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Modelling time-lapse S-wave velocity changes in an unsaturated river dyke due to water infiltration

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SUMMARY

Understanding the effect of saturation is important in assessing the failure mechanism on the land-side of a river-dyke due to rising water level in a river after heavy rainfall. S-wave velocity is controlled by soil suction and degree of saturation. Therefore, there is a possibility to estimate the unsaturated soil properties from the temporal changes in S-wave velocity. For this purpose, we model the temporal changes in S-wave velocity due to seepage of water in a dyke under rainfall. We propose a new approach for interpolating/extrapolating experimental data, in order to obtain shear modulus as a function of suction and confining stress. The seepage analysis of a river dyke under heavy rainfall shows that the temporal change in the S-wave velocity is determined more by the shear modulus than by the density. Furthermore, the S-wave velocity at shallow depths is more sensitive to seepage than the S-wave velocity at greater depths. These, together with the fact that a simple relationship exists between the shear modulus, suction and saturation, lead us to the new possibility of predicting shear modulus as a function of suction from the time-lapse S-wave velocity monitoring.

Introduction

Failure on the land-side of a river-dyke due to rising water level in a river after heavy rainfall has become an increasingly common and disastrous occurrence in Japan. Seepage of water typically causes piping, suffusion, slip-slope failure and static liquefaction. To prevent disasters due to dyke failure, detection of weak zones along a dyke is necessary. Because a dyke is initially unsaturated, understanding the effect of water saturation on shear strength and hence on dyke stability is important.

Unsaturated soil properties are generally described as functions of degree of saturation and suction (capillary pressure). Recent experimental studies have shown a relationship between suction and several critical soil properties (Han and Vanapalli, 2016). The shear modulus is controlled by soil suction. Therefore, shear-wave velocity (Vs) changes during water infiltration. In a recent in-situ experiment it has been possible to observe the temporal changes in Vs due to water infiltration (Konishi et al., 2015). It appears possible to estimate the critical properties of the unsaturated soil that constitutes a dyke from the temporal changes in Vs. Correct modelling of time-lapse Vs changes due to water infiltration is, therefore, crucial.

In this study, we model the temporal changes of Vs due to seepage of water in a dyke. The relationship of shear modulus with suction is used. A few earlier physical models attempted to predict the shear modulus in unsaturated soils (e.g., Sheng et al., 2016). We propose a new model which is simple yet powerful, and allows interpolating/extrapolating the laboratory experimental data based on the soil-water characteristic curve (SWCC) and the Bishop-type effective stress. In this abstract, at first, the relation between unsaturated soil properties and the Vs will be derived. Appling a new concept based on SWCC, the shear modulus as a function of suction will then be estimated for an experimental dataset. We will then perform seepage analysis and estimate the temporal changes in Vs.

Relationship between SWCC and Vs

In unsaturated soil, the suction plays an important role in explaining saturation-dependent hydraulic and mechanical properties (e.g., van Gnuchten 1980, Han and Vanapalli, 2016). Suction (s) changes with the degree of saturation (S_r). The s-S_r curve is called the soil-water characteristic curve (SWCC, Fredlund el al., 2012). Fig. 1a shows an example of SWCC for silty sand from an experimental dataset (Hoyos et al., 2015). SWCC depends on the soil type.

Small-strain shear modulus (G_0) is a function of suction (Sawangsuriya et al., 2009). Considering the Bishop-type effective stress, the following relation can be obtained (Han and Vanapalli, 2016):

$$G_0(s,\sigma_C) = k_1\left(\sigma_C\right)^{k_2} + \Gamma s S_r(s), \tag{1}$$

where (σ_c) is the net confining stress; k_1, k_2 and Γ are fitting parameters. The first term on the right-hand side of equation (1) indicates the shear modulus at s=0 (full saturation), while the second term addresses the effect of SWCC.

In the subsequent numerical modelling, we require the $G_0(s, \sigma_c)$ surface in predicting the Vs changes due to water infiltration in a river dyke. To this end, we use equation (1) in order to derive Γ:

$$\Gamma = \frac{G_0(s_1,\sigma_C) - G_0(s_2,\sigma_C)}{s_1 S_r(s_1) - s_2 S_r(s_2)}. \tag{2}$$

Equation (1) and (2) indicate that the shear modulus corresponding to two arbitrary suction values but fixed confining stress and SWCC can be enough to estimate the shear modulus as a function of suction in general. In order to further resolve the dependence of the confining stress, we invert k_1 and k_2 in equation (1) using the estimated value of Γ.

Using the above idea, we estimate shear modulus $G_0(s, \sigma_c)$ from an experimental dataset of silty sand shown in Fig. 1a (Hoyos et al., 2015). In this experiment, shear modulus was measured at different suction values and different net confining stresses. We use the fitted theoretical SWCC (solid line in

Fig. 1a) which was developed by van Gnuchten (1980). The best-fit equation is found to be as follows:

$$G_0(s,\sigma_C) = 2.644(\sigma_C)^{0.568} + 0.185sS_r(s)\,. \tag{3}$$

The experimental data (open circles) and the estimated curve (line) are shown in Fig. 1b and 1c, respectively. Encouragingly, our estimates match closely with the experimental data.

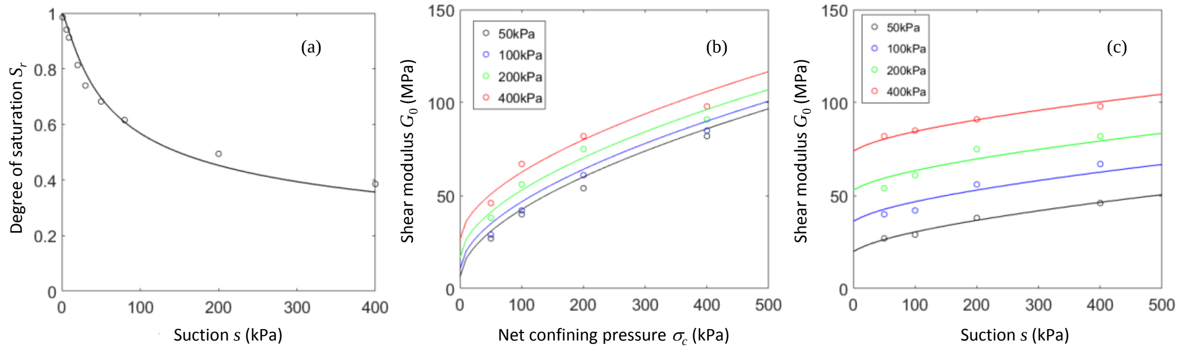

Figure 1 *(a) The soil-water characteristic curve (SWCC): open circles show the experimental data (Hoyos et al., 2015); solid line represents theoretical curve using the model of van Gnuchten (1980). (b,c) The relationship between shear modulus and suction at different net confining stress values: open circles show the experimental data (Hoyos et al., 2015); solid lines represent our estimate.*

In order to obtain Vs, we define the bulk density (ρ_b) as a function of saturation:

$$\rho_b(S_r) = \phi S_r \rho_w + (1-\phi)\rho_g\,, \tag{4}$$

where ϕ is a porosity, ρ_w and ρ_g are water density and grain density, respectively. Finally, Vs can be expressed as $V_S(s,\sigma_C) = \sqrt{G_0(s,\sigma_C)/\rho_b(S_r)}$.

Modelling Vs changes in a river dyke due to rainfall

To assess the importance of in-situ measured Vs changes in an unsaturated soil, we numerically implemented the seepage analysis. We used the program "UNSAF" (Unsaturated-Saturated Analysis by Finite element method) which solves the Richard's equation in unsaturated and saturated soils (Akai el al., 1977; Lam et al., 1987). The numerical calculation is done for a model of a river dyke under heavy rainfall (maximum 50 mm/h) for 4 hours. The model is shown in Fig. 2. The assumed material for the dyke is the same silty sand, as used in the previous section. The porosity ($\phi = 0.46$) is known/measured for this experiment. We assume the grain density (ρ_g) to be 2600 kg/m^3 in equation (4). Furthermore, the saturation-dependent hydraulic permeability is obtained using the saturated permeability and SWCC (van Gnuchten, 1980). The initial water level is assumed to be z = –1 m, and the initial spatial distribution of saturation is obtained from the hydrostatic condition. Note that, for now, we only consider infiltration due to rainfall on the dyke and ignore the effect of the river water. However, it is also possible to incorporate in the model the seepage due to rising river-water level.

We estimate the temporal changes in the spatial distribution of suction and the degree of saturation (Fig. 3). Because we focus on the unsaturated soil area, the suction values in the saturated zone are shown in white. One can see that the suction decreases as the water saturation increases. Furthermore, due to water infiltration from the surface, the shallow part of the dyke experiences large changes in saturation. Fig. 4 shows the temporal changes in bulk density, shear modulus, Vs, degree of saturation and suction at different heights (marked in Fig. 2). Here, the confining stress (σ_c) at each height, as needed in equation (3), is obtained from the vertical distribution of grain density. The results show that the change in shear modulus is largest at the shallowest depth (Fig. 4b). This is because the change in shear modulus at the constant confining stress is dominated by the change in suction, as indicated in equation (1). The temporal changes in Vs are controlled more by the changes in shear modulus than those in density (Fig. 4c).

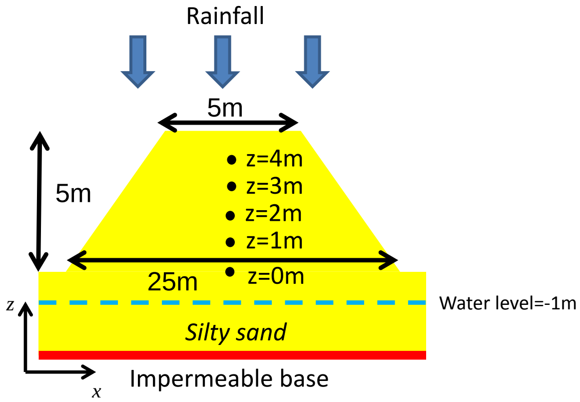

Figure 2 *Model of a dyke. Black dots indicate the points where the temporal changes in bulk density, shear modulus and Vs are looked at.*

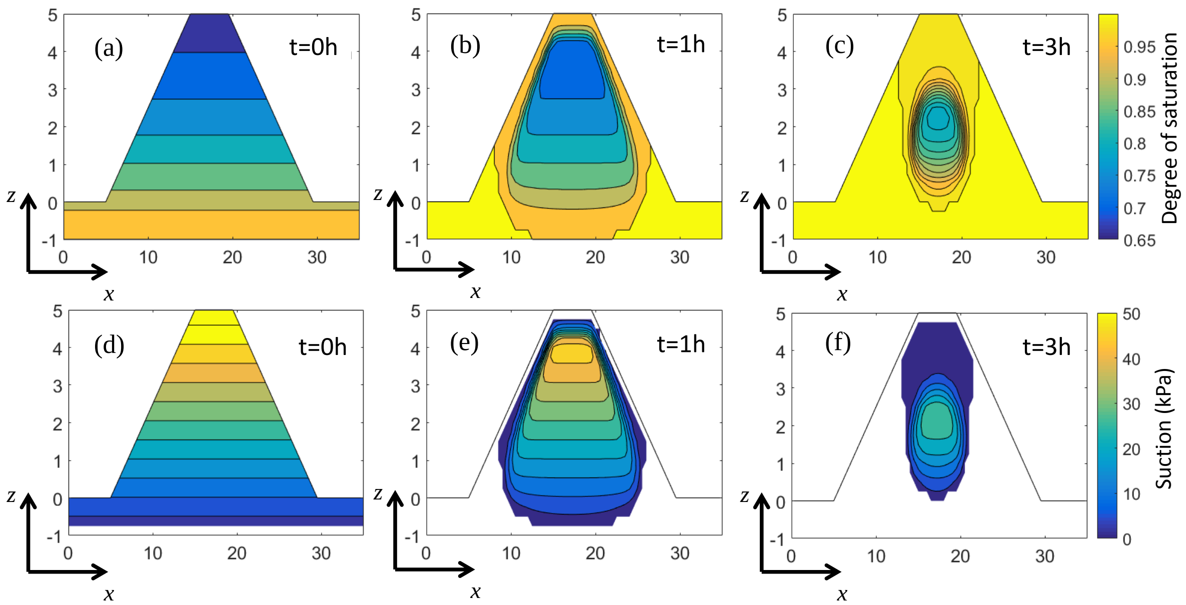

Figure 3 *(a-c): Spatial distribution of the effective saturation at different times (initial i.e., before seepage, 1h and 3h after the start of seepage). (d-f): Spatial distribution of the suction in kPa at different times (initial, 1h and 3h after the start of seepage).*

Conclusion

We have modelled the temporal changes in Vs due to seepage of water in a dyke under rainfall. We have considered unsaturated soil properties based on SWCC in predicting the Vs. The results of numerical modelling show that Vs at the shallow depths is more sensitive to water seepage than at greater depths, in the dyke. This is because the effect of suction is more dominant at the shallower depths. The facts that the effect of shear modulus dominates the value of Vs change and that a simple relationship exists between shear modulus, suction and saturation (equation (1) and (2)) indicate the possibility of predicting (extrapolating and/or interpolating) shear modulus as a function of suction from the time-lapse Vs monitoring under water infiltration, which could be further used in estimating the SWCC. For this purpose, developing an integrated approach using seismic and electrical (GPR/ERT) measurements will be crucial in order to constrain the values of saturation.

Furthermore, the spatial distribution and the magnitude of reduction of Vs, as estimated in our study, are useful in explaining the recent experimental data of Konishi et al. (2015). Although we focus only on the unsaturated soil area, it is also possible to include the effect of the pore-pressure build up in saturated soil area during seepage by introducing the effective stress as a function of pore pressure in the shear modulus (equation (1)).

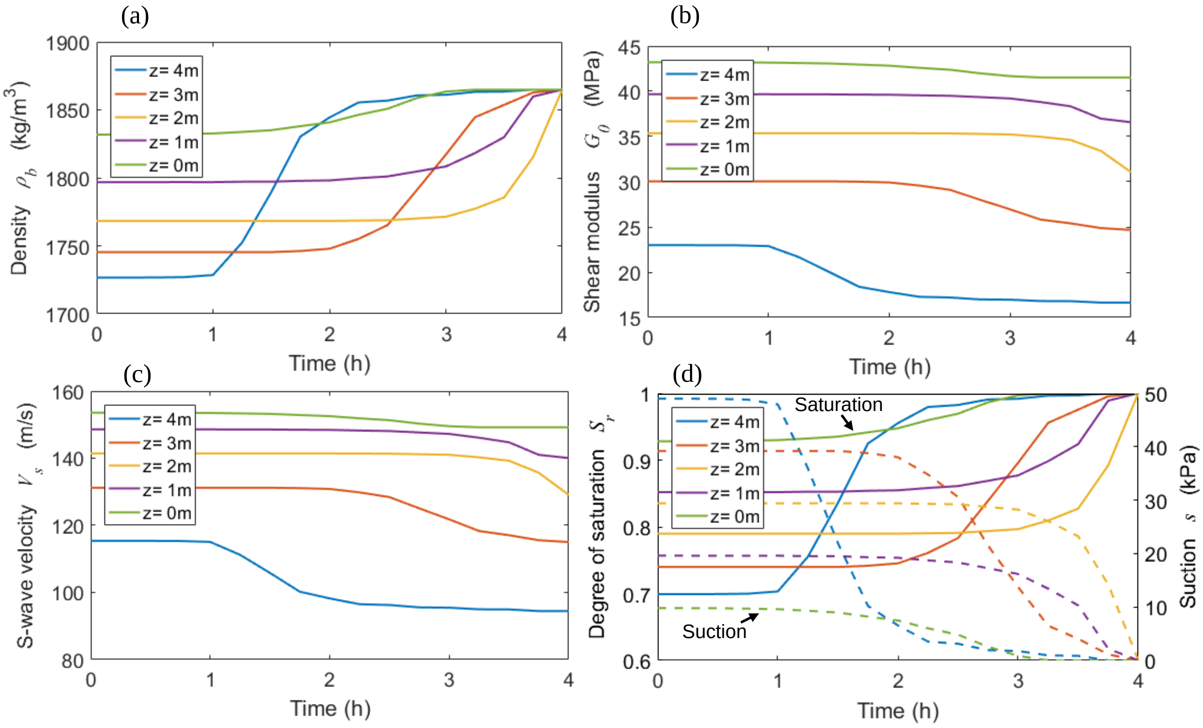

***Figure 4** Estimated temporal changes in bulk density, shear modulus, Vs, suction and saturation at various heights in a dyke (marked in Fig. 2).*

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