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A new permeability model for shrinkable soils undergoing desiccation

Un nouveau modèle de perméabilité pour les sols rétractants en phase de dessiccation

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ABSTRACT
Desiccation of shrinkable soils can result in cracking of the ground. The cracks subsequently close on wetting up of the soil. The cracks can increase the mass permeability of a soil by several orders of magnitude. The modelling of crack formation and their closure involving seasonal changes in rainfall and evapotranspiration presents a challenge in boundary value problems where permeability has a significant influence on the accuracy of predictions. This paper presents a smeared permeability model which simulates the variation in permeability during cracking and subsequent wetting up of a soil.

RÉSUMÉ
La dessiccation des sols rétractants peut résulter en une fissuration du terrain. Les fentes se referment ensuite après humidification du sol. Les fentes peuvent augmenter la perméabilité de masse d'un sol de plusieurs ordres de grandeur. Modélisation la formation et la fermeture des fentes en tenant compte des variations saisonnières de précipitations et de l'évapotranspiration présente des difficultés pour les problèmes de valeurs aux limites où la perméabilité a une influence non négligeable sur la précision des prédictions. Cet article décrit un modèle de perméabilité moyenne qui simule la variation de perméabilité au cours de la fissuration puis de l'humidification d'un sol.

1 INTRODUCTION

Permeability is a key input parameter in boundary value problems when determining stress and strain changes associated with pore fluid movement in a soil mass. A variety of permeability models have been developed, ranging from simplistic models in which homogeneity and isotropy are assumed, to more sophisticated models where permeability is assumed to be a function of mean effective stress or void ratio.

In clayey soils which experience alternate desiccation cracking and swelling, the magnitude of permeability is highly variable and complex because other factors such as partial saturation and the influence of crack width and geometry begin to play a significant role eg. (Anderson *et al*, (1982) and Blight (1997)). The permeability of a soil reduces during desiccation and in clayey soils can result in cracking. The presence of cracks then increases the mass permeability of a soil and significantly increases the rapidity of infiltration upon wetting up. The development of realistic models to reproduce this complex behaviour is still in its infancy eg. Kodikara *et al* (2000), Prat *et a*l (2002), Konrad & Ayad (1997) and Wallace & Lytton (1992).

This paper presents a new permeability model which reproduces the changes in permeability associated with crack formation. Numerical predictions of pore water pressure changes were made under seasonal variations of infiltration and evapotranspiration rates. To illustrate the use of the new model it was incorporated into the Imperial College Finite Element Program (ICFEP). This was then used to obtain predictions of pore water pressure changes due to seasonal variations of infiltration and evapotranspiration at the surface of level ground.

2 DEVELOPMENT OF CRACK PERMEABILITY MODEL

The crack permeability model uses a smeared approach ie. the initiation and propagation of individual cracks is not modelled. Isotropic conditions are assumed in the model, ie. the direction of cracking is not considered in the computation of the permeability. In the model, cracking is assumed to occur when the minimum total principal stress, σ_3, equals a prescribed value (ie. zero). For clarity, the changes in permeability as a result of desaturation were excluded in the numerical algorithm. The description of the model shall be made with reference to Figure 1. The crack permeability model presented here was used in conjunction with a permeability model dependent on mean effective stress, p'.

Figure 1 shows the relation between σ_3 (the most tensile principal stress) and coefficient of permeability, k, assumed in the model. The value of σ_{3_1} defines the magnitude of σ_3 at which crack initiation occurs whilst σ_{3_2} marks the magnitude of σ_3 at which full cracking is assumed to have occurred. The permeability is assumed to increase from an initial value, k_i (uncracked ground) to a final value, k_f, (fully cracked ground) according to a logarithmic relationship. The program identifies the integration points where the tensile stress of the soil exceeds σ_{3_1} and appropriates a permeability value by interpolating along the curve shown in Figure 1. The user inputs the values of σ_{3_1}, σ_{3_2}, and the ratio of the final to the initial permeabilities, k_f/k_i, at the beginning of the analysis. In the analyses reported in this paper, the values of σ_{3_1} and σ_{3_2} were assumed to be zero and 100kPa, respectively. Further details of the model are described in Nyambayo (2003).

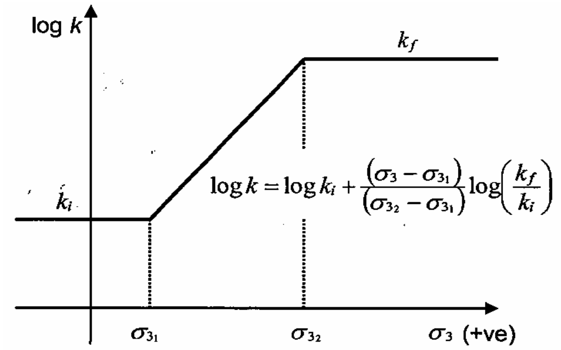

Figure 1 Variation of mass permeability with σ_3 in the new model.

In the field the rate at which the mass permeability changes from an initial value, k_i, to a final value k_f, depends on the rate at which the cracks propagate and their spatial density. The magnitude of the final permeability, k_f, is primarily a function of the crack widths and patterns. In the field open cracks can get infilled with debris. The behaviour of infilled cracks is even more complex and primarily affects the rate at which the cracks close during wetting. This aspect has not been considered in this model ie. the curve in Figure 1 has been assumed to be reversible along the same path.

3 METHODOLOGY OF ANALYSIS

3.1 *Stratigraphy and mesh*

A 45m deep London Clay stratum was assumed. A one-dimensional situation was analysed using a 1m wide column. The finite element mesh was denser in the top 10m where most of the pore water pressure and stress changes were expected to occur. No horizontal movements were allowed along the vertical boundaries. The bottom boundary was fixed whilst the top boundary was assumed to be free. Infiltration and evapotranspiration was imposed along the top boundary. The side boundaries were assumed to be no flow boundaries. Along the bottom boundary the pore pressures were maintained at their initial value.

3.2 *Soil parameters and constitutive modelling*

The London Clay was assumed to have a density of 18.8 kN/m^3. The coefficient of earth pressure at rest, K_o, was assumed to be 2 at ground level, reducing linearly to 1 at 10m depth and remaining constant at 1 below 10m depth. Drained strength parameters φ' and c' equal to 20° and 5kPa respectively, were assumed. The stiffness of the clay in loading was modelled using Equation 1. The unloading/reloading stiffness was double that given by Equation 1.

$$E_i' = E_0'\left[\frac{p_a + p'}{p_a}\right] \tag{1}$$

where E_i' is the loading Young's modulus, p_a is atmospheric pressure, p' is the mean effective stress and E_0' is a model parameter. The value of E_0' was taken as 2500 and a minimum value of 4000kPa was specified for E_i'. A Poisson's ratio of 0.25 was assumed.

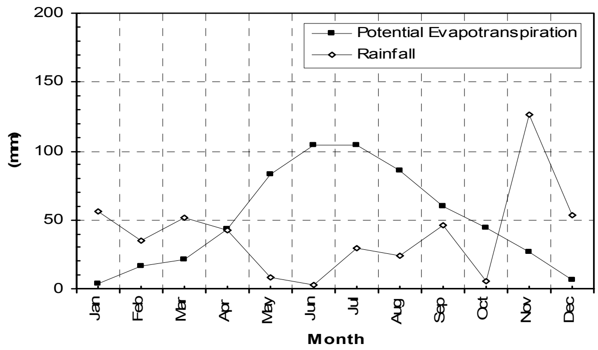

Figure 2 Meteorological data used in analyses.

The meteorological input data comprised median monthly data for potential evapotranspiration and rainfall for deciduous tree cover for a test site in SE England (Figure 2). Actual evapotranspiration was computed using a root water uptake model (Nyambayo, 2003). Rainfall was modelled using a precipitation boundary condition (Potts & Zdravkovic, 1999). Ponding of rain water was not allowed at ground level in the model to mimic runoff and this was achieved in the analyses by limiting the maximum predicted compressive pore water pressure at ground level to 0kPa. Automatic incrementation was employed in the FE analysis to improve the accuracy of pore water pressure predictions (Smith, 2003).

The initial conditions assumed the phreatic surface to be at 1m below ground level (typical of winter pore water pressures in the UK) and hydrostatic below this surface. Above the phreatic surface, a hydrostatic suction profile was assumed with a suction of 9.81kPa at ground level.

The results presented here are for analyses executed using three permeability models as follows:

Model 1: inhomogeneous permeability ie. $k = k_0 - bz$ where k_o = 2x10^{-9} m/s, $b = 0.0393s^{-1}$ and z is depth below ground level.

Model 2: permeability dependent on mean effective stress, p' ie. $k = k_0 e^{-(\beta p')}$ where k_o = 2x10^{-9} m/s and β = 0.007kPa^{-1}

Model 3: the new crack permeability model in tandem with model 2.

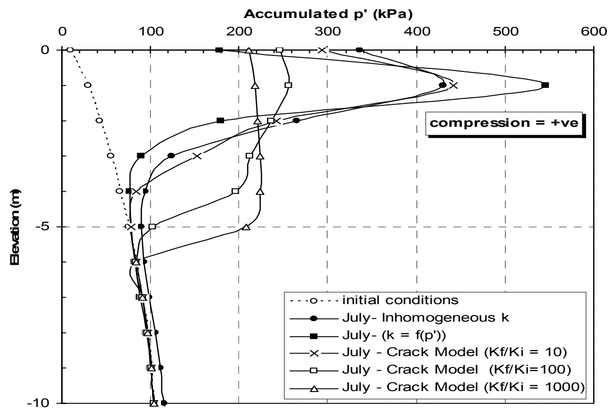

Figure 3 Influence of cracked permeability model on accumulated p′ at the end of July.

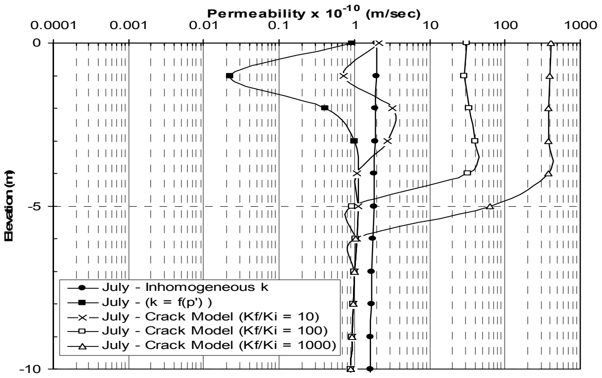

Figure 4 Influence of k_f/k_i ratio on magnitude of permeability at the end of July.

4 RESULTS

The predictions of pore pressure changes and p′ using the new crack model are compared with those using inhomogeneous and *p′* dependent models. In the figures, ground level is at elevation 0m. Figure 3 shows the predictions of *p′* in July (summer) by the 3 models. The figure shows that at shallow depth (less than 2m), *p′* has significantly reduced by invoking the crack model. The reduction in stress increases as the k_f/k_i ratio increases. There is also evidence from Figures 3 that the desiccated profile extends to deeper horizons when using the crack model. This behaviour has been observed in the field (eg. Crilly and Driscoll (2000)).

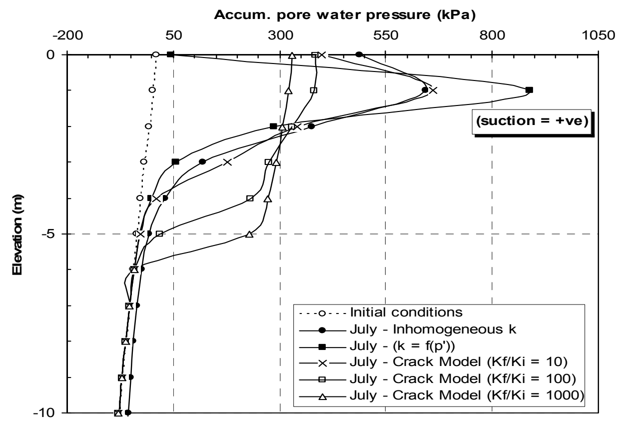

Figure 5 Influence of cracked permeability model on accumulated pore water pressure at the end of July.

Figure 4 shows the corresponding permeability profiles after 6 months (end of July); which coincides with larger evapotranspiration rates compared to rainfall. The huge reduction in permeability for the p′ dependent model is clearly portrayed in the top 2m of the strata. Similarly, the increase in permeability with increasing k_f/k_i ratio is also evident. Note that when the crack model is invoked, the k_i value is equal to the k for the *p′* dependent permeability model.

Figure 5 shows the accumulated pore water pressure profiles at the end of July. At 1m depth, maximum suctions of 890kPa predicted by the *p′* dependent permeability model have reduced to 660kPa, 380kPa and 320kPa using k_f/k_i ratios of 10, 100 and 1000, respectively. Larger redistribution of suctions occurs to deeper horizons in the crack permeability model.

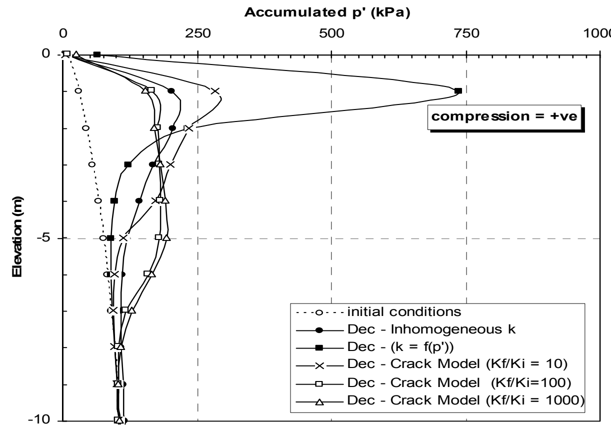

Figure 6 Influence of cracked permeability model on accumulated p′ at the end of December.

Figure 6 shows the profiles of accumulated mean effective stress after 12 months (end of December). It can be seen that *p′* has increased at shallow depth in the analysis involving the *p′* dependent permeability model, whereas the predictions by the crack model with a k_f/k_i ratio of 10 yields a much lower *p′* eg. at 1m depth the value of *p′* increases from 540kPa (end of July) to 740kPa (end of December) for the analysis with a *p′* dependent permeability model compared to a reduction from 440kPa (end of July in Figure 3) to 290kPa (end of December) in the analysis involving a crack model with a k_f/k_i ratio of 10.

The corresponding reductions in *p′* for higher k_f/k_i ratios are 260kPa to 160kPa for a k_f/k_i ratio of 100 and 220kPa to 150kPa for a k_f/k_i ratio of 1000. The latter reduction in *p′* during winter associated with the crack permeability model is consistent with observed field behaviour ie. a reduction in evapotranspiration coupled with increasing precipitation contributes to an overall reduction in *p′*.

The permeability profiles corresponding to the end of December conditions are shown in Figure 7. Overall, the magnitude of permeability reduces near ground level where the effects of precipitation are greatest; notwithstanding that the change in permeability for a crack model with a k_f/k_i ratio of 10 are generally small.

The accumulated pore water pressures at the end of December are shown in Figure 8. It is interesting to note that at this stage, the predictions by the crack models with k_f/k_i ratios of 100 and 1000 are nearly of the same order of magnitude. This would suggest that any further increase in k_f/k_i ratio is unlikely to yield significant differences in the pore water pressure predictions.

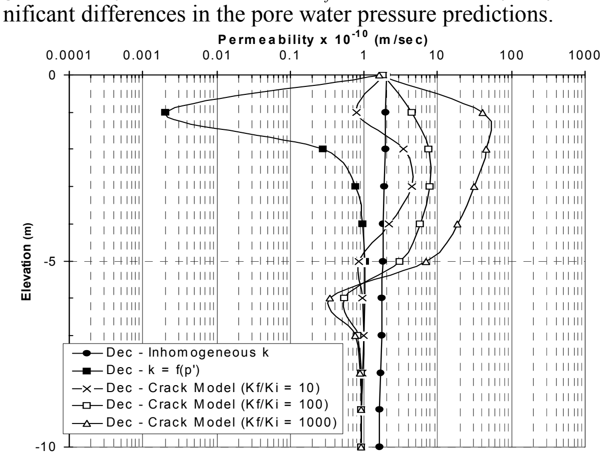

Figure 7 Influence of cracked permeability model on magnitude of permeability at the end of December.

It can also be seen from Figure 8 that for crack models with k_f/k_i ratios of 100 and 1000, the effect of redistribution of suctions at depth results in a larger spread of the zone of maximum suctions. Maximum suctions of 200kPa are predicted between 1m and 5m below ground level. For the crack model with a k_f/k_i ratio of 10, the maximum suctions (310kPa) are localized at 1m - 2m depth below ground level.

Figure 9 shows the variation of the accumulated pore water pressures from January to December at 1m depth. The figure corroborates the fact that the p' dependent permeability model over-predicts the magnitude of p' because it cannot take account of permeability increase due to cracking. This results in less rainfall being absorbed and leads to higher suctions being retained within the ground. In comparison, crack permeability is capable of mimicking the significant reduction in suction that occurs in cracked ground. This is borne testimony to in Figure 10 which compares the variations in the magnitude of permeability during the 12 month period.

In general, the patterns display a strong correlation with the meteorological data (Figure 2) whereby the stress changes and corresponding increase in permeability (to simulate the influence of cracking) are dependent on the magnitude of evapotranspiration and rainfall.

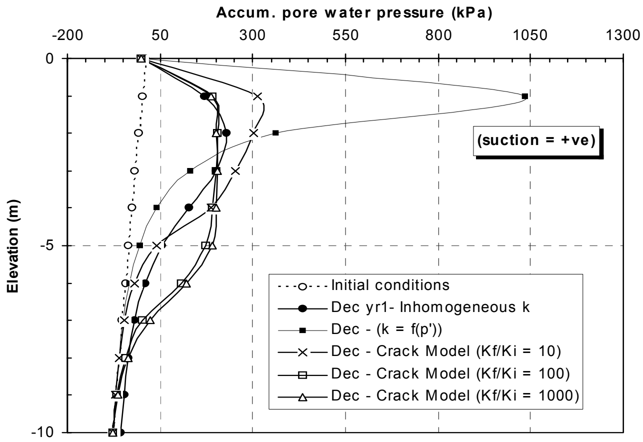

Figure 8 Influence of cracked permeability model on accumulated pore water pressure at the end of December.

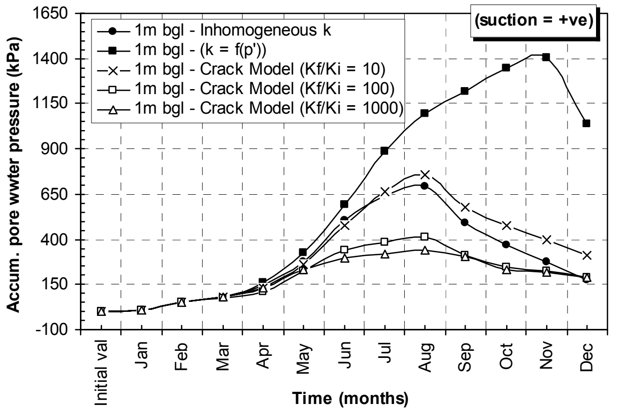

Figure 9 Influence of cracked permeability model on accumulated pore water pressure at 1m bgl.

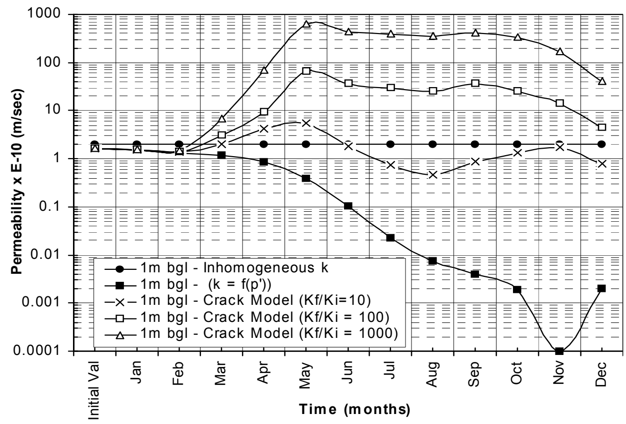

Figure 10 Influence of k_f/k_i ratio on permeability at 1m bgl.

5 SUMMARY AND CONCLUSIONS

Desiccation of clayey soils reduces its permeability, however, when the ground cracks its mass permeability increases. The process is complex and conventional permeability models are unable to mimic field behaviour.

A smeared crack permeability model was developed to model the effects of cracking on the mass permeability of the soil. The predictions by the new model were compared with an inhomogeneous permeability and one where permeability is dependent on p'. It has been shown that because the inhomogeneous model maintains the same magnitude of permeability at each elevation within a soil profile, it is unable to mimic the reduction in permeability that occurs during desiccation and the subsequent increase due to cracking. In comparison, although a model dependent on p' is capable of simulating the gradual reduction in permeability as desiccation increases, it is unable to model the increase in the mass permeability of the ground if cracking occurs by retaining a high p'. In comparison, the new crack model has been shown to be capable of simulating the increase in permeability associated with crack formation and the subsequent enhanced permeability that occurs upon wetting-up and closure of the cracks.

Overall, the predictions by the new crack model yield pore water pressure profiles which most resemble observed field patterns compared to the inhomogeneous and p' dependent permeability models. The relatively large redistribution of suctions associated with the new crack model arises from the assumptions that cracks form when a threshold value of σ_3 is exceeded. The model is therefore predicting an increase in permeability in all the zones where the criterion for crack formation (as assumed) is satisfied. The authors believe that crack formation (being a very complex process) is dependent on more than one parameter (σ_3), as currently modelled. Therefore there is scope for improvements to the model. The formation of cracks in soils is currently not well researched and understood by geotechnical engineers.

The overall pattern of pore water pressures and p' suggests that in order to obtain realistic predictions for soil undergoing alternate desiccation and wetting-up, it is necessary to use a permeability model which combines dependency on p' (or void ratio) with the ability to reproduce the influence of cracks on the mass permeability of the soil as demonstrated in this paper.

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