# Experimental Modelling for the Effect of Rainfall and Earthquake on Slope Stability of Engineered Fill

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## Abstract

The collapse of several houses in some residential developments in Sendai during the M9 Tohoku earthquake warranted the health monitoring of several slopes in southern California. Majority of the houses developed in southern California are in engineered fill and the qualities of compaction may not be sufficiently checked. Due to recent trend of unpredictable rainfall and being located in the high seismic activity area, houses constructed on slopes in southern CA have strong potential to slide during earthquake or heavy rainfall. This study involves a systematic study of an engineered fill at Mission Viejo, California for potential slide activities. The materials borrowed from the site were compacted in a Plexiglass container at the field density, moisture content, and field slope angle. The slope was poured with the 100 year return period rainfall expected in the area using, a rain simulator. Variation in suction in the soil mass was recorded with duration of rainfall. Slope stability analyses were performed to evaluate the effect of earthquake in those slopes in reducing the factor of safety. The study result shows that the combined effect of antecedent rainfall and seismic shaking has significantly high effect on slope stability, compared to strong magnitudes of either rainfall or seismic acceleration acting separately.

## Keywords

Clay • Antecedent rainfall • Seismic shaking • Slope stability • Soil suction

## Background

Landslides cause an annual loss of $1–2 billion (USGS). Heavy rainfall, earthquake and associated hazards related to these events such as typhoon, tsunami, hurricane etc. are considered to be the major triggers of landslides. However, combined effects of earthquakes and rainfall were ignored in the past. We have evidenced several high magnitude earthquakes in recent years; many of them were either during or slightly prior to or after the rainy season. These earthquakes triggered several landslides. Therefore, the current research works pertinent to landslides are focusing on the combined effect of rainfall and earthquake. Several large scale landslides occurred after the M9.0 Tohoku Earthquake (Tiwari et al. 2013). More than 50 houses were damaged in a built-in area that was developed on embankment slopes. The area did not have much rainfall prior to the earthquake. However, it is believed that the soil lost suction during the heavy shaking that could have triggered the landslide.

With a desire to have a beautiful view, there is a growing tendency in southern California to construct houses on slopes. Majority of these houses are constructed on

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engineered fills. As the houses are mainly developed by the real estate developers, the construction quality control may not be as severe as required for the public infrastructures. Therefore, stability of the slopes where these houses are constructed should be checked for possible combined effect of rainfall and earthquake. In this study, we considered a case study of a site located in the city of Mission Viejo, 50 miles south of Los Angeles, California. The housing community was developed around 1998, mostly on the engineered fills. A total of 209 single family homes were constructed. The landslide investigation that took place from 2005 to 2010 concluded that there is no slope movement. However, some of the home owners were concerned that if the area gets a good amount of rainfall for a long period during an earthquake event, the slope may not remain stable.

The authors conducted field investigation and collected soil samples from the slope. Soil samples collected from the site were utilized to prepare slopes at various angles of inclination in a model container, which were later subjected to a rainfall of 21 mm/h for several days. The depth of water front and values of suction at various locations were measured during the rainfall event. The data obtained during the experimental modelling was utilized to conduct slope stability analysis and evaluate the stability of slope during various magnitudes of ground shaking.

## Results of Field Investigation

### Site Condition

Presented in Fig. 1 is the google earth image of the study area. As can be observed in Fig. 1, the property is located at the corner of the filling and both east and south sides of the building have slopes. During the field investigation, the authors noticed that the area, especially at both banks of the river, had several existing landslides. Two of those landslides are presented in Fig. 2. The meandering pattern of the river shows possible landslide events in the past on the opposite bank of the river as well.

Close view of the south side of the slope, which will be considered during this study is presented in Fig. 3. The area is currently covered with grass. A good drainage network has been constructed in the area. The authors didn't detect any cracks in those drains during the field investigation. However, as presented in Figs. 4, 5, 6, and 7, cracks were identified on stuccos, swimming pools, drive ways, and the compound walls.

### Field Investigation Result

Cross-section survey was conducted with a total station to measure the details of the slope (Fig. 8). Likewise, position



**Fig. 1** Google earth image of the study area



**Fig. 2** Google earth image of the study area—two existing landslides are clearly visible in the area
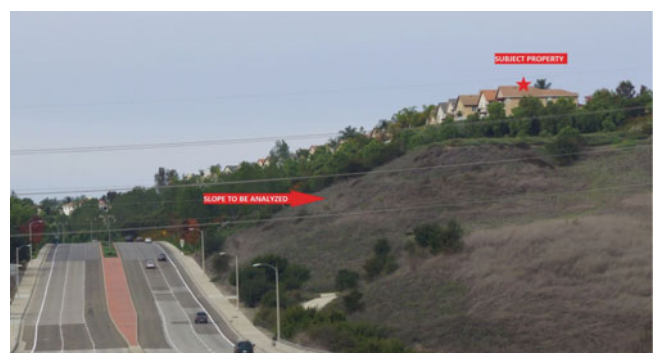


**Fig. 3** Close view of the south side of the slope

of water table during the field investigation was measured at an inclinometer located at the backyard of the building (Fig. 9). At the time of survey i.e. December 2012, the depth of water table was much lower than 21 m (limit of the inclinometer) below the ground level. Soil samples were collected from an excavation area, which is located near the

**Fig. 4** Cracks on the stucco of the building



**Fig. 5** Separation of compound wall from the main building—identified during the field visit



**Fig. 7** Separation of garage slab from the driveway—identified during the field visit



**Fig. 6** Separation of pool walls from the floor slab—identified during the field visit



**Fig. 8** Field surveying to prepare the cross-section of the slope

swimming pool (Fig. 10). Profile of the soil at the excavation area is presented in Fig. 11. Plan and sections of the study area are presented in Figs. 12 and 13, respectively.

**Fig. 9** Location of inclinometer in the study area



**Fig. 10** Location of soil sampling point

As presented in Fig. 13, the embankment slope was approximately 23.4°. This slope was utilized to prepare experimental model of the slope in the laboratory.

## Soil Test Result

The soil samples collected from the site is used to measure geotechnical properties of soil. Grain size distribution analysis with both sieve and hydrometer analysis, Atterberg limit tests, specific gravity test, falling head permeability tests, Proctor compaction tests, and direct shear tests were performed in the laboratory following the pertinent ASTM standards. The field moisture content was 26.8 %. This moisture content was slightly higher because the sprinkler system was on a day prior to excavation. Field dry density was 15.3 kN/m³. Liquid limit and plasticity indices of the



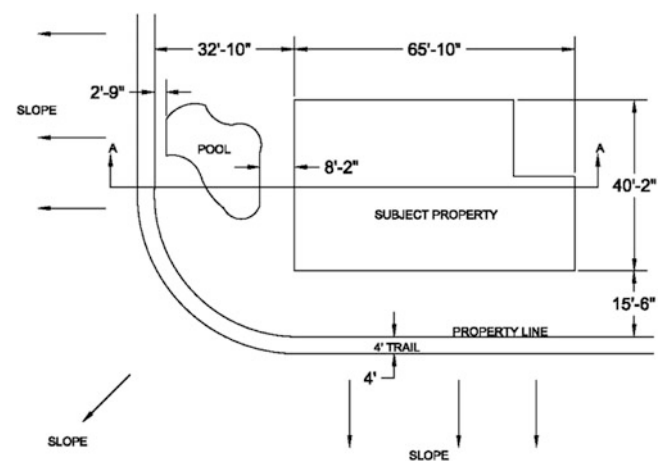**Fig. 11** Close view of the compacted soil profile



**Fig. 12** Plan of the study area

soil were 44.1 and 10.8, respectively. Specific gravity of the soil was 2.69. Proportions of sand, silt and clay were 10 %, 75 %, and 15 %, respectively. The maximum dry unit weight and optimum moisture contents were 17.0 kN/m³ and 15.0 %, respectively. The direct shear test that was conducted on the saturated soil sample showed the fully
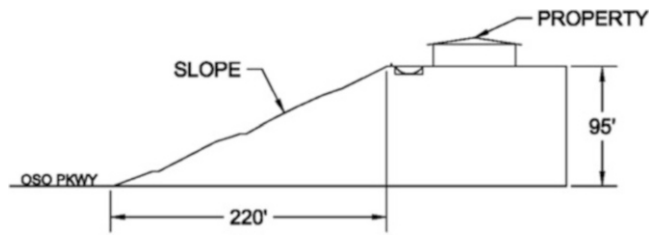
**Fig. 13** Cross-section of the study slope



**Fig. 14** SWRCC prepared for the tested soil sample



**Fig. 15** Photograph of the slope model after its completion
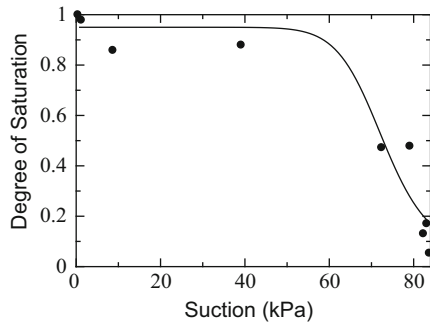
softened shear strength of 23° with no cohesion. However, the peak shear strength parameters (c and ϕ) when the soil was compacted at the field density were 11 kPa and 22°, respectively. Soil Water Retention Characteristics Curve (SWRCC) was prepared by measuring suction of soil prepared at various degrees of saturation. Presented in Fig. 14 is the SWRCC prepared for the tested soil sample. The result presented in Fig. 14 was for the dry to wet cycle. The data for the wet to dry cycle to complete the hysteresis is not presented here. The SWRCC presented in Fig. 14 was used to estimate the values of suction at different degrees of saturation.
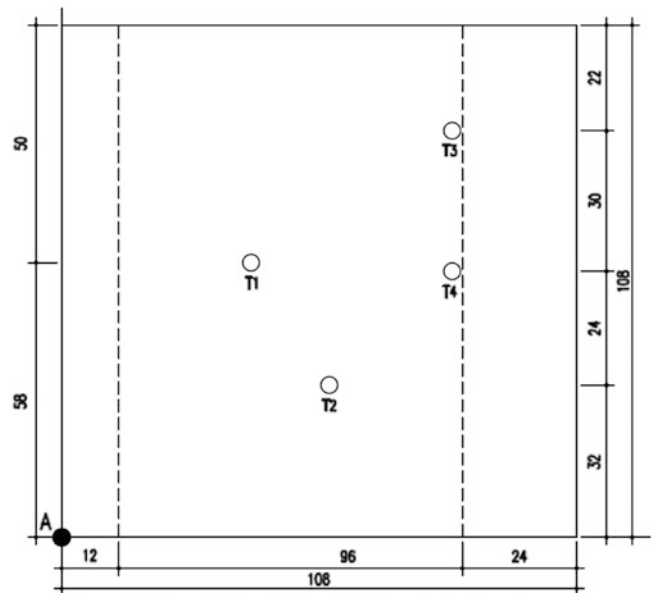
## Experimental Modeling

Experimental modelling of slopes were performed by many researchers to evaluate the stability of slope during rainfall (Orense et al. 2004; Tohari et al. 2007). Many of these studies involved externally applied seepage. However, the objective of this study was to evaluate the effect of rainfall and seismic ground motion on the stability of the proposed slope. Therefore, the soil samples collected from the site were utilized to prepare the model slope at the dry unit weight of 14.3 kN/m$^3$ and moisture content of 15 %. The soils were compacted at the relative density of approximately 84 % to keep the model in a conservative side. Slope of the model was kept close to the field slope. Presented in Figs. 15, 16 and 17 are the photographs and sketches of the experimental model.
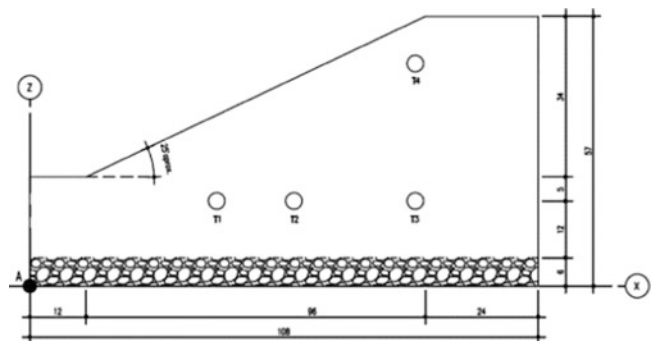


**Fig. 16** Location of tensiometers shown in plan



**Fig. 17** Location of tensiometers shown in section

The locations of four tensiometers that were used to measure the suction during rainfall are shown in Figs. 16 and 17. The internal dimension of the box was
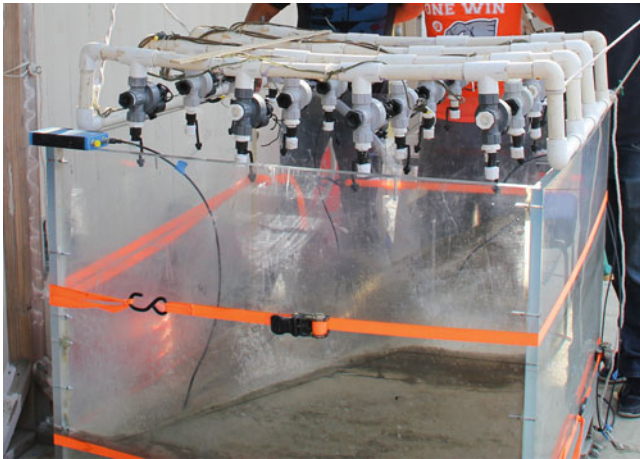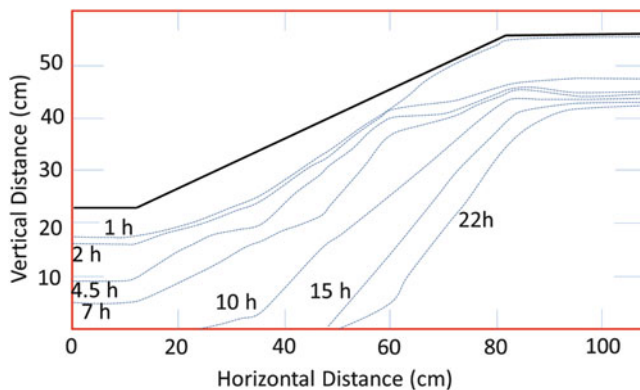
**Fig. 18** Photograph of the sprinkler system



**Fig. 20** Variation of suction with duration of rainfall

**Table 1** Calculated factors of safety for various conditions of seepage and seismic coefficients

| Prior to rainfall | After 4 days of rainfall | Rainfall with k of 0.1 | Rainfall with k of 0.3 | Rainfall with k of 0.5 |
|---|---|---|---|---|
| 1.85 | 1.56 | 1.22 | 1.10 | 0.98 |



**Fig. 19** Depth of water front with duration of rainfall

$1.08 \times 1.08$ m. Likewise, height of the model above 6 cm thick gravel bed was 51 cm. Photograph of the sprinkler system is presented in Fig. 18. A rainfall of 21 mm/h was applied to the slope for different periods of rainfall and the depths of water front were measured with time. Presented in Fig. 19 is the depth of water front recorded with time. Please note that amount of run-off was also recorded during the experimental modeling. Average run-off was 7 mm/h. This shows the net rainfall responsible for infiltration was 14 mm/h. As can be observed in Fig. 19, water could infiltrate 12 cm depth in 7 h. The seepage profile was steeper than the slope. The average infiltration rate was 17 mm/h. Likewise, suction values were measured during the application of rainfall. Recorded values of suction with time for the four tensiometer locations presented in Figs. 16 and 17 are presented in Fig. 20. As can be observed in Fig. 20, tensiometer T4 took 154 min to have suction reduced to 0, i.e. have the water front reach T4. Likewise, it took 500 min for the water front to reach T1. Water front never reached to T2 and T3.

Slope stability analyses were performed prior to rainfall and for the measured values of suction after the completion
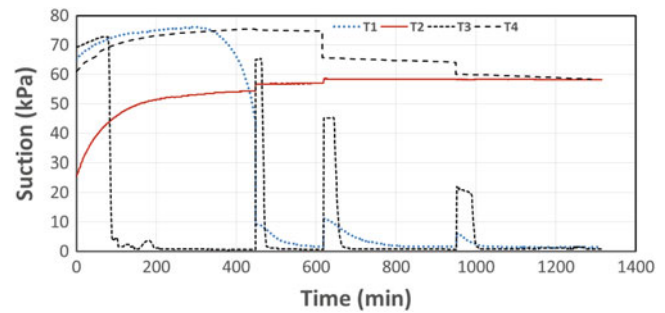
of the test i.e. 4 days of rainfall. Please note that the rainfall lasted for 450 min and was stopped for 18 h on the first day; continued for 166 min and stopped for 20 h on the second day; continued for 330 min and stopped for 17 h on the third day; and continued for 360 min on the fourth day. This was done to simulate the real situation. The slope stability analysis was performed with Spencer's method using "RocScience, Slide 6.0". The total calculated building load of 12.8 kPa was added on top of the slope as a uniformly distributed load. Apparent cohesion and friction angles measured at different suction levels were used to divide the entire soil mass into different zones based on suction values. At the end, factors of safety were also calculated for the slope using seismic coefficients ranging from 0.1 through 0.5. The calculated factors of safety are presented in Table 1. Based on the data presented in Table 1, the slope should be stable when the seismic shaking is less than 0.3 g when 4 days of rainfall is applied as used in the experimental study. However, a detailed study is underway to evaluate the stability of slope when the slope subjected to rainfall is shaken on the shake table at different magnitudes of shaking.

## Summary and Conclusion

Field investigation and laboratory tests were performed to evaluate the effect of rainfall and seismic shaking on the stability of an engineered slope. A case of a house that was constructed near existing landslide was used for this study. Experimental modelling was performed by applying different amount (but same intensity) of rainfall with durations ranging from 166 to 450 h for 4 days. The values of suction recorded with the tensiometers and water fronts marked during the modeling process

were utilized to assign different soil boundaries for slope stability analysis. The experimental result shows that the slope will have safety factor higher than 1 under normal amount of rainfall and at the seismic shaking of 0.3 g. As this result is preliminary, detailed study is underway. It should be noted that the results presented in this study are mainly for academic purpose and should not be used for any type of interpretation pertinent to the safety of the houses in the study area. The actual situation in the field depends on many factors and this result does not cover those factors.

## References

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