encountered in the borings generally consisted of firm to very stiff, sandy and clayey silts with interbedded, loose to medium dense, silty sands. A recent geologic map of this area (3) indicates that these materials are recent alluvium which was deposited during the Holocene epoch (the past 10,000 years). Because the alluvium has filled the steeply incised Russian River channel, the alluvial materials may be as thick as 200 to 300 feet (1). Groundwater was encountered in the deeper borings drilled at the site at depths of about 38 to 44 feet (elevations of about 8 to 12 feet).

LIQUEFACTION EVALUATION

Description

Liquefaction is the "transformation of a deposit of cohesionless soils from a solid state to a liquefied state as a consequence of increased pore pressure and reduced effective stress" (4). Often, this transformation results from the cyclic loading of an earthquake and the soil acquires a "mobility" sufficient to permit both horizontal and vertical movement. Soils that are most susceptible to liquefaction are clean, loose, saturated, uniformly-graded, fine-grained sands which lie within 50 feet of the ground surface.

Analytic Assessment

One of the principal means for evaluating the liquefaction potential at a specific location is by a comparison of certain site variables (soil grain size and density, possible ground surface accelerations, and groundwater levels) with similar variables at other sites which have or have not liquefied during past earthquakes (5). Recent studies by both the United States Geological Survey (6) and Seed (7) have confirmed the usefulness of this approach. Both of these studies were performed after liquefaction had occurred in specific areas during recent earthquakes. Using this type of analysis, each team of investigators was able to make predictions about where liquefaction should and should not have occurred, and their predictions generally conformed to the observed results during the earthquakes studied. In our assessment of liquefaction at the site, a similar analysis was performed by evaluating each variable separately, and then performing a combined assessment.

Soil Grain Size

In order to evaluate the range of soils which are susceptible to liquefaction, studies of soil performance in the laboratory, as well as in past earthquakes, were undertaken for the Atomic Energy Commission, and were published by Shannon, et al (8). These studies concluded that only fine-grained sands, or sandy silts, have a grain size which allows pore pressure to increase at a sufficient rate to cause liquefaction. At the Russian River site, soil samples were taken from the borings and tested for grain size distribution; the test results are presented on Figure 1. Five of the samples had a grain size distribution which fell in a very narrow range, while the remaining three samples contained more fine-grained materials. To determine if these materials from the site possess a grain size distribution which is susceptible to liquefaction, these distribution curves were compared to the results of the Shannon study. Based on this comparison, we concluded that a band representing the five samples falls well within the size distribution of soils susceptible to liquefaction, while a band representing the other three samples may possess too much clay to liquefy. However, for our assessment, we have made the conservative assumption that all site soils possess a grain size which is susceptible to liquefaction.

Soil Density

One of the principal tools to assess the density of the soil in this liquefaction evaluation procedure is through the use of the Standard Penetration Reisistance (or "N" value). This resistance value represents the number of blows by a 140 pound weight required to drive a hollow, 2-inch diameter, soil sampling tube into the ground one foot. The N values recorded at the site are summarized on Figure 2 by band widths at each sampling depth which contain the majority of the values obtained. The only values which did not fall within the indicated band widths were isolated high values; these values are represented by individual dots to the right of the bands on Figure 2. Using the values within the bands, a mean value of N was established at each sampling depth, as well as a mean value minus one average deviation (standard deviation was not used because of the small sample involved). It should be noted that use of these values represents a conservative assessment of the soil density, because the high blow counts outside the bands were not used.

Earthquake-Induced Accelerations

In the liquefaction evaluation procedure, a key variable is the level of acceleration at the site caused by an earthquake. To determine the level of earthquake-induced accelerations which might occur at the site, we utilized two recent studies which predict the maximum acceleration values which may occur in relation to a given return period (9,10). The Kiremidjian and Shah study (9) used a Bayesian model to compile isoacceleration maps of California for return periods of 200, 300, 400, and 500 years. The Thenhaus study (10) developed a seismogenic zone map of Western California and the adjacent outer continental shelf to formulate peak bedrock acceleration value maps of the area for return periods of 100, 500 and 2500 years. The data points interpolated from each of the maps for these two studies are plotted on Figure 3, and a peak acceleration versus return period curve developed. It should be noted that the acceleration values predicted by Kiremidjian and Thenhaus for a return period of 500 years are 0.39g and 0.38g, respectively, indicating that these studies are in relatively good agreement.

We should also note that we have assumed that the ground surface acceleration values at the site will be equal to the bedrock acceleration values predicted by Thenhaus, et al (10). Seed, et al (11) has indicated that for bedrock acceleration values in excess of approximately 0.12g, deep cohesionless soils tend to slightly attenuate peak bedrock acceleration values. Therefore, we have made the conservative assumption that the bedrock acceleration values will not be attenuated as they propagate to the ground surface at the site.

Groundwater Level

In order for the soils to liquefy, they must be located below the level of groundwater. In the lower Russian River valley, "water levels in wells near streams fluctuate with stream levels because of hydraulic connection" (12). Further, our conversations with the manager of the local water district indicated that water levels in wells near the Russian River generally reflected the water level in the river. Therefore, in our assessment, we assumed that the groundwater level at the site would be the same as the water elevation in the Russian River adjacent to the site.

Our telephone conversations with the U.S. Army Corps of Engineers provided us with data concerning the annual percentage of time the Russian River is at given elevations at a nearby gaging station. Using other data supplied by the Army Corps (13), we were able to translate this information into a flow elevation versus duration chart for the Russian River adjacent to the site. This chart is reproduced as Table 1. An examination of this chart indicates that the highest water level the river reaches for any significant period of time is about 18 feet below the site (higher levels occur, but remain for only very short perods of time). For perspective, if the river is at or higher than a level of 18 feet below the site for 0.001 of the year, this represents a period of only about 9 hours. Similarly, on the average, the water level in the river is typically at or higher than 30 feet below the site for only about 43 hours each year.

Combination of Variables

As discussed earlier, liquefaction can only occur when loose, saturated sands are subjected to sufficiently high ground accelerations to cause significant increases in pore pressure. Therefore, if high earthquake accelerations occur when the ground is not saturated, no liquefaction will occur. Thus, at the subject site, a moderate earthquake must occur at the same time that a relatively high water level is present in the Russian River.

The Seed procedure (6) computes the ground surface acceleration value required to produce liquefaction for a given soil profile and groundwater depth; this acceleration value is sometimes called the "critical acceleration". To apply this procedure, the subsurface profile between depths of 20 and 50 feet was divided into three 10-foot sections (soils at depths shallower than 20 feet were not considered statistically susceptible to liquefaction because the groundwater level is present so infrequently in these materials). The groundwater level was then varied from depths of 20 to 50 feet to determine the effective stress profile for the different groundwater depths. For each assumed groundwater level, each 10-foot layer below the groundwater was evaluated and the critical acceleration was determined for each layer using mean N values and then using mean minus average deviation N values. By this procedure, it was found that no saturated soils would liquefy with ground surface accelerations of less than 0.15g, and all saturated soils would liquefy with accelerations in excess of 0.40g.

If the critical acceleration occurred when the soil layer was saturated, the soil would then liquefy and would tend to densify. To estimate the magnitude of compression of each soil layer following liquefaction, we utilized the procedure developed at UCLA (14), assuming each soil layer would densify to about 75% relative density.

Combining the peak acceleration versus return period curve, the river level frequency chart, and the total compression settlement of soil layers which were determined would be saturated when the critical acceleration occurred, we have produced Figure 4, which indicates estimated settlement values for various return periods. For example, return periods similar to the life of the development (50 to 100 years) correspond to less than one inch of settlement whether mean or mean minus average deviation N values are used. Large settlement values on Figure 4 (in excess of 5 inches), correspond to return periods of about 20,000 years (mean minus average deviation N values) to 90,000 years (mean N values). Further, we should note that these settlement values could conservatively be assumed to represent ground surface settlement, although the settlement would likely be reduced somewhat by transmission through a minimum of 20 feet of soil.

Consequences

As discussed above, a conservative interpretation of the data could conclude that the settlement values shown on Figure 4 represent ground surface settlement values for the indicated return periods. However, because at least the upper 20 feet of soil would not liquefy, this 20-foot layer would likely perform as a "mat" and tend to equalize settlement values across the site. Thus, the settlement would probably be areal in nature, and very limited differential settlement would occur below any one structure. Since differential settlement, and not total settlement, is typically the primary cause of building distress from settlement, it appears that even the calculated settlements for long return periods might not cause major damage to a well-engineered structure.

The other primary concern during liquefaction is slope failure (or lateral spreading). However, if liquefaction did occur, it would likely take place in the lower portions of the sloping river banks (below elevations of 25 to 30 feet). Because all buildings will be set back a minimum of 30 feet from the top of all slopes, and all buildings will be supported on pier foundations 10 to 20 feet deep, it is not anticipated that any major structural damage would occur if any slope failure takes place.

Historic Assessment

The largest earthquake which would affect the site would probably be a magnitude 8.25 event on the San Andreas fault. Since such an earthquake occurred on April 18, 1906, we have studied the reported consequences in the general vicinity of the site. It should be noted that peak flood levels in the Russian River during the 1905-1906 rainy season reached the 11th highest level since flood recording began in 1897 (15), so the Russian River was probably at a relatively high level at the time of the earthquake. Soil failure, probably as a result of soil liquefaction, was widespread along the Russian River from Healdsburg to the Pacific Ocean (16, 17, 18). However, the accounts of liquefaction along the Russian River generally refer to soil failure within the river's flood plain, and the subject site would probably not be classified as a flood plain in the sense intended by the authors be classified as a flood plain in the sense intended by the authors because of its elevation above most flood levels. Further, these sources did not report any damage in the immediate vicinity of the site. The weekly Russian River Advertiser of April 21, 1906 indicates that very little earthquake damage occurred in Guerneville (the town adjacent to the site). Several brick buildings and chimneys were severely damaged (brick is notoriously susceptible to earthquake damage), but "wooden buildings experienced very little damage." No significant signs of liquefaction (slope failure, sand boils, etc.) were reported in the newspaper account. It should be noted the majority of Guerneville is located on alluvial materials similar to those at the site, and at similar elevations.

Finally, it is our understanding that a resort and inn were in operation on the site in 1906. The primary structures in this facility were located at the top of the bank above the Russian River (where the new inn is proposed). No mention of any damage to this facility is reported in any historical accounts that were reviewed.

CONCLUSION

Both analytical and historical assessments have been made of possible liquefaction at the site. The analytical evaluation indicates that liquefaction is possible, but the return period for such an event is significantly longer than the economical life of the development. Further, any liquefaction would likely result in areal settlement (rather than localized settlement), and well-engineered structures should perform well during areal settlement. The historical assessment concluded that no evidence of liquefaction was reported on the site or in the area during the 1906 San Francisco earthquake, the maximum magnitude event postulated for this area.

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Figure 1 – Grain Size Distribution of Site Samples

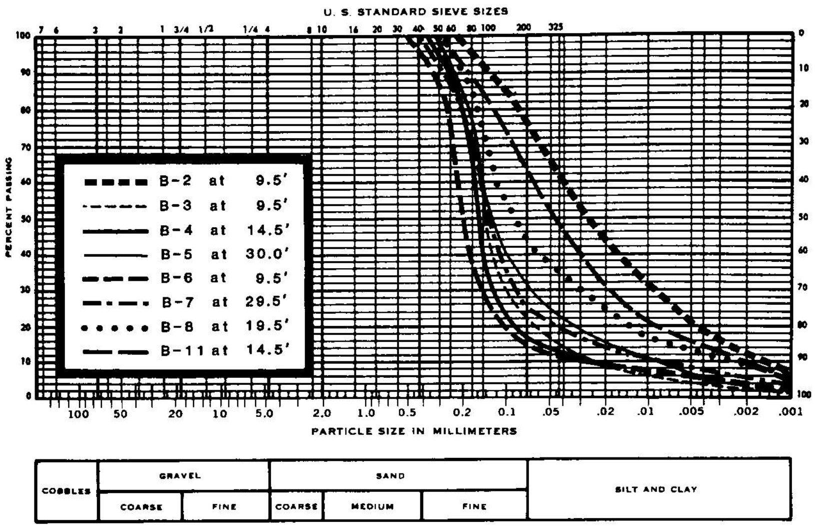

Figure 2 – Standard Penetration Resistance Values of Site Soils

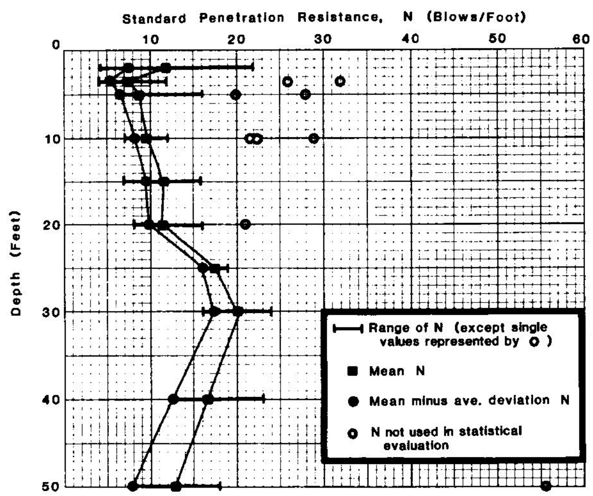

Figure 3 – Predicted Site Accelerations

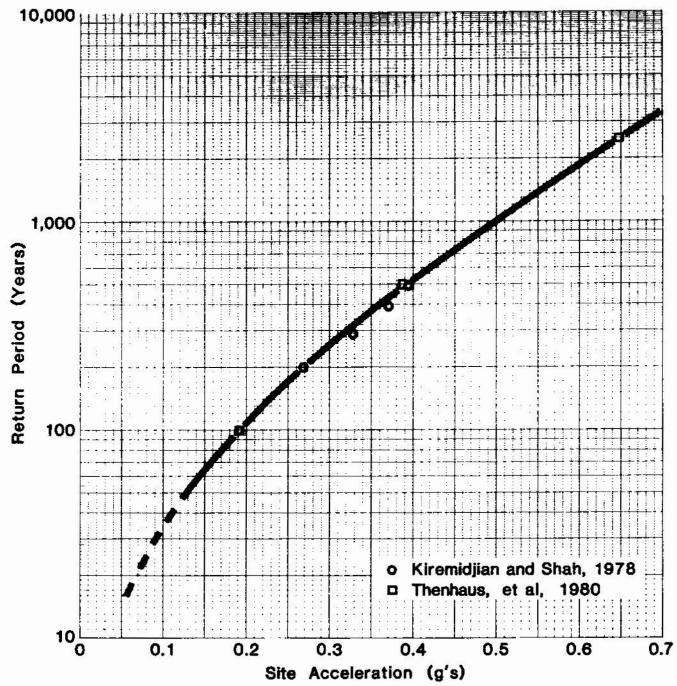

Table 1

Flow Elevation Versus Duration
Adjacent To Site At Russian River

Elevation of River Stage At Site (Feet)	Approximate Depth Below Site (Feet)*	Fraction Of Time
1.0	49.0	0.10
2.7	47.3	0.07
5.5	44.5	0.05
10.0	40.0	0.03
16.0	34.0	0.01
20.0	30.0	0.005
25.0	25.0	0.004
32.0	18.0	0.001

* Assumes entire site is at Elevation 50 (Feet)

Figure 4 – Predicted Liquefaction Settlements