Effectiveness of PV drains for mitigating earthquake-induced deformations in sandy slopes

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ABSTRACT: This paper considers the effectiveness of a Pre-fabricated Vertical (PV) drain array for mitigating the earthquake-induced permanent ground deformations of a water-fronting loose sand fill based on results of numerical simulations. The numerical simulations are performed using the OpenSees finite element framework to represent the non-linear coupled ground deformation and transient pore pressures with customized 1-D finite elements to describe flow in the PV drains. Soil behavior is modeled using an advanced elasto-plastic effective stress soil model ("DM" for Dafalias & Manzari, 2004). The analyses focus on the performance of an 18.3m high sand fill, representative of many west-coast port facilities, and compare the response with and without the PV drain mitigation system for a suite of 58 reference seismic ground motions. The computed permanent slope deformations are well correlated with the peak ground accelerations (PGA) and especially the Arias intensity (I_a). The PV drain mitigation system is effective in reducing permanent lateral deformations at the crest of the slope by a factor of 1.2 – 3.5. The system effectiveness is largely independent of the characteristics of the ground motions. The damage results have been incorporated in slope fragility curves that can be used to quantify the expected costs from earthquake damage.

INTRODUCTION

Many natural or man-made sand slopes are marginally to moderately stable. Earthquake-induced ground motions exert additional inertial forces on the soil mass and can cause material strength degradation in loose granular, liquefiable soils due to cyclic shearing, leading to permanent ground deformations and potentially to slope failure. These concerns are particularly significant for US ports where there are many vulnerable waterfront facilities comprising pile-supported wharves embedded in loose hydraulic fills. It is thus very important to be able to estimate the seismic-induced deformations within the soil mass and to design effective slope damage mitigation systems.

Many analytical and numerical solutions have been presented in the literature for

estimating seismic-induced slope deformations. Variants of the Newmark sliding block analysis (Newmark, 1965), such as Makdisi-Seed (Makdisi, 1978), are the most commonly used methods of analysis, whereas more advanced stick-slip deformable sliding models, such as the one used by Rathje and Bray (2000), have also been proposed. Other approaches attempt to correlate the computed permanent ground movements with earthquake intensity measures (e.g., Jibson, 1994; Bray and Travasarou, 2007) but are formulated under very particular conditions. These results are mostly effective in predicting damage on dry slopes. In saturated sandy slopes, cyclic shearing due to earthquakes causes an increase in excess pore pressures and an associated reduction in effective stresses and available shear strength, a mechanism critical to understanding and estimating damage in these slopes.

This paper focuses on the use of PV drain systems (Rathje, 2004), a drainage-based technique which offers a mechanism for minimizing the accumulation of excess pore pressures and which can potentially be installed with minimal disruption of port activities. PV drains comprise perforated, corrugated plastic pipes encased in a geo-synthetic fabric (geo-textile), ranging from 75 to 200 mm in diameter. They are encased in a filter-fabric and can be installed by conventional drilling equipment by jacking or vibration with little disturbance to nearby structures. During an earthquake, PV drains offer high transmission pathways to relieve the buildup of excess pore pressures within the soil mass and hence, reduce ground deformations associated with cyclic mobility.

Engineers design a specific drain spacing based on a selected design excess pore pressure ratio. The typical designs assume a design excess pore pressure ratio, $R_u=50\%$ (when an average excess pore pressure ratio for the whole liquefiable layer is considered) or $R_{u,max}=60\%$ (when the maximum excess pore pressure ratio is considered) (Onoue, 1988; Iai & Koizumi, 1986). Various methodologies have been published to estimate the expected excess pore pressure ratio during an earthquake (Seed and Booker, 1977; Onoue, 1988; Pestana et al., 1997).

Current analytical tools can only provide an approximation of the earthquake induced slope deformations (for untreated slopes), or an approximation of the excess pore pressure reduction achieved by means of a PV drain system (in treated slopes). In this study, a series of 58 plane-strain, dynamic, coupled pore-pressure displacement, seismic slope stability finite element analyses has been performed for a reference case of a partially submerged slope, enabling comparisons between the response of the slope for untreated conditions and those with the PV drain mitigation system. The analyses represent realistically the free field boundary conditions, material behavior, and drainage conditions.

NUMERICAL MODEL

The numerical model was built in the OpenSees finite element software framework (Mazzoni et al., 2005) using GiD as a pre- and post-processor. The OpenSees framework has been validated against simple one-dimensional analytical solutions to verify that it can correctly solve the necessary dynamic coupled pore pressure displacement PDE's (Vytiniotis, 2009).

Model Geometry

The geometry of the modeled problem along with parameters of the FE model are presented in FIG. 1. An 18.3m high slope made of loose hydraulic fill (D_r=40%) overlies a dense sand base (D_r = 80%, 2.6m thick) and a deep layer of stiff clay. The analyses compare results for the untreated/natural slope geometry with a proposed PV drain mitigation system comprising an array of HDPE prefabricated vertical drains (with outside diameter, 75mm, and wall thickness, 1mm) with 1m spacing. The drains extend through the full height of the sand fill and cover a 30m wide strip behind the crest of the slope.
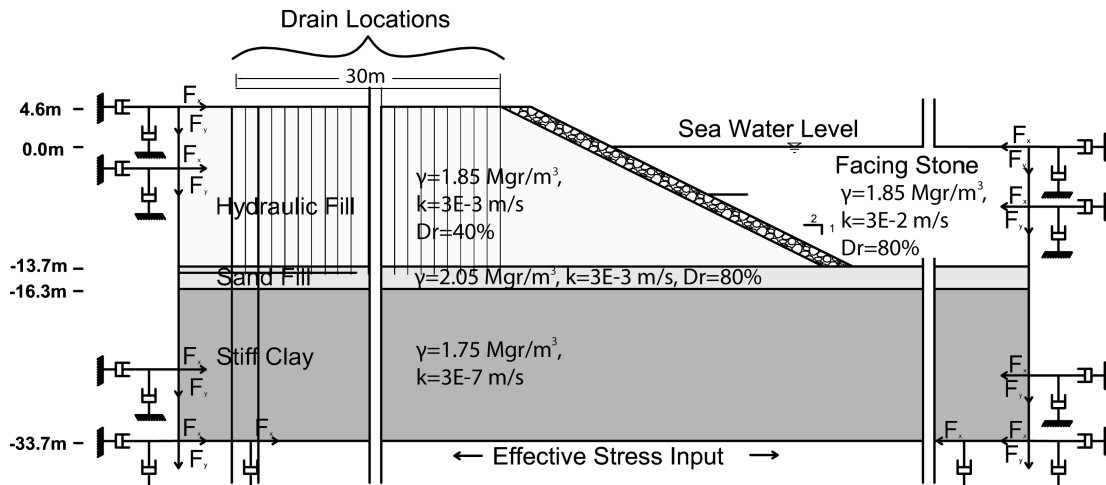

FIG. 1. Analyzed section with details of the properties of the FE numerical model.

Boundary Conditions

Damping elements are introduced on both the sides and base of the model (Lysmer, 1978) in order to absorb incident waves. Seismic loading is applied by means of force input at the base of the model according to the substructure theorem in order to avoid spurious wave reflections, following a procedure described by Assimaki (2004).

The sea water is modeled as an elastic layer with very small elastic shear stiffness while the bulk modulus is prescribed to match the p-wave velocity of water. This approach has been found to be successful in the past (Zienkiewicz and Bettess, 1978). It is assumed that the groundwater level remains constant during cyclic loading. The slope immersed in the sea acts also as a free draining boundary.

Ground Motions

The ground motions used as input are typical of firm-site conditions in coastal California. Fifty-five ground motions were selected from the database of the Next-Generation Attenuation of Ground Motions (NGA) project (Chiou et al., 2008) with minimum moment magnitude M=5.5, closest distance to rupture, R, ranging from 0 to 60km, including strike-slip, reverse, or reverse-oblique, for a C site class (very dense

soil and soft rock), and minimum usable frequency of less than 0.5Hz. Three ground motions are produced from the M=7.8 ShakeOut simulation on the southern San Andreas Fault. The records have maximum peak ground acceleration PGA $\leq$ 0.96g, Arias intensity $I_a \leq$ 8.37m/s, and bracketed duration (time span of record between the first and last occurrence of an acceleration spike of 0.05g), $T_d \leq$ 33.10s.

Constitutive Model

The DM2004 critical state elasto-plastic constitutive soil model is used to simulate the effective stress-strain behavior of sand during cyclic loading events. This model predicts reasonably well both the monotonic and the cyclic behavior of sand measured in laboratory tests, and is able to capture the effects of void ratio and confining stress with a single set of model parameters. It simulates shear-induced volumetric plasticity during loading and subsequent unloading paths, effectively modeling pore pressure generation during cyclic loading. Input parameters for the DM2004 model have been calibrated for Toyoura sand by Dafalias and Manzari (2004) and are used in the current numerical simulations. The facing stone was assumed to behave mechanically similarly to very dense Toyoura sand, while the underlying clay is simulated as a viscoelastic material.
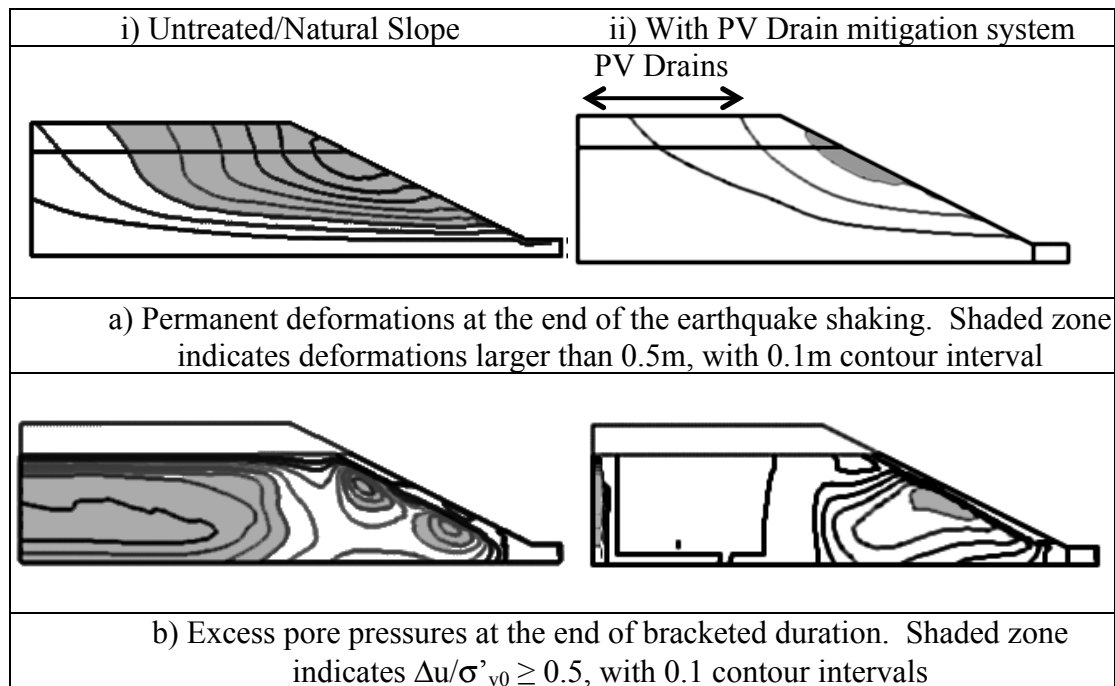
i) Untreated/Natural Slope	ii) With PV Drain mitigation system
a) Permanent deformations at the end of the earthquake shaking. Shaded zone indicates deformations larger than 0.5m, with 0.1m contour interval	
b) Excess pore pressures at the end of bracketed duration. Shaded zone indicates $\Delta u/\sigma'_{v0} \geq$ 0.5, with 0.1 contour intervals	

FIG. 2. Computed ground response for reference ground motion record, *nga0753* (PGA=0.64g, I_a=3.24m/s)

RESULTS

FIG. 2a and 2b present comparisons of permanent deformations and excess pore pressures, respectively, at the end of the bracketed duration of shaking for a reference ground motion, *nga0753*. The PV drains effectively separate the zones of excess pore pressures below the slope and in the far field and hence, reduce significantly the magnitude of the permanent slope deformations and the extent of shearing (indicated by the shaded zone where absolute displacements, $|\delta|>0.5m$). This result shows clearly that the proposed system can be effective in reducing deformations within the slope and potentially can be effective in mitigating damage to an embedded piled-wharf structure.

Effect of Drains in Reducing Earthquake-induced Slope Deformations

Throughout this paper, slope deformations are represented by the average horizontal shear strain, γ_{ave}, over the height of the fill, H:

$$\gamma_{ave} = \frac{\delta_x[0,H]}{H} \qquad (1)$$

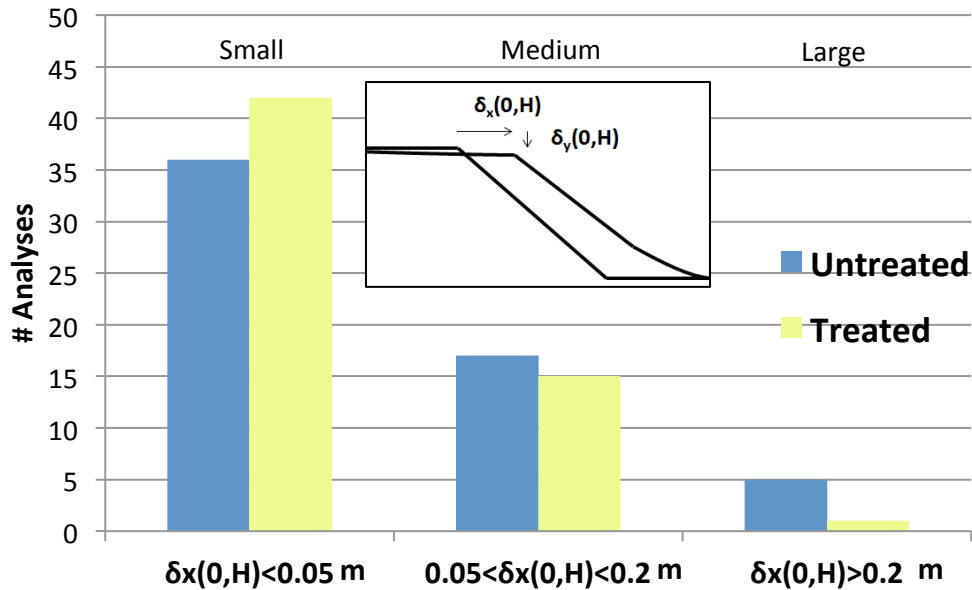where $\delta_x[0,H]$ is the horizontal displacement at the crest of the slope.

FIG. 3. Effect of PV drains in reducing permanent horizontal displacements at the crest of the slope for a suite of 58 earthquake ground motions

FIG. 3 compares the computed permanent horizontal displacements at the crest of the slope for the untreated geometry and PV-drain mitigated slope configurations for

the suite of 58 ground motions. The data are binned in three groups corresponding to small ($\delta_x[0, H] < 0.05$m), medium (0.05m $< \delta_x[0, H] < 0.2$m) and large ($\delta_x[0, H] > 0.2$m) deformations. The PV drains reduce the number of cases of large (from 5 to 1) and moderate (17 to 15) permanent ground deformations.

The effectiveness of PV drains in mitigating earthquake induced slope deformations can be quantified through the improvement ratio (IR), relating the average shear strains for the untreated and treated configurations:

$$IR = \frac{\gamma_{ave}[untreated]}{\gamma_{ave}[treated]} \tag{2}$$

In order to examine the effect of various motion characteristics on the improvement ratio we ignore the ground motion records that produce small permanent deformations ($\delta_x[0, H] < 0.05$m, $\gamma_{ave} < 0.24\%$) in the untreated geometry (36 records). FIG. 4(a) and (b) show the improvement ratio as functions of Arias Intensity, and T_d for the remaining 22 records. While the PV drain system clearly produces improvements in the predicted ground deformations and strains (IR = 1.2 – 3.5 for all cases), there is no correlation with Arias Intensity. This illustrates that PV drains will be similarly effective under different acceleration time-histories.

FIG. 4(b) shows that the improvement ratio generally increases with the duration of the strong ground motion, but appears to reach a plateau (with IR = 3-4) for $T_d > 15$s. For long duration ground motions, we can assume that all slopes reach a limiting excess pore pressure (generation of excess pore pressures equals dissipation) and thus no significant increase in improvement ratio can be achieved through drainage alone. Analyses by Papadimitriou et al. (2007), Pestana et al. (1997), and design charts by Seed and Booker (1977) all imply similar behavior where partial drainage in the soil prevents further accumulation of excess pore pressures.
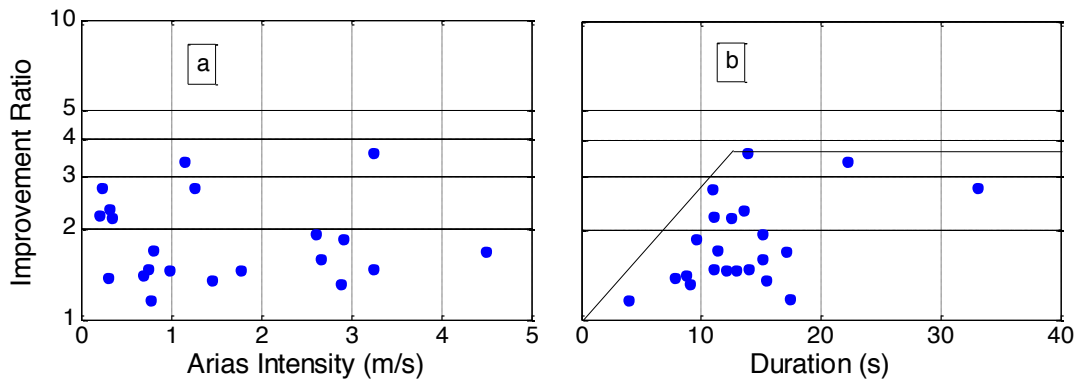

FIG. 4. Effect of (a) Arias intensity, (b) Bracketed duration on improvement ratio using treatment with PV-drains

Slope Fragility Curves

This section considers the effectiveness of the proposed PV drain system in reducing the fragility of the sand fill. The demand in this problem is the average shear strain over the height of the slope (γ_{ave}), and is assumed to be a random variable following a lognormal distribution, where the median is approximated by a power law function (Cornell et al., 2002) of two Intensity Measures (IM); PGA and I_a:

$$\gamma_{ave} = a \cdot IM^b \cdot \varepsilon \tag{3}$$

where a, b are empirical constants, and ε is a lognormal random variable with median 1 and logarithmic standard deviation β.

Next we relate the average shear strain with the three intensity measures using the above equation for the untreated slope, and the configuration with the proposed PV drain mitigation system, as shown in FIG. 5. The simulations produce good correlations for both PGA and I_a, but the latter generally has higher regression coefficients (r^2). There is better correlation for the treated fill because response is less affected by cyclic mobility and partial drainage mechanisms.
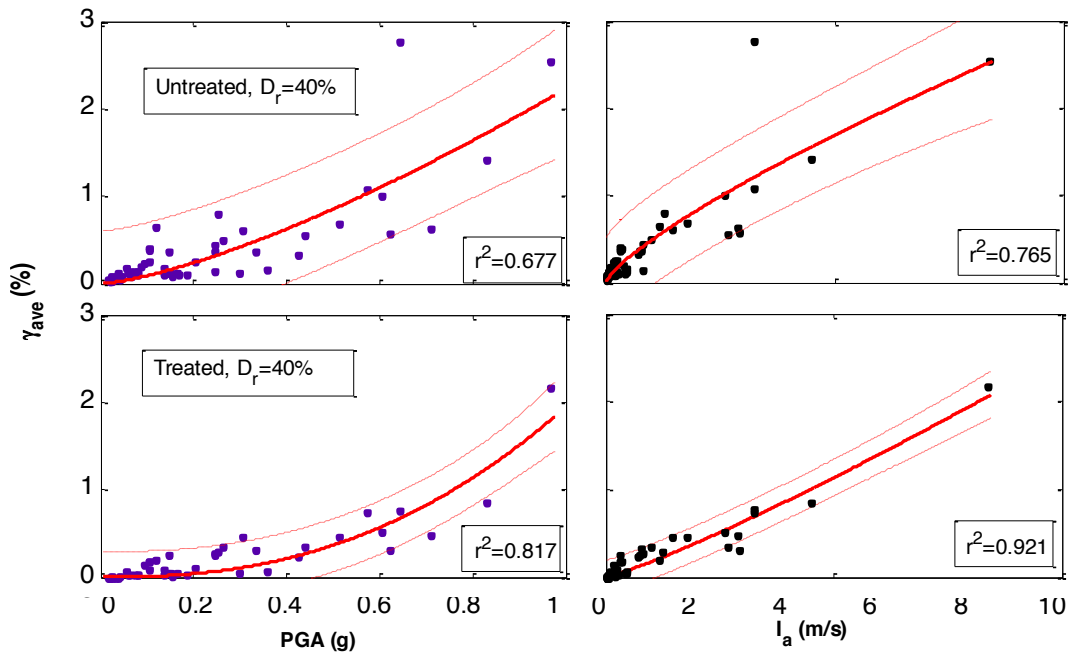

FIG. 5. Computed demand model for average horizontal shear strain, γ_{ave}, as functions of Peak Ground Acceleration (PGA) and Arias Intensity (I_a) for the untreated configuration and slope mitigated with PV-drains (dashed lines represent 95% confidence bounds)

Using these demand models it is now possible to estimate the probability of 'zero damage', defined as the probability of exhibiting less than 0.01m of permanent

horizontal displacement at the crest of the slope. The probability that a structure exceeds a particular damage state for a given intensity measure is then:

$$p(C < D|IM) = 1 - \Phi\left(\frac{\ln(\gamma_{ave_C}) - \ln(\gamma_{ave_D})}{\sqrt{\beta^2}}\right) \tag{4}$$

where Φ is the standard normal distribution and γ_{aveC} and γ_{aveD} are the capacity and demand average shear strains over the height of the slope, and β is the logarithmic standard deviation for the demand. In a population of n samples (in this case n=58) β can be estimated as:

$$\beta = \left[\sum_{i=1}^{n}\left(\ln(\gamma_{ave.i}) - \ln(a) - b \cdot ln(IM_i)\right)^2/(n-2)\right]^{\frac{1}{2}} \tag{5}$$

The probability of 'zero damage' is computed as a function of PGA and I_a as shown in FIG. 6. The limits in intensity measures are controlled by the chosen suite of ground motions. For moderate levels of ground motions, PV drains can be very effective in decreasing the probability of 'zero damage' along the slope (FIG. 6). However, for strong motions their presence has limited effect. This is reasonable as very strong motions can be expected to cause damage even if mitigation techniques are used (although there will still be reductions in permanent deformations due to drainage). These results together with those presented in FIG. 5 illustrate that PV-drains are effective as a liquefaction mitigation technique, but they should be used together with other seismic risk mitigation techniques if strong earthquake motions are expected at the site of interest and significant reduction in expected damage is needed.
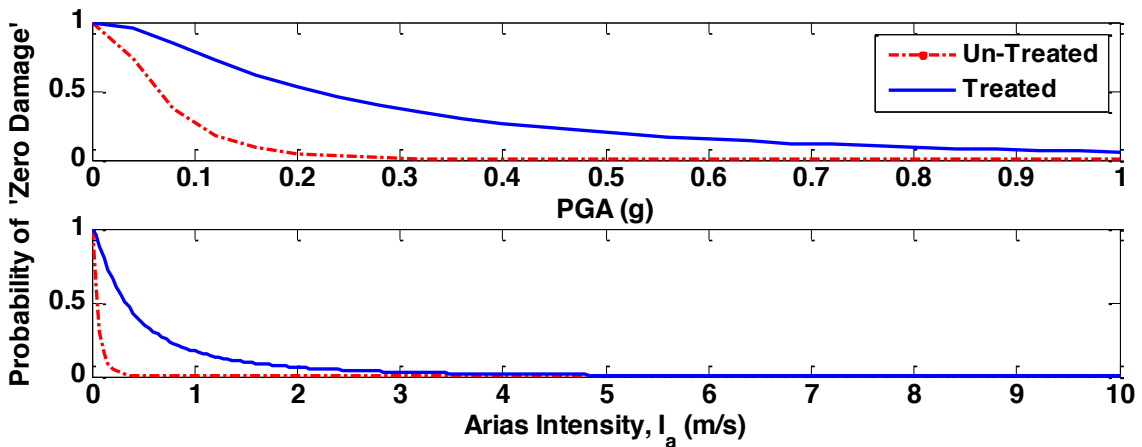

FIG. 6. Probability of 'zero damage' vs. PGA and Arias Intensity, Ia, for Un-treated vs. treated geometries

CONCLUSIONS

Numerical simulations have shown that a commonly employed 75mm diameter PV drain system is effective in reducing earthquake-induced permanent lateral deformations at the crest of an 18.3m high partially submerged saturated sandy slope by a factor of 1.2 – 3.5 for a typical design spacing of 1m. The PV drain system was shown to be effective even though it was installed behind the crest of the slope, by prohibiting the diffusion of excess pore pressures from the far field to the slope. The computed permanent slope deformations are well-correlated with the peak ground accelerations (PGA) and especially the Arias intensity (I_a). It was shown that PV drain system effectiveness is largely independent of the characteristics of the ground motions. Finally, the seismic slope stability damage results have been incorporated in slope fragility curves to be used to quantify the expected costs from earthquake damage.

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