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ASSESSMENT OF GROUND DEFORMATION DUE TO SOIL LIQUEFACTION IN THE SAN JOSE, CALIFORNIA AREA BY USING GEOTECHNICAL IT

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ABSTRACT

This paper presents a study on the permanent lateral deformation and potential flow of ground due to soil liquefaction in the San Jose area of Northern California. Assessment of ground deformation by lateral flow is made through the use of a set of geotechnical Information Technologies, including GIS, LiDAR, and FEM analysis. By using a geotechnical database consisting of approximately 600 borehole logs, geological data, and topographic data such as DEM of the San Jose area, the key geotechnical and geological features were identified that indicate the locations most susceptible to lateral flow due to liquefaction. A FEM analysis of lateral flow is made to estimate the lateral flow of ground during the 1989 Loma Prieta earthquake, and earthquakes that occurred during 1868 and 1906. The results calculated for the Loma Prieta earthquake at Coyote Creek are in good agreement with the conclusion obtained by a previous study. The results of this study show the usefulness of various IT tools available for geotechnical earthquake hazard analysis.

Introduction

Because urban infrastructure can be so extensive, and so important to the functioning of large cities, risk assessments that judge how infrastructure and lifeline networks will respond to natural disasters are being performed throughout the world. A wide variety of infrastructure, such as highways, airports, water and gas pipes and communication lines are constructed in or on ground that may be shaken very intensively during earthquakes. The disruption of lifelines such as gas, water and communication lines results in catastrophic consequencse to the activities of large cities, and therefore the everyday functions of these infrastructures need to be monitored by a very sophisticated network of sensors and GIS systems in order to respond immediately in the case of emergency.

The amount of information being gathered from monitoring of such infrastructure networks is vast, but usually includes little information on the ground or soil where these

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infrastructures are constructed. There is, however, a very large amount of information available to the public, including elevations, geological and hydrological data, and the geotechnical data as contained in borehole exploration reports. A system to integrate such valuable ground data is needed, and such a system could be used to assess the seismic risk of various infrastructure components to ground failures under various earthquake scenarios.

This paper examines the use of various geotechnical information and technologies to assess the seismic risks in urban areas where a large accumulation of past geotechnical studies are available. Geotechnical seismic hazard studies using a large geotechnical information database, the Kobe Jibankun, have been made after the Great Hanshin-Awaji Earthquake in Kobe to understand why there was a narrow zone of intensified housing damage (Tanaka and Okimura, 2001). A similar approach was used here to study the ground failure risks in the San Jose area of Northern California, where a high possibility of liquefaction exists. The geotechnical information examined herein, include 600 borehole logs collected by the California Geological Survey (*http://gmw.consrv.ca.gov/shmp/index/htm*), a digital elevation map produced by the US Geological Survey (found on San Francisco Bay Area Regional Database-BARD), and a geotechnical Finite Element Model (FEM) program, ALID (Analysis for Liquefaction Induced Deformation) (Yasuda et al., 1999) is used to predict the amount of permanent lateral ground movement.

Previous Studies on Lateral Flow of Ground in the San Jose Area

The 1989 Loma Prieta Earthquake produced very extensive liquefaction-related damage in areas surrounding the San Francisco Bay, for example, those at Oakland and at San Francisco's Marina district. However, the liquefaction was not so severe in the area near San Jose, although the distance to the ruptured fault was much less for San Jose than for Oakland and San Francisco. Because of this abnormal observation, Egan et al., 1992 studied the reason that extensive liquefaction and lateral flows did not occur at Coyote Creek near San Jose. The review of past earthquake damage, including that of the 1868 Hayward fault earthquake and the 1906 great San Franicsoc earthquake, showed that more extensive liquefaction was observed at Coyote Creek during the earlier earthquake events.

Figure 1 Location of Coyote Creek (data from Google Map)

Figure 1 shows a plan view of the study site at Coyote Creek of Egan et al., (1992). It was reported that the 1868 and 1906 earthquakes caused significant ground movement at the site. However, there were no signs of liquefaction and no significant lateral flows at the site during the Loma Prieta earthquake. Eleven CPT soundings and four borehole investigations (including three piezometer observations) were made to examine the liquefaction resistance of ground in this area. These detailed geotechnical studies showed that the ground at the site consists of layers of medium dense clayey sands, loose to medium silty sands, firm to stiff highly plastic clays, and dense sand and gravel to a depth of 12-14 meters. The ground water level may vary between 1.5m to 4m, depending on the amount of precipitation over the preceding year(s). The maximum acceleration at the ground surface was estimated by Egan et a. (1992) to be 0.17g at the site during the Loma Prieta earthquake, while at the accelerations during the 1868 and 1906 earthquakes were estimated to be 0.40g and 0.28g, respectively.

The susceptibility to liquefaction at the site was evaluated by Egan et al. (1992) under each of these earthquake scenarios and the range of ground water conditions. The liquefaction resistance profile of ground with depth was compared with the induced shear stresses for various levels of shaking and groundwater. The main conclusions of their study were: 1) the ground below the water level is moderately to highly susceptible to liquefaction, and 2) the absence of liquefaction during the Loma Prieta earthquake is the combined result of moderate ground shaking (i.e., PGA=0.17g), relatively short duration of shaking, and lower than historical groundwater levels.

Reassessment of Lateral Flows of Grounds in the San Jose Area

The Egan et al. (1992) study was conducted through a set of field investigations and liquefaction analyses on the soil profiles in individual boreholes. As noted earlier, there are vast amounts of data available to the public, for example DEM, LiDAR data and geotechnical data in borehole GIS database (e.g. http://gmw.consrv.ca.gov/shmp/). A detailed LiDAR study using an air-borne LiDAR is available for the San Francisco Bay (Foxgroverand Jaffe, 2005). However, the area surveyed is limited to near-shore areas and, unfortunately, the liquefaction

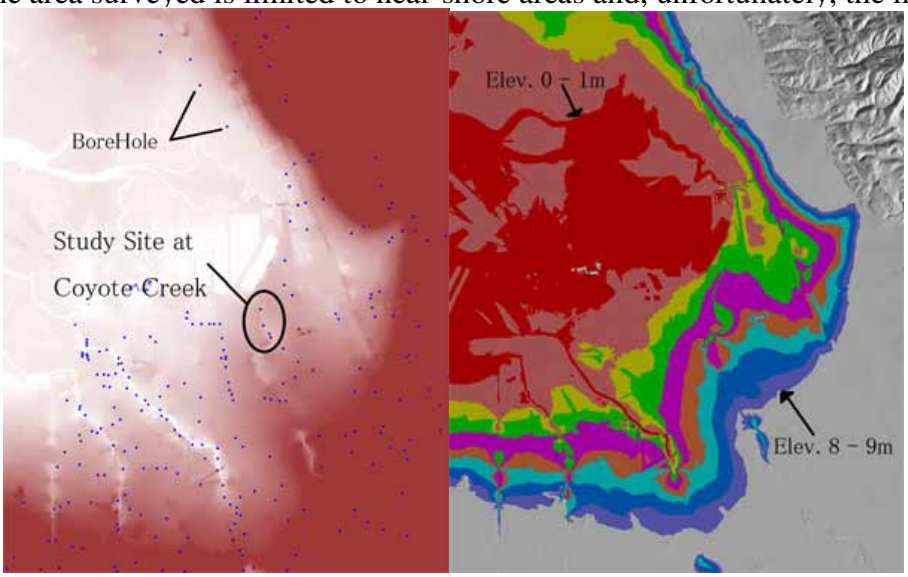
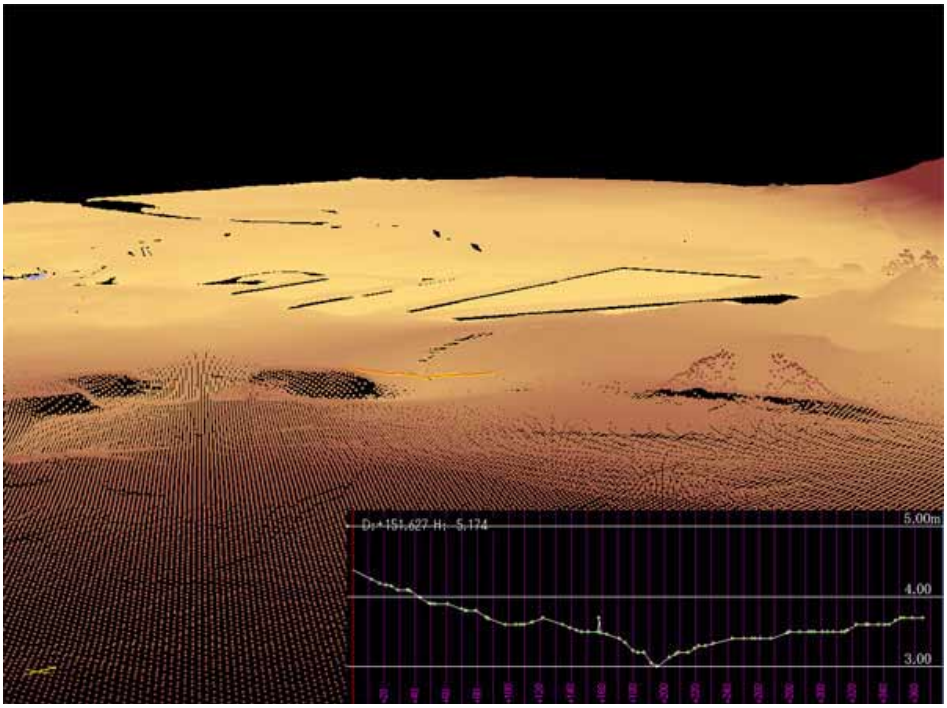


Fig 2 DEM (Digital Elevation Map) and Borehole Data near the study site.

sites studied in this paper were not covered. In addition to using digitized geotechnical data, there is a benefit to evaluating the amount of ground movement due to both ground shaking and liquefaction by using some form of numerical analysis. Given the availability of such valuable geotechnical data and analytical techniques, it was decided to perform a similar study to Egan et al. (1992) on ground lateral flows at Coyote Creek and at Guadalupe River near the San Jose airport. The difference between this study and the earlier work of Eagan et al. (1992) is the use of DEM, borehole database, and FEM deformation analysis for assessing the liquefaction susceptibility of the study sites.

Figure 2 shows the available DEM and borehole GIS data in the Coyote Creek area. The blue dots denote the location of boreholes. A bird's-eye view of the study site at Coyote Creek can be seen in Figure 3, which was produced using the available DEM and borehole GIS. The DEM data is based on 10m x 10m mesh, and the power of having such fine digital elevation maps is clearly seen. As can be seen from Figure 3, a cross section across Coyote Creek for lateral flow analysis can be drawn easily by specifying the two end points of the section. For the previous study of liquefaction susceptibility by Egan et al. (1992), the cross section was drawn



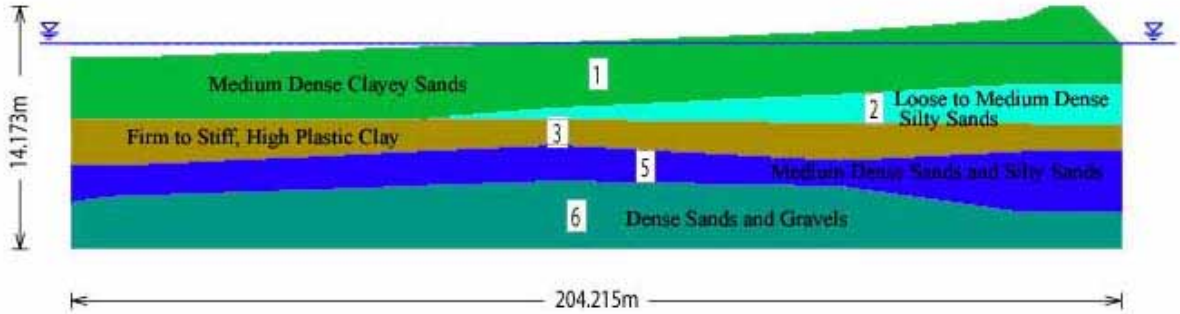


Fig.4 Geological Cross Section at Coyote Study Site by Egan et al. 1992

by using site-specific survey data. Figure 4 shows a cross section of the west bank that is based on the field investigation (CPT and boreholes) data. As can be seen from Figure 4, the stratigraphy at the site consists of five soil layers; the layers most susceptible to liquefaction are the second layer of loose to medium dense sands and the fourth layer of medium dense silty sands. It is also clear that the layers are nearly parallel to the ground surface, which slopes gently away from the riverbank. There is a slight discrepancy in the surface profile between those shown in Figs. 3 and 4, and such discrepancy may be due to the errors in either the DEM data or of field survey, or due to some modification of ground surface such as field cultivation. It was decided to perform a FEM analysis based on the cross section shown in Fig.4 that was constructed by Egan et al. (1992).

For the FEM analysis of lateral flow due to liquefaction, a number of computer programs are available. The most elaborate program uses an effective stress elasto-plastic soil model to perform a dynamic response analysis. The input geotechnical parameters, however, for such elaborate programs are difficult to obtain and/or define. Thus, in this study, an attempt was made to perform the deformation analysis of lateral flow using a computer program that was developed specifically for that objective by Yasuda et al. (1999). The deformation analysis was carried out for three different PGAs that represent the estimated intensities of 1989 Loma Prieta (0.17g), the 1986 (0.40g) and 1906 earthquakes (0.28g).

FEM Analysis of Ground Lateral Flow at Coyote Creek

Yasuda et al. (1999) have described the details of their methodology for analyzing the permanent ground movement caused by liquefaction, ALID (Analysis for Liquefaction Induced Deformation). The principals of their methodology are as follows: 1) establish stress-strain relationships of various soils under undrained simple shear after being subjected to various degrees of liquefaction (i.e., under various level of FS=Seismic Resistance/Seismic Shear Stress with FS<1.0). The increasing slope of deformation in a stress-strain curve immediately after undrained shear is very small, but it will increase after a certain threshold strain. Thus a bi-linear stress-strain curve is usually assumed (Yasuda et al. 1995). 2) Analyze the initial stress state of the sloped ground under static loading before the seismic shear. 3) By analyzing the seismic response of ground under a target earthquake, assess the FS value of soil. 4) Compute the ground movements due to liquefaction by applying the post-liquefaction stress-strain curve for the level of FS induced by the scenario earthquake.

The FEM analysis of ground lateral flow induced by liquefaction was made by using the geological section shown in Figure 4. The soil layers that are assigned to liquefy were the second layer of loose to medium dense sands and the fourth layer of medium dense silty sands, as discussed earlier. The loose to medium dense sands are given higher potential of liquefaction by reducing the friction angle to 25 degrees, and the medium dense sand with moderate liquefaction potential is assigned a friction angle of 30 degrees. These values are selected based on the site investigation data as reported by Eagan et al.(1992). Other soil layers are assumed to non-liquifiable. The stress-strain relationship for the liquefied sands was assumed to have a similar relationship to ones reported by Yasuda et al. (1999). The analysis was performed by applying three PGAs to compare the amounts of permanent ground movements due to liquefaction under the different historical earthquake loadings. It may be noted that, by assigning three different PGAs, the FS value for two sands at various depths can be estimated by using an empirically established shear stress reduction with depth curve.

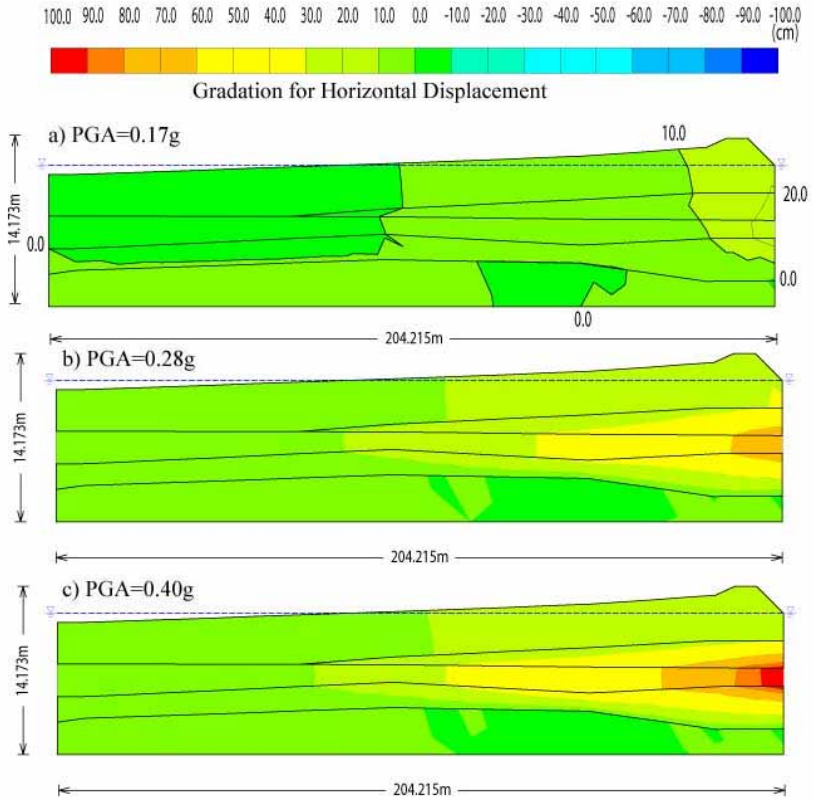


Fig. 6 Variation of Horizontal Displacement at Coyote Creek, a) 0.17g, b) 0.28g, c) 0.40g

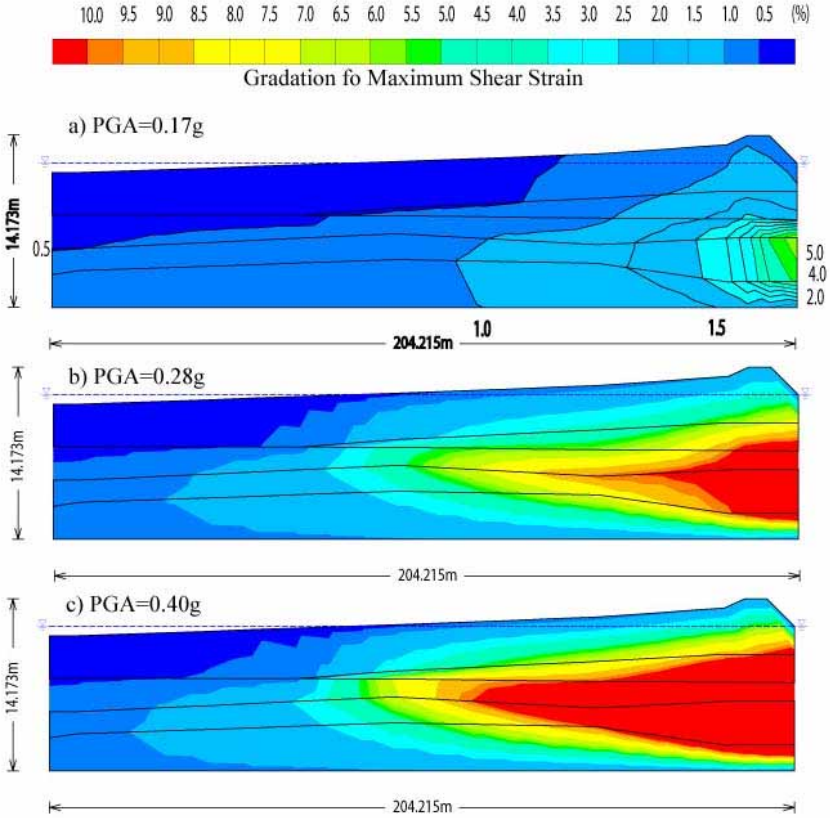


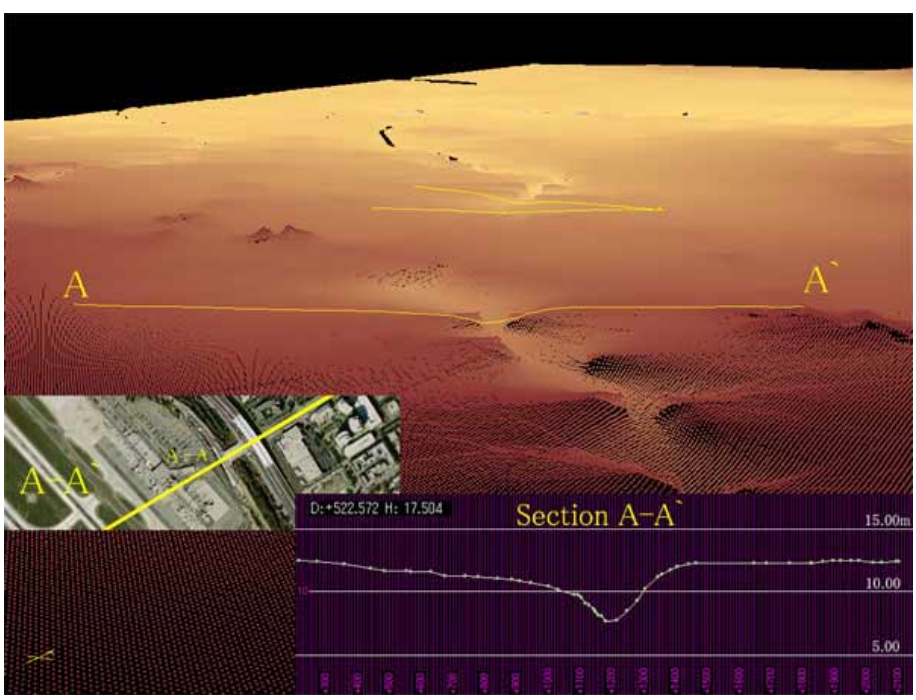
Fig. 7 Variation of Maximum Shear Strain at Coyote Creek, a) 0.17g, b) 0.28g, c) 0.40g

Figures 5a to 5c show the variation of horizontal displacement estimated by FEM analysis for three different PGAs (0.17, 0.28, and 0.40g). Similarly, Figures 6a to 6c show the variation of induced shear strain for the three cases. The results from the Loma Prieta earthquake case (i.e., PGA=0.17g) show much less ground movement, both in terms of horizontal displacement (Fig. 5a) and maximum shear strain (Fig. 6a), as compared with other two cases of more intense shaking from earthquakes in 1868 and 1906. For example, the maximum horizontal displacement and the maximum shear strain under the Loma Prieta earthquake are 20cm and 4-5%, respectively. The two other earthquake scenarios (i.e., 1868 and 1906 earthquakes) show very large estimated displacements, for example more than 1m for the 0.4g case, and maximum shear strain in excess of 10%. The earlier study by Egan et al. (1992) showed that the liquefaction susceptibility is marginal for the Loma Prieta earthquake, while the two earlier earthquakes of 1868 and 1906 result in much greater depths of liquefied soil over the total 14m depth.

From the above discussions, it is clear that the FEM deformation analysis for lateral ground flow gave a result that is very much in agreement with the observations obtained following the Loma Prieta earthquake and the conclusions by Egan et al. (1992). Thus, the analysis method presented herein to assess the ground lateral flow by using the available digital data and the numerical analysis would be useful is assessing more details of expected ground failure during the earthquake.

FEM Analysis of Ground Lateral Flow at Guadalupe River

During the Loma Prieta earthquake, some sand boils and ground cracks were observed along the river bank of the Guadalupe River near the San Jose airport. Thus, it was thought useful to assess the possibility of ground lateral flow due to liquefaction of the area near the San Jose airport. The area of study is shown in Figure 8 and a cross-section is provided that spans both the west and east banks of the Guadalupe River and extends over a 2 km distance. The



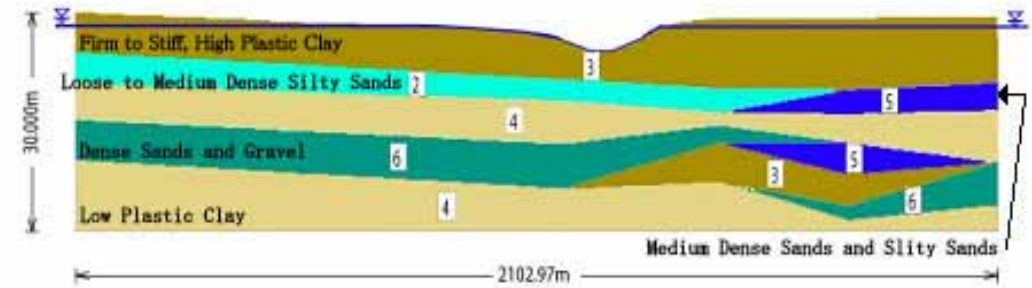


Fig.9 Geological Cross Section at the Guadalupe River

analysis of ground lateral flow was made for three different PGAs (PGA=0.17g, 0.28g, and 0.40g) as in the Coyote Creek case.

Figure10 presents the distribution of horizontal displacement for the three PGAs, and it can be seen that the amount of ground displacement is larger on the east bank than the west bank. I t is also seen that the maximum ground movement is 30cm for the Guadalupe River in comparison with less than 20 cm that occurred well below the ground for the Coyote Creek case. Although the difference of displacement magnitude is not so large, but the difference in the location of ground deformation in Coyote Creek and Guadalupe River may have resulted in a difference in observed liquefaction damages during the Loma Prieta earthquake reconnaissance. It is also very interesting to observe that the amount of ground movements become larger as the

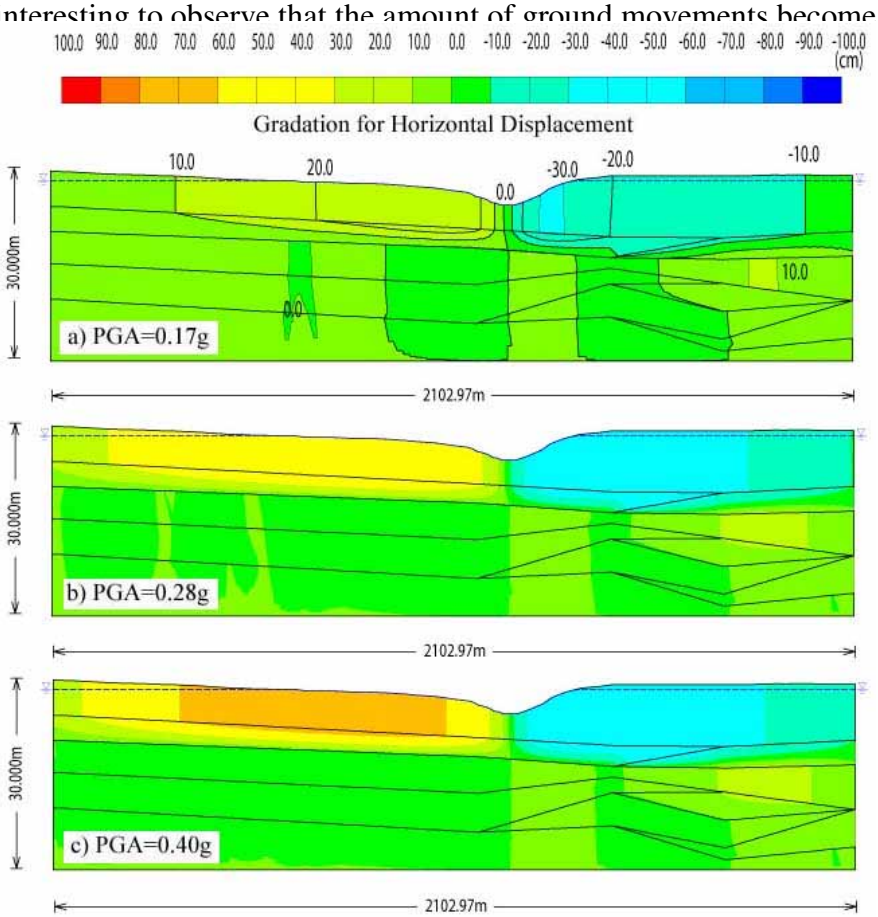


Fig. 10 Variation of Horizontal Displacement at Guadalupe River, a) 0.17g, b) 0.28g, c) 0.40g

Figure 11 shows the distribution of maximum shear strain for the three scenarios. Similar to the trend observed in Figure 10, the shear strain develops widely with increased PGA. However, it is to be noted that only two boreholes were used on the west bank, where the San Jose airport is located, so the continuation of a weak silty sand layer beneath the airport is a conservative assumption. More detailed geotechnical data in the area is necessary to confirm the

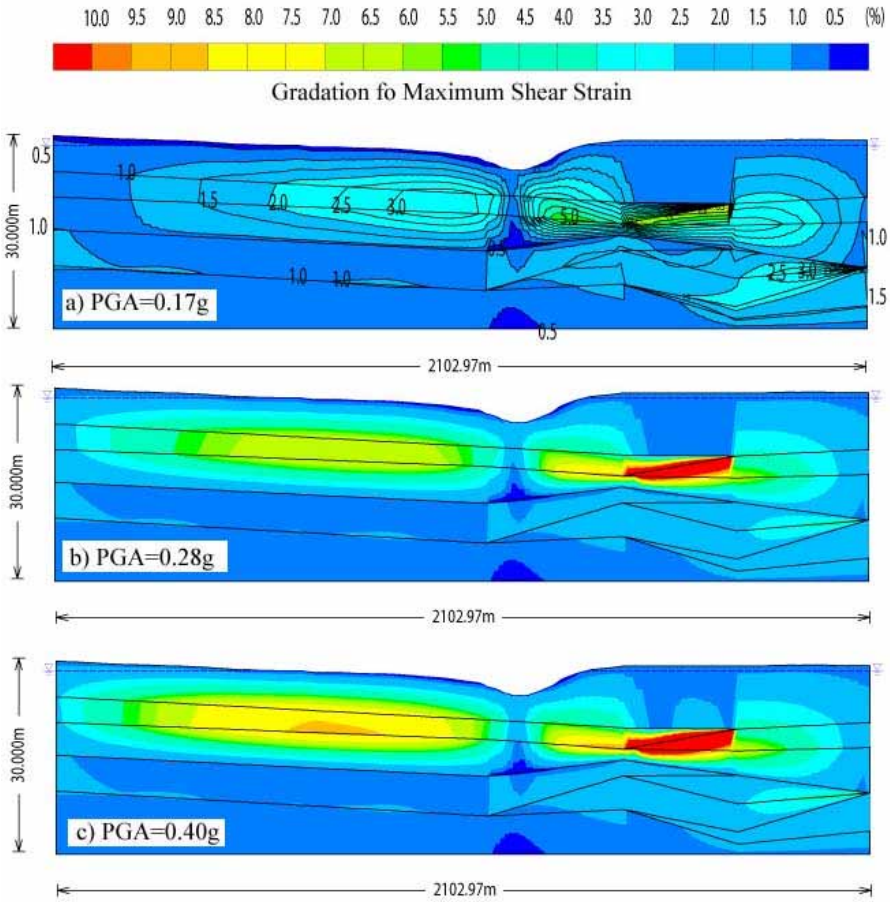


Fig. 11 Variation of Maximum Shear Strain at Guadalupe River, a) 0.17g, b) 0.28g, c) 0.40g

results presented here. However, these results should be viewed as an example of how the soil strength and the nature of the stratigraphy influence the magnitude and mode of ground movement due to liquefaction.

Conclusions

In this study, a variety of geotechnical informationand technologies are used to assess the liquefaction hazard in an urban area where a large accumulation of past geotechnical studies are available. In order to examine the applicability of such geotechnical information and technologies, a study was performed to invesitgate the ground failure hazard in the San Jose area of Northern California, where a high possibility of liquefaction exists. The geotechnical information used consists of 600 borehole logs collected by the California Geological Survey, and a fine digital elevation map produced by the U.S. Geological Survey. The geotechnical analysis tool used is an FEM program, ALID by Yasuda et al. (1999). These geotechnical Information Technlogies are used to predict the amount of permanent lateral ground movement

during the 1989 Loma Prieta earthquake (whichcaused only minor ground damage in the area) and during two other damaging earthquakes of 1868 and 1906. The following conclusions may be drawn from the studies made in this paper:

1) The use of DEM and GIS borehole information together with a FEM liquefaction analysis tool is very powerful in carrying out the seismic hazard assessment. The obtained results of for the Loma Prieta earthquake at Coyote Creek are in a good agreement with the conclusion obtained by Egan et al. (1992).
2) The deformation analysis for lateral flow of ground using the FEM tool is very useful as it indicates how the mode of deformation would change as the seismic intensity and the stratigraphic/geologic features change. By carefully examining the geotechnical properties and geological structures, the accuracy of FEM prediction would improve so that the analysis result may be used to evaluate the performance of various infrastructures placed in or near the liquefiable ground.

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