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SYNOPSIS A large landslide in San Jose, California, has experienced displacements during past earthquakes. Future earthquakes on the Hayward fault, which is located about a mile east of the slide, are expected to cause larger displacements. Potential deformations induced by a major earthquake (M 7) on the Hayward fault were evaluated using a non-linear dynamic finite element analysis.

PROJECT DESCRIPTION AND GEOLOGIC SETTING

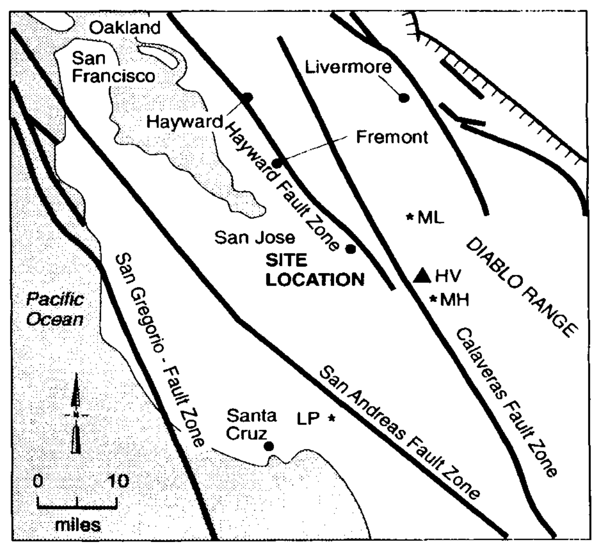
This study was conducted to assess the potential risk of earthquake induced landslide movement beneath the Penitencia Water Treatment Plant (PWTP). The plant is on an active landslide located on the lower slopes of the western foothills of the Diablo range as shown in Figure 1. Additional facilities are required to bring the plant into compliance with new, more stringent federal and state drinking water regulations. The objective of this study was to provide an evaluation of the earthquake induced landslide displacement.

The topography of the site around the PWTP is gently sloping at about 8 horizontal to 1 vertical. The results of geologic mapping (Nilsen and Brabb, 1972) indicate that the PWTP is located on a very large landslide. Coyle (1984) indicates that the site is located on sedimentary deposits of the Santa Clara Formation, of Plio-Pleistocene age. The Santa Clara Formation abuts sandstone and conglomerate of the Berryessa Formation, of Cretaceous age, to the east of the site.

The northwesterly trending Quimby (Clayton) fault passes a few hundred feet to the east of the site, and may be responsible for having diverted the westerly flowing Dutard Creek to a southerly course. Coyle (1984) presents a geologic cross-section of the foothill area, showing the locations of the local faults. The Crosley fault is about 1,000 feet to the north of the site, and the Berryessa fault zone is about 500 feet wide and passes 1,000 feet to the northeast of the PWTP (Figure 2). The Hayward fault is about 4,500 feet to the northeast of the site.

PAST EARTHQUAKES AND SLOPE DEFORMATIONS

Three past earthquakes that had a significant impact on the landslide were identified as being closely correlated to sharp changes in the displacement rate of the slope. They were the Morgan Hill earthquake (1984, M6.2) 11 miles south-east of the site, the Mount Lewis earthquake (1986, M5.7) 10 miles north-east of the site, and the Loma Prieta earthquake (1989, M7.1) 24 miles south-west of the site. Slope displacement data were obtained from 27 inclinometers installed within the landslide, and from 10 surveyed monuments and survey lines along the slope surface.



LEGEND

ML	Mt. Lewis Earthquake Epicenter
MH	Morgan Hill Earthquake Epicenter
LP	Loma Prieta Earthquake Epicenter
HV	Halls Valley Recording Station

Figure 1. EARTHQUAKE EPICENTER AND RECORDING STATION LOCATIONS

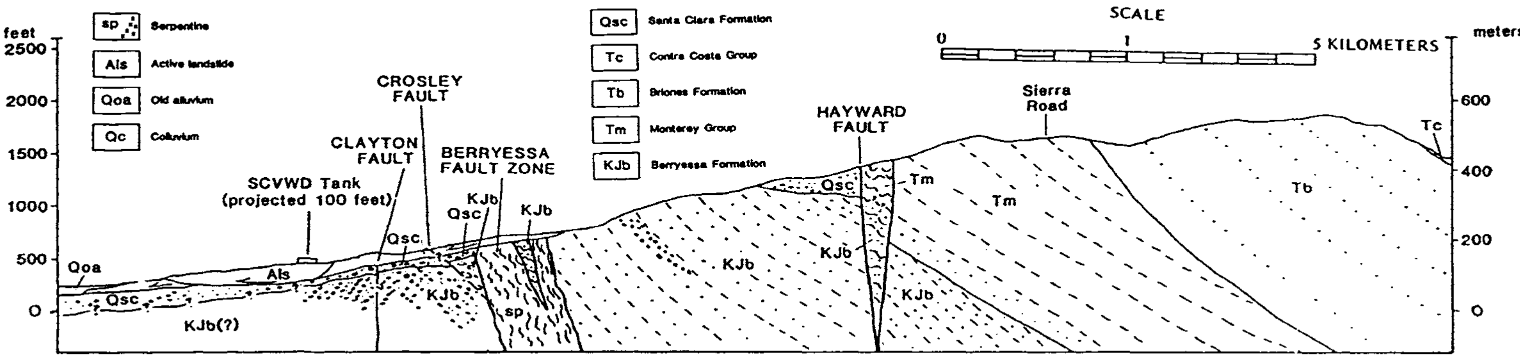


Figure 2. Geologic Cross-Section, after Coyle (1984)

The closest strong-motion accelerograph station to the PWTP site is the Halls Valley-Grant Ranch Park Station, located about 7.2 miles south-east of the project site. Recorded ground motions at the Halls Valley-Grant Ranch Park station from the three earthquakes were used to perform the calibration analysis of the behavior of the landslide. The horizontal component which was the closest to the east-west direction (corresponding to the sliding direction), was selected from each earthquake to perform the analysis. The location of the Halls Valley-Grant Ranch Park station, the project site, and the estimated epicentral location of the above earthquakes are shown in Figure 1.

DEFORMATION ANALYSIS METHODOLOGY

The behavior of the slope during past earthquakes was first reviewed to evaluate whether strong correlations existed between recent past earthquake events and recorded changes in the slope displacement rate. A flow-diagram illustrating the methodology and approach used in the deformation analysis is presented in Figure 3. The method consists of three steps as described below:

- Selection of Slide Geometry and Material Characterization (Step-1) - This step of analysis consisted of evaluating the slide geometry using data from field instruments, and characterizing the material properties using in situ and laboratory test results.

- Model Calibration (Step-2) - In this step, the calculated deformations from one past earthquake were compared to the recorded deformations. If the observed and the calculated displacements did not match, the material strength curves for each soil layer were adjusted proportionally to match the recorded target strain. The calibration procedure is schematically illustrated in Figure 3.

- Slope Deformation (Step-3) - In this final step, the slide displacement was estimated for a magnitude 7 event on the Hayward fault using the material properties obtained from step 2.

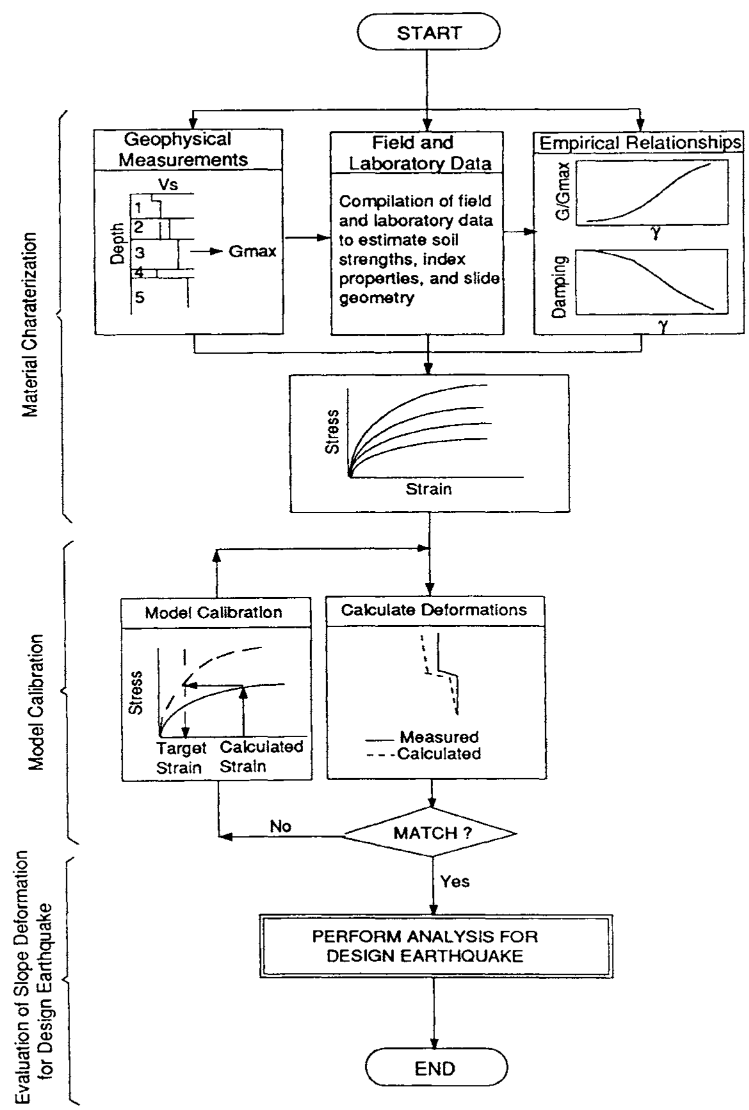


Figure 3. Methodology for the Calibration Analysis

The analyses of the slope deformation were performed using the two-dimensional dynamic non-linear finite element code DYSLAND (Salah-Mars, 1989). The selected slide mass geometry was discretized into a series of four- and three-node isoparametric plane-strain elements. The equations of motion were solved in the time-domain using an implicit unconditionally stable corrector algorithm based on the Newmark method. The material non-linearity was represented by a multiple nested virtual surface plasticity model following a kinematic hardening rule (Salah-Mars, 1992).

The motions recorded at the Halls Valley-Grant Ranch Park station from previous earthquakes were scaled for distance effect using five published attenuation relationships. The scaled free-field ground motions were used to generate the input time-histories at the boundaries of the FE mesh using the computer code SHAKE (Schnabel et al., 1972). The input motions for the dynamic analysis at the base and the sides of the FE mesh were generated by deconvolution at each boundary node. The mesh was progressively extended sideways until the deformation of the slide mass was no longer sensitive to the boundary distances. The final mesh was then retained for the calibration study using the three past earthquakes and for the magnitude 7 earthquake on the Hayward fault.

In addition to the FE method, simplified methods to estimate the potential slide movement were used. These methods included the Makdisi and Seed (1978) simplified procedure, and the Newmark sliding block method (1965).

LANDSLIDE GEOMETRY

The review of the geologic and geotechnical data which included surface features, photo interpretation, distress of existing facilities, survey monuments, inclinometer readings, piezometer readings, and faults in the area, were used to estimate the geometry of the landslide on which the PWTP is located. Available inclinometer and survey monument data were compiled and reviewed to estimate the depth, rate, and direction of slope movement in the area of the suspected landslide beneath the PWTP.

The location of the landslide toe was inferred from the available survey data, air photo interpretation and reports of damage to improvements. The position of the slide plane beneath the body of the landslide was estimated using available inclinometer data. The section of the slide mass selected for analysis is presented in Figure 4. It appears that the inclination of the slide plane is almost horizontal from the toe to an inclinometer about 1,430 feet away. Further upslope, the data are inconclusive regarding the location of the slip plane. However, it is likely this inclinometer does not reach the main slip surface which is projected on Figure 4 to be at a depth of about 300 feet or more. In the absence of evident headscarp, we assumed that steeply inclined surfaces of weakness representing the two nearest faults that traverse the hillslope to the east of the PWTP to be the possible headscarps of the slide. From the branching of the slide plane, two "head scarps" are assumed to exist. The lower head location is associated with the upper branch of the slide plane and is located in the Quimby fault zone; the second is associated with the lower branch of the slide plane and is assumed to correspond with the Berryessa fault zone. Both assumed head scarp locations are shown in Figure 4.

MATERIAL CHARACTERIZATION

The soil properties of the landslide were compiled, from the results of field investigations and laboratory tests performed by others during previous studies. The limited existing soil property data were supplemented by two downhole geophysical soundings performed at exciting inclinometer casings. In addition to the material index and strength properties, the deformations recorded by the inclinometers were also used to back calculate the material properties of the landslide and underlying formation during the FE calibration analysis. The slope response during past earthquakes was considered a "true scale" test to which the FE model could be calibrated.

The materials composing the sliding mass consisted of four soil layers, the formation underlying the slide consisted of two soil layers, and the slide plane material was represented by one soil type. The selection of the soil layers was based

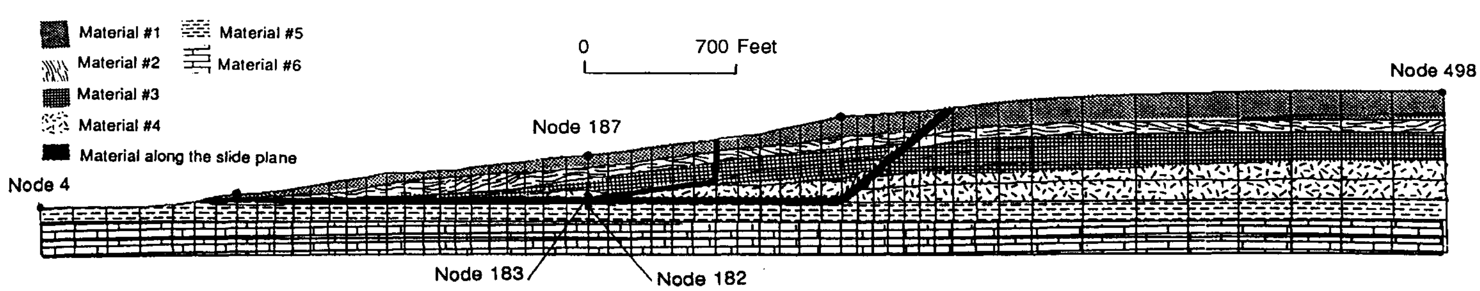


Figure 4. Soil Stratigraphy and Slide Plane used in FE Model

on similar index properties (plasticity index, unit weight, water content), shear strength, and shear wave velocity. The material properties used for this study are summarized in Table 1 for the different soil layers.

Table 1. Material Properties Estimated for Dynamic Analysis

Material Type	Total Unit Weight (pcf)	Vs (1) (ft/sec)	Vp (2) (ft/sec)	Shear Strength (psf)
1	125	700	2,500	3,670
2	133	870	6,425	6,030
3	139	1,280	6,425	13,660
4	145	1,500	6,425	19,530
5	145	2,160	4,500	40,540
6	145	2,600	4,500	58,730
Slide Plane	129	1,500	5,250	Su/P = 0.143 (3) Su/P = 0.205 (4)

Notes:
1. Shear wave velocity
2. Compression wave velocity
3. After limit equilibrium
4. After FE calibration

A limit equilibrium analysis was performed to estimate the undrained shear strength along the slide plane. The strength of the material along the slide plane was back-calculated from limit equilibrium analysis by setting the factor of safety equal to one for the assumed landslide geometry. Spencer's method for sliding wedges coded in the computer program UTEXAS3 was used for this purpose. The back-calculated average normalized shear strength ratio (S_u/P) was equal to 0.14. This value represented the initial undrained strength of the material along the slide plane used in the FE analysis.

The small strain shear moduli (G_{max}) for the different soil layers used in the analysis were estimated from the results of the geophysical soundings performed at the location of two inclinometers which extend about 40 feet and 60 feet below the slide plane, respectively.

The shear modulus ratio (G/G_{max}) versus shear strain curves were based on the shear modulus reduction model presented by Vucetic and Dobry (1991). The G/G_{max} reduction curve corresponding to a Plasticity Index (PI) of 50 (from Vucetic and Dobry, 1991) was selected for the slide mass and its underlying formation based on test results. These curves were used to generate the initial stress-strain relationships for the calibration study.

The damping coefficient used in the model consists of two components. At the very low strain level (elastic range) a viscous damping ratio of about two percent was assumed consistent with Seed and Idriss (1970) and Vucetic and Dobry (1991) data. Beyond the elastic range, a hysteretic strain-dependant damping associated with the energy dissipation via material non-linearity is internally generated in accordance with the material stress-strain relationships used. The damping curve was used in the soil column response to generate the boundary input motions from the computer program SHAKE (Schnabel, et. al., 1972).

RESULTS OF CALIBRATION ANALYSIS

The displacements during past earthquakes were documented by field data collected from inclinometer readings and electronic horizontal distance measurement (EDM) surveys of the landslide surface. Generally the surface displacements recorded during past earthquakes indicate an average slope displacement of about 1/2 inch during the Morgan Hill earthquake (Tepel, 1985), which is believed to have generated a peak horizontal ground acceleration (PGA) of about 0.17g at the site. During the Mount Lewis earthquake, nearly 3/4 inch of slope displacement occurred for a corresponding PGA of about 0.14g. Since most of the inclinometers located in the mid-portion of the PWTP site had failed before or possibly during the 1989 Loma Prieta earthquake, fewer data were available for this event than the previous earthquakes. However, inclinometers installed between 1985 and 1986 indicated an average yearly slope displacement of about 0.57 inches.

The Mount Lewis earthquake was used as the calibration earthquake. The calibration consisted of an iterative process during which the stress-strain curves representing each soil layer were adjusted after each computer run in the manner shown in Figure 3, until a "reasonable" match was obtained. The stress-strain curves producing displacements of 0.50 to 0.93 inches along the slide plane were considered reasonably close to the recorded values of 0.65 to 0.90 inches. Selected displacement time-histories at few nodes along a vertical line through the middle of the slide are shown in Figure 5. The site response indicates a ground amplification factor of about 2-1/2 for the Mount lewis earthquake.

For the same properties, the program was used to simulate the slope response to the 1984 Morgan Hill earthquake. This case produced slope deformations that varied between 0.38 to 0.51 inches. These values are in good agreement with the recorded 0.31 to 0.67 inches of displacement surveyed between March 19 and March 24 at four surface monuments. Selected displacement time-histories at few nodes along a vertical line through the middle of the slide are shown in Figure 6. The site response indicates a ground amplification factor of about 2 for the Morgan Hill earthquake.

A similar analysis with the above material properties was performed using the input motions from the 1989 Loma Prieta earthquake. The analysis resulted in slope deformations varying between 0.23 and 0.87 inches. The

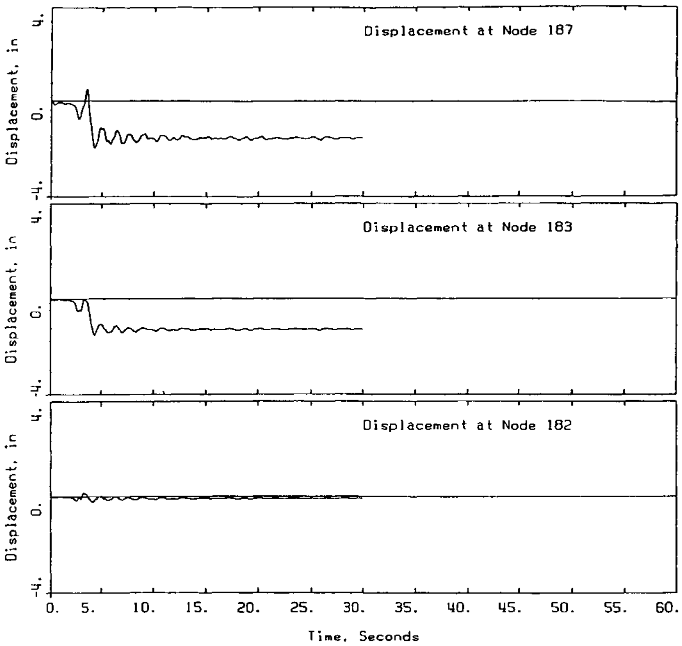


Figure 5. Displacement Time-History at Selected Nodes for the Mount Lewis Earthquake (1986)

estimated values are in good agreement with the recorded 0.18 to 0.72 inches of displacement recorded at the slip surface. Selected displacement time-histories at few nodes along a vertical line through the middle of the slide are shown in Figure 7. The site response indicates a ground amplification factor of about 3 for the Loma Prieta earthquake.

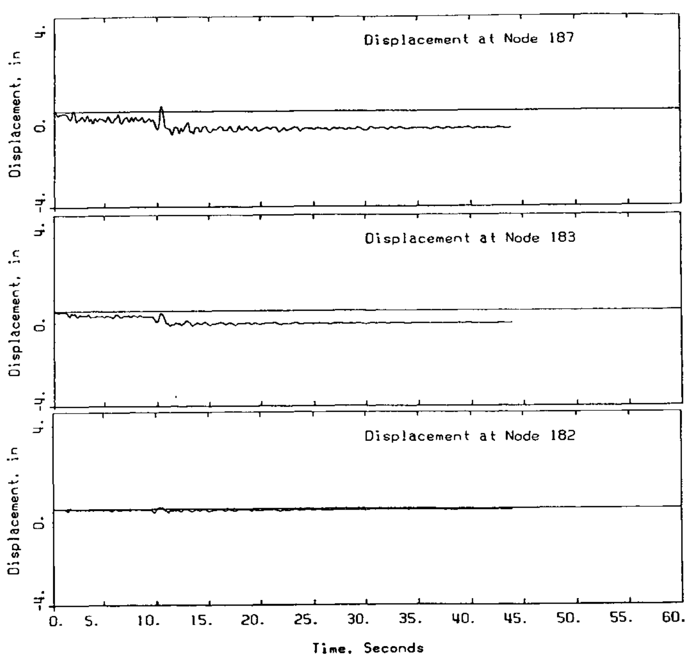


Figure 6. Displacement Time-History at Selected Nodes for the Morgan Hill Earthquake (1984)

PREDICTION OF THE SLIDE DISPLACEMENT

Semi-synthetic accelerograms were generated at the site by matching a response spectrum representing the near-field effects for a magnitude 7 earthquake on Hayward fault (WCC, 1992).

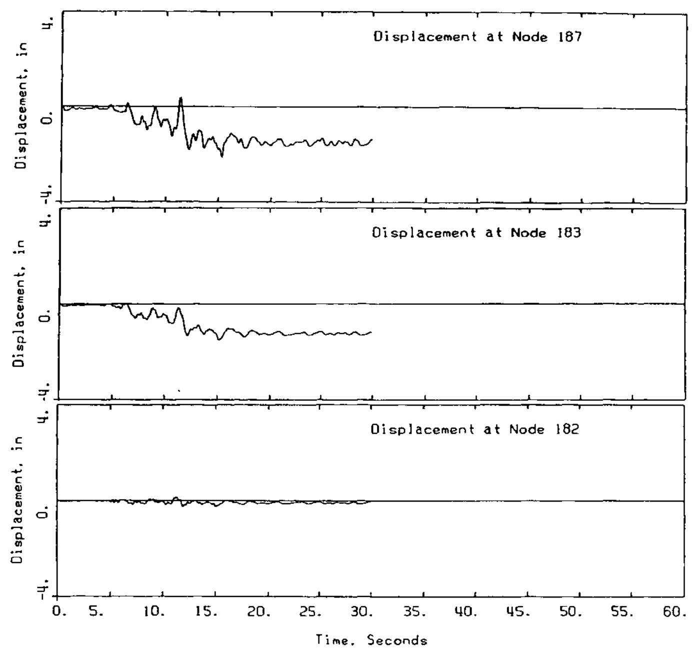


Figure 7. Displacement Time-History at Selected Nodes for the Loma Prieta Earthquake (1989)

The acceleration time-history at the base and the sides of the finite element mesh were calculated using a similar deconvolution procedure as for the past earthquakes. The calculated slope deformations ranged between 1 and 2 feet as a result of a magnitude 7 earthquake on the Hayward fault. Some representative displacement time-histories along the assumed slide surface and along a vertical line through the middle of the assumed slide mass are shown in Figure 8. The site response indicates a ground amplification factor of about 1.4.

The earthquake-induced slide deformation of the PWTP site was also estimated using the simplified procedure by Makdisi and Seed (1978) and the Newmark sliding block (1965) method. These methods produced deformations that ranged between 1 and 6 feet, and 1 and 3 feet respectively.

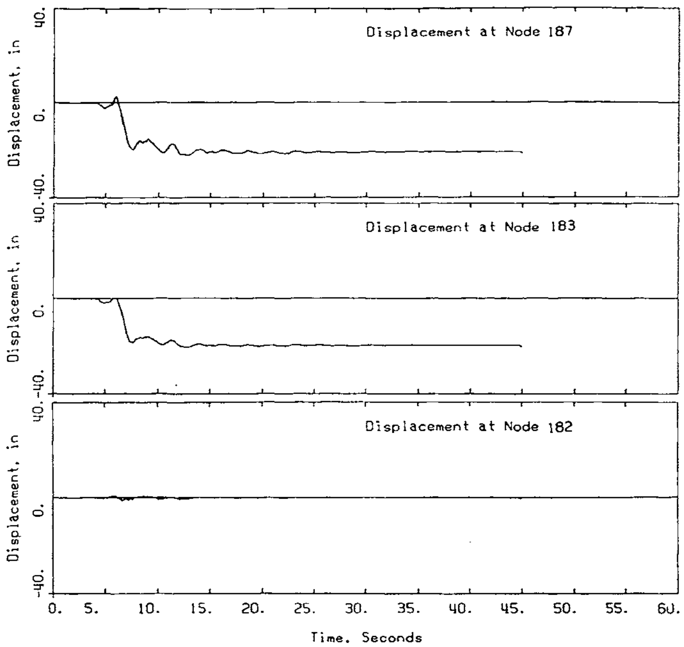


Figure 8. Displacement Time-Histories at Selected Nodes for the M 7 Earthquake on Hayward Fault

CONCLUSIONS

The numerical simulation of slope displacements during past earthquakes were well matched by the finite element model. The results of the finite element simulation are also in reasonable agreement with accepted simplified and empirical procedures. The simplified procedures tend to predict larger ranges of deformation (1 to 6 feet) as opposed to the finite element method (1 to 2 feet). The shear strength ratio (S_u/P) after calibration is in good agreement with values measured by Nelson (1992) on Santa Clara Formation samples (S_u/p = 0.205).

This approach proved to be a valuable tool to evaluate potential deformation of a slow moving slide and to assess whether the expected deformations from a major earthquake will be tolerated by the existing and future costly improvements at the PWTP.

The calibration method implicitly accounts for the effects of potential insitu stresses that may be prevalent at the site. The insitu stresses may have different origins, among which are: 1) possible slide induced shear stresses; 2) actions from interactive slides; 3) hydrostatic pressure from water built-up in the sheared Clayton (Quimby) fault from Dutard Creek, and 4) 3-D effects. Other parameters may have significant effects on the outcome of the analysis. Among these is the landslide geometry. The head-scarps were inferred to be located along weak planes corresponding to the location of existing faults mapped upslope of the site.

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