Impacts of plant-induced uptake on the stability of the earth structure

Effets de la prise d'eau induite par les plantes sur la stabilité de la structure en terre

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ABSTRACT

It is empirical knowledge that vegetation can influence the behavior of earth structure. It prevents surface failure and erosion due to rain and wind, and contributes to the stability of earth structure. Moreover, it encourages water circulation with transpiration, fixes atmospheric nitrogen and carbon via photosynthesis, and improves the environment. Therefore, surface seeding is purposely performed when an earth structure, such as an embankment or an earth dam, is constructed. Typically, vegetation grows on unsaturated soil. Consequently, a constitutive model for unsaturated soil is needed for understanding the effects of vegetation on the ground. In this study, we focus on the effect of vegetation-induced water uptake. The effect of water uptake due to evapo-transpiration can be regarded as reduction of water content within soil and appropriately represented in simulation studies. The constitutive model proposed by Ohno et al. (2007) is used for the simulation. In this model, the effective degree of saturation is treated as a parameter expressing hardening/softening. Moreover, the 'root element,' where the reduction of water content occurs, is applied to the soil/water coupled analysis with unsaturated soil mechanics. To verify the applicability of this model, the accident in Poland where non-uniform settlement and building damage were caused by water uptake of vegetation was simulated. The results show that water uptake increased suction and induced non-uniform settlement. This method is effective for understanding the effects of vegetation on the ground.

RÉSUMÉ

Nous savons par expérience que la végétation a une influence sur le comportement d'une structure en terre. Elle empêche les ruptures de surface et protège contre l'érosion dûe à la pluie et au vent et ainsi contribue à la stabilité de cette strucure en terre. En outre, elle favorise la circulation de l'eau grâce à la transpiration, fixe l'azote atmosphérique et le carbone à l'aide la photosynthèse et améliore l'environnement. Ainsi, l'ensemencement de la surface est pratiqué à dessein quand une structure en terre, comme une digue ou un barrage en terre, est construite.Naturellement, la végétation pousse sur un sol non saturé. Par conséquent, le modèle constitutif pour un sol non saturé est nécessaire pour comprendre les effets de la végétation sur le sol. Dans cette étude, nous nous concentrerons principalement sur l'effet de la prise d'eau causée par la végétation. L'effet de l'évapotranspiration est considéré comme une réduction de la teneur en eau dans le sol et peut être simulé. Nous utiliserons le modèle constitutif proposé par Ohno et al. (2007) pour la simulation. Dans leur modèle, le degré effectif de saturation est un paramètre exprimant le durcissement et le ramollissement. De plus, ''l'élément racine'', où la réduction de teneur en eau se produit, est appliqué à l'analyse couplée sol/eau grâce à la mécanique des sols non saturés. Afin de vérifier l'applicabilité de ce modèle, nous avons simulé un accident en Pologne où la prise d'eau causée par la végétation a entraîné le tassement non uniforme du sol, ce qui a eu pour conséquence d'endommager le bâtiment qui se trouvait là. Les résultats nous ont permis d'établir que la prise d'eau augmente la succion et peut induire un tassement non uniforme. Cette méthode est effective pour comprendre les effets de la végétation sur le sol.

Keywords : unsaturated soil, vegetation, soil/water coupled analysis

1 INTRODUCTION

We cannot neglect the influences of vegetation in geotechnical engineering. Vegetation plays a beneficial role in contributing to the stability of earth structures while it plays a negative role in transmitting wind power and denudating surface soil. However, we have not had any technique to quantify these influences in the past. Kawai et al. (2007) have succeeded in expressing the water uptake work of vegetation in soil/water coupled simulation. Azuma and Oka (2002) reported that the amount of uptake water corresponds to transpiration and water reduction within soil can be regarded as the amount of transpiration. In this study, an actual accident, caused by water uptake work, was simulated using the model for its validation.

2 APPLICATION OF WATER UPTAKE TO UNSATURATED SOIL/WATER COUPLED ANALYSIS

The place where many plants grow is the region above the groundwater level. It is known that the root grows while avoiding groundwater. Therefore, in geotechnical engineering, unsaturated soil mechanics and formulation of soil/water coupled problems considering water balance, such as rainfall and evapo-transpiration, is needed for proper inclusion of the effects of vegetation on the ground. Here we introduce the constitutive model used for simulations, and the 'root element,' used to express water reduction within soil.

2.1 *Expressing hardening/softening with effective degree of saturation*

Some constitutive models for unsaturated soil (Alonso et al. 1990, Kohgo et al. 1993, and Karube and Kawai 2001) have been introduced since Bishop (1960) first proposed effective stress for unsaturated soil. Ohno et al. (2007) indicated that these constitutive models were equivalent in terms of expressing yield function with effective stress and parameters associated with stiffness, applied effective stress, shown as equation (1), and proposed a general yield function shown as equation (4).

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma}^{net} + p_s \mathbf{1} \quad (1)$$

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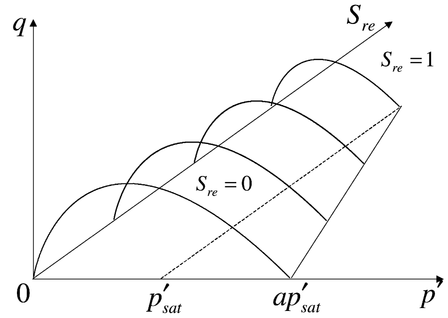


Figure1 Yield surface for unsaturated soil

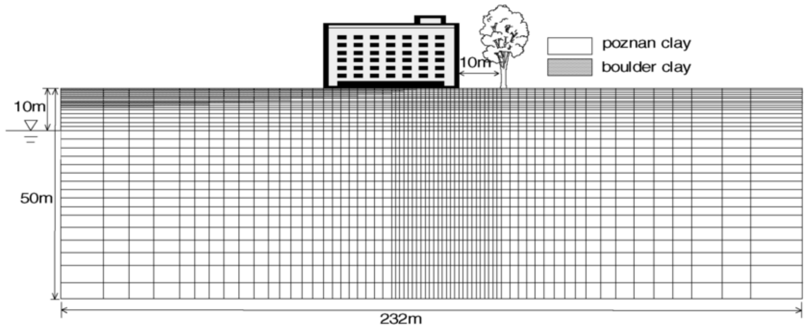


Figure 3 Mesh for simulation

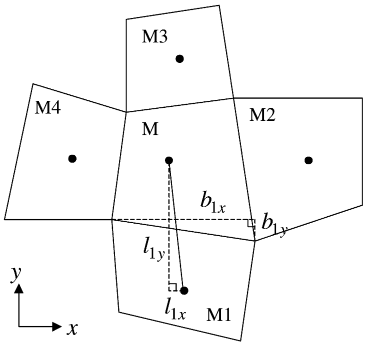


Figure 2 Akai and Tamura Method
(Akai and Tamura 1978)

Figure 4 Development of root element

$$\boldsymbol{\sigma}^{net} = \boldsymbol{\sigma} - p_a\mathbf{1},\ p_s = S_{re}s \tag{2}$$

$$s = p_a - p_w,\ S_{re} = \frac{S_r - S_{rc}}{1 - S_{rc}} \tag{3}$$

In the above equations, $\boldsymbol{\sigma}'$ is the effective stress tensor; $\boldsymbol{\sigma}^{net}$ is the net stress tensor; $\mathbf{1}$ is the second rank unit tensor; $\boldsymbol{\sigma}$: is the total stress tensor; s is suction, p_s is the suction stress; p_a is pore-air pressure; p_w is the pore-water stress, S_r is the degree of saturation; S_{re} is the effective degree of saturation; and S_{rc} is the degree of saturation at $s \to \infty$.

$$f\left(\boldsymbol{\sigma}', \zeta, \varepsilon_v^p\right) = MD\ln\frac{p'}{\zeta p'_{sat}} + D\frac{q}{p'} - \varepsilon_v^p = 0 \tag{4}$$

$$p' = \frac{1}{3}\boldsymbol{\sigma}' : \mathbf{1},\ q = \sqrt{\frac{3}{2}\mathbf{s} : \mathbf{s}},\ \mathbf{s} = \boldsymbol{\sigma}' - p'\mathbf{1} = \mathbf{A} : \boldsymbol{\sigma}',\ \mathbf{A} = \mathbf{I} - \frac{1}{3}\mathbf{1}\otimes\mathbf{1} \tag{5}$$

In the above equations, M is q/p' at the critical state; D is the dilatancy coefficient; $\mathbf{I}$ is the four rank unit tensor; and : and $\otimes$ are the inner and outer product operators, respectively. Plastic volumetric strain, ε_v^p , is applied as a hardening parameter. Increase of yield stress due to desaturation is expressed as the product of yield stress in the saturated state, p'_{sat} , and a parameter contributing to hardening, ζ . Ohno et al. (2007) introduced this parameter, ζ , shown as equation (6).

$$\zeta = \exp\left[\left(1 - S_{re}\right)^n \ln a\right] \tag{6}$$

Here, equation (4) corresponds to the Cam-Clay Model for the saturated state ($S_{re} = 1$ and $\zeta = 1$). Figure 1 shows the yielding surface for the unsaturated soil, expressed as equations (4) and (6), where a and n are fitting parameters and influence the shape of the yield line at $p' - q$ plane in Figure 1.

2.2 *Application of 'root element'*

Kawai et al. (2007) regarded the effect of water uptake due to transpiration as water reduction within soil and expressed water continuity equation as;

$$v_{i,i} = S_r\dot{\varepsilon}_v - n\dot{S}_r - \xi \tag{7}$$

where v_i is pore-water flow velocity; S_r is the degree of saturation; ε_v is the volumetric strain; n is the porosity; ξ is the water-loss rate; and the superscript dot represents increment. We can obtain the discretized equation shown as equation (8) by applying Darcy's Law and discretizing spatially with the Akai and Tamura Method (shown in Figure 2).

$$\begin{aligned} -\int_{S_q^e} k_{ij}\frac{\partial h}{\partial x_j} n_i dS &= -\sum_{i=1}^{4}\left(\frac{k_{xx}}{\gamma_w}\frac{b_{iy}}{\ell_{ix}} + \frac{k_{yy}}{\gamma_w}\frac{b_{ix}}{\ell_{iy}}\right)\gamma_w h^M \\ &+ \sum_{i=1}^{4}\left(\frac{k_{xx}}{\gamma_w}\frac{b_{iy}}{\ell_{ix}} + \frac{k_{yy}}{\gamma_w}\frac{b_{ix}}{\ell_{iy}}\right)\gamma_w h^{Mi} = -\beta\gamma_w h^M + \sum_{i=1}^{4}\beta_i\gamma_w h^{Mi} \end{aligned} \tag{8}$$

$$\begin{aligned} &S_r\left[K_v\right]\left\{\Delta u^N\right\} + \left(\alpha n\frac{\partial S_r}{\partial s} + \Delta t\beta\right)\gamma_w h^M|_{t+\Delta t} - \sum_i \Delta t\beta_i\gamma_w h^{Mi}|_{t+\Delta t} \\ &= \alpha n\frac{\partial S_r}{\partial s}\gamma_w h^M|_t + \Delta t\alpha\xi \end{aligned} \tag{9}$$

$$\dot{\varepsilon}_v = \left[B_v\right]\left\{\dot{u}^N\right\},\ \left[K_v\right] = \int_{V^e}\left[B_v\right]dV,\ \alpha = \int_{V^e} dV \tag{10}$$

Here, k_{ij} is the hydraulic conductivity; h is the total head; u^N is the nodal displacement; and γ_w is the unit weight of water. The element formulated in this fashion is called 'root element.'

3 EVAPO-TRANSPIRATION SIMULATIONS

Wojtaski and Jez (2000) reported that the water uptake work of the vegetation encouraged non-uniform settlement of the ground and caused building damage. The case history of a multi-story apartment building, constructed in 1961, was reported when a crack on its north wall was first found in 1973. The crack area had gradually been developing toward the south for twenty years. The ground used to be originally wet. However, the water content of the ground on the north side of the building was much lower than usual when the research was performed in 1986. Some trees were cut down in 1993, when the development of the crack area stopped. This non-uniform settlement, due to water content reduction, was regarded as shrinkage induced by water uptake of trees. Here,

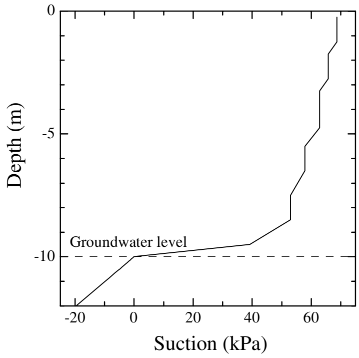


Figure 5 Distribution of initial suction

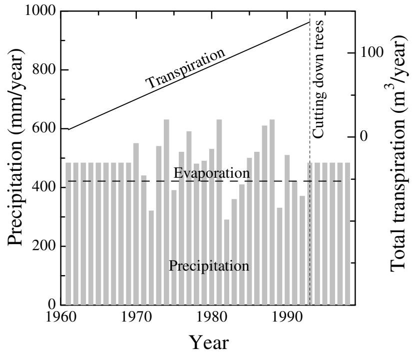


Figure 6 Evaporation, transpiration rate and precipitation used for simulations

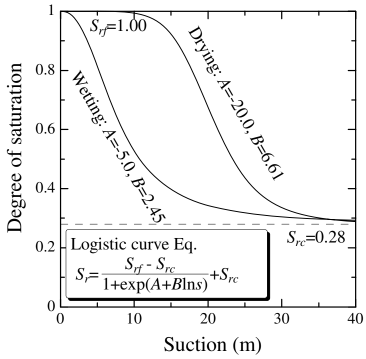


Figure 7 Soil-water retention characteristic

Table 1 Soil parameters used for simulations

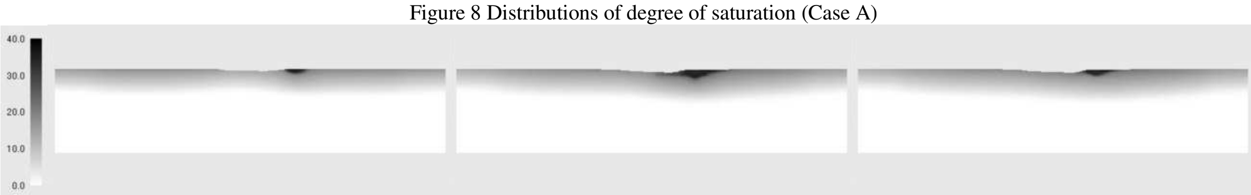
λ (Compression index)		κ (Expansion index)		M	ν (Poisson's ratio)	a	n
Poznan	Boulder	Poznan	Boulder				
0.18	0.097	0.037	0.023	1.4	0.333	150	1.0
k (Saturated hydraulic conductivity)				m (Parameter of Mualem's equation (1974))			
Poznan		Boulder		Poznan		Boulder	
8.64×10^{-4}		1.0		0.6		0.6	

Table 2 Simulation Cases

	Case A	Case B	Case C
Evaporation and rainfall	Taken account	Taken account	Taken no account
Transpiration	Taken account	Taken no account	Taken no account

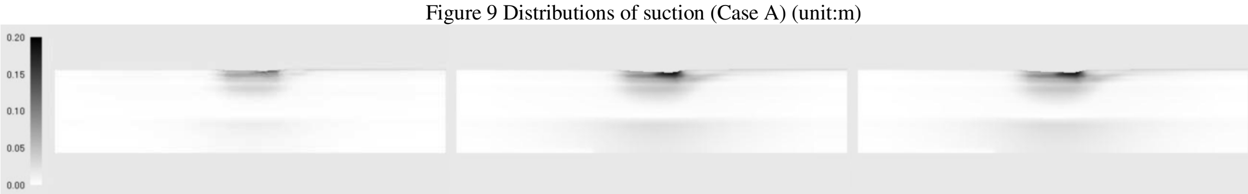
(a) 1970 (b) 1993 (c) 1998

Figure 8 Distributions of degree of saturation (Case A)



(a) 1970 (b) 1993 (c) 1998

Figure 9 Distributions of suction (Case A) (unit:m)



(a) 1970 (b) 1993 (c) 1998

Figure 10 Distributions of volumetric strain (Case A)

this actual accident is simulated with the soil/water coupled simulation protocol formulated in the previous chapter.

3.1 *Conditions of simulations*

Figure 3 shows the mesh used for simulation. The ground consists of Boulder clay and Poznan clay. Poznan clay, raised up to the ground surface by a glacier, occupies one third of the building. There are Italian poplars, willows and maple trees at a distance of 10m from the building. The distribution of the root element shown in Figure 4 is set up considering the development of typical root systems. According to Wojitask and Jez's report, the root developed under the building in 1993. The bottom boundary is undrained and the right and left boundaries are head boundary of G.L. –10m. The upper boundary is flux boundary corresponding to evaporation and rainfall. Figure 5 shows the distribution of initial suction in the ground. This distribution was determined from the distribution of water content measured in 1961. Figure 6 shows the potential evaporation rate, precipitation, and transpiration rate applied to simulations. The potential evaporation, 412mm/year, was obtained from the climate condition in Poland with Penman's Method (1948). We assumed that the transpiration rate increases with the

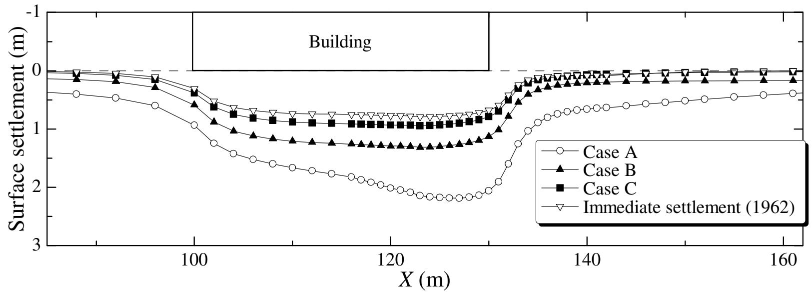


Figure 11 Settlements of ground surface in 1998

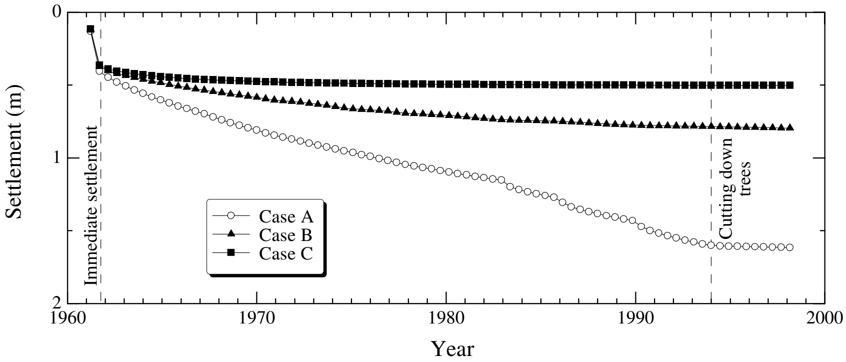


Figure 12 Changes in the settlement in the north side of the building

development of the root system. Table 1 shows parameters used for simulations. Poznan clay consists of particles that are smaller than Bouldar clay, and has a higher compressibility and lower permeability. The soil-water retention characteristics used for simulation are shown in Figure 7. Three cases of simulations were performed see Table 2. The effect loading had on the building was taken into account only in Case C.

3.2 *Simulation results and discussion*

Figures 8 and 9 show changes in distributions of degree of saturation and suction in Case A, respectively. It was found that decrease of soil moisture due to water uptake, induced by vegetation and suction, increase simultaneously and occur around the vegetation from 1970 to 1993. Though it is not clear from the contours, soil moisture recovered in 1998 and the suction decreased, five years after the trees had been cut down. Figure 10 shows distributions of volumetric strain. The dissymmetric volumetric strain appears since compression in north side (right side) of the building produces notable shrinkage induced by water uptake. The settlement remained even when suction decreased after cutting down trees. Figure 11 shows the settlements of ground surface in 1998. The immediate settlement due to loading of the building is rather large. For comparison, the settlement that took place in the 9 months after construction is shown in the figure. Non-uniform settlement in Case A, considering the effects of vegetation, is most notable. Figure 12 shows changes in settlement in the north side of the building. In Case A, the settlement monotonically increases up to 1993, after cutting down of the trees. The settlement rate changes in 1983 and 1989. This is because annual precipitation in these years was less than in others. For this reason, it is found that the effects of water uptake are greater on drier ground.

4 CONCLUSIONS

In this study, we formulated the effects of water uptake work of the vegetation as the root element and applied this to unsaturated soil/water coupled analysis. The constitutive model proposed by Ohno et al. was used. Their model applies effective degree of saturation as a parameter expressing hardening/softening of unsaturated soil, and has an advantage in setting soil parameters from experimental results deductively. An actual accident in Poland was simulated with the unsaturated soil/water coupled analysis. Our results showed that water uptake work of the vegetation brought about non-uniform settlement. The simulation results showed good agreement with the actual accident. In conclusion, the effect of water uptake of the vegetation on the ground is significant and cannot be neglected.

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