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A consolidation model for bleeding of cement paste*

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I was delighted to read the paper by Dr Tan and his colleagues as it mirrors some of the work that we have been doing at King's College London.

The following comments on the paper are made in the light of many years of experience with the use of consolidation theory for the prediction of bleed. They may be of use to the authors in developing the next stage of their work and to others who wish to make use of a concept widely applied in soil mechanics but to date little used in cement technology.

FORMULATION OF THE PROBLEM

The formulation which the authors have adopted would seem more complex than is strictly necessary and perhaps justified for a small strain situation. For example the authors propose a relationship between permeability and void ratio in their Equation (15):

$$k = K_0(1 + e) \dots \dots \dots (15)$$

This seems unsatisfactory, for when $e = 0$ (that is a solid with no porosity which should have zero permeability)

$$k = K_0$$

Equation (15) is unlikely to be valid except over a very limited range of values for e and indeed it may introduce errors. Unless there are experimental data to confirm the validity of Equation (15) it would seem more satisfactory to adopt the assumption used in

small strain consolidation theory that the permeability is a constant.

If constant permeability is adopted then the classical self-weight consolidation theory presented by Terzaghi and Frohlich⁽¹⁾ may be used. From this theory it can be shown that, for the initial stages of consolidation, the rate of bleeding Q , is given by

$$Q = k(\gamma_g - \gamma_f)/\gamma_f \dots \dots \dots (1)$$

where k is the permeability and γ_g is the unit weight of the grout. This equation is analogous to Equation (24) of the paper which, by making appropriate substitutions and evaluating the numerical component, can be reduced to:

$$Q = K_0(\gamma_g - \gamma_f)/\gamma_f \dots \dots \dots (2)$$

The advantage of Equation (1) is that k is a permeability and directly measurable and has physical significance whereas K_0 is a hypothetical permeability at zero voids ratio. This may be a small point. However, the introduction of K_0 would seem to reduce the clarity of the model without increasing the reality. The important fact is that it is not necessary to adopt a variable k to produce the result that the rate of bleeding is independent of depth. It is of course appreciated that the form of Equation (15) was adopted for numerical convenience as Gibson *et al.*⁽²⁾ adopted $\gamma_s = \gamma_f$.

Thus, in general, small strain theory is quite adequate to predict the bleeding of grouts. Indeed grouts which show large bleed (high water/cement ratio mixes) are likely to show channelled bleed which requires a significantly more complex analysis.

*Pages 18 to 26 of ACR, Vol. 1, No. 1.

EFFECT OF DEPTH OF GROUT

The authors show that using two parameters such as C_v and β it is possible to predict a theoretical curve for the bleeding of a grout. For drainage solely to the top surface, the initial rate of bleeding is independent of the depth of the sample and thus samples of all depths should show a settlement-time curve of the same initial slope. The only effect of the sample depth is to change the time at which the period of diminished bleeding rate becomes apparent. The problem is that the model presented in the paper predicts the theoretical bleeding of the grout, that is the bleeding which would occur if there were no set. The problem then remains to predict the actual bleed that will occur which, due to set, may be only a small fraction of the theoretical maximum bleed (the bleeding capacity).

Thus the model, although capable of describing bleed in shallow samples, does not answer the problem: how much bleed will occur in a real grout mass. How can laboratory data be scaled to represent bleed in say a 10 m tall prestressing duct? A reasonable estimate of the actual maximum bleed that will occur in a grout column can be obtained by considering just the early stages of the consolidation process. At any stage of consolidation, the degree of consolidation (the amount of settlement at any time/the ultimate settlement if there were no set) can be predicted from the time factor as defined in Equation (17b) or, if small strain theory is used, from the simpler equation

$$T = C_v t / h^2 \dots \dots \dots (3)$$

where C_v is the coefficient of consolidation and h is the height of grout. (Note that for the corresponding definition in the paper, Equation (17b), h_z is the equivalent height of solids.) For either formulation of the problem the time factor is inversely proportional to the square of the depth of the grout. Thus for example it will take 100 times as long for the grout in a duct 1 m high to reach the same degree of consolidation as it would in a 100 mm duct and so the degree of consolidation achieved in 30 min in a 100 mm duct would take 3000 min in a 1 m duct. Hence, in almost all practical ducts, bleed will be stopped by set and complete consolidation will not occur unless there are other drainage surfaces. Indeed in most practical ducts only a small fraction of the maximum possible bleed (the bleeding capacity) will occur and Equation (1) above or (24) of the paper can be used to predict the rate of settlement. Equation (1) is valid for values of the time factor, T , less than about 0.15. It follows that if relatively 'deep' samples are tested so that set occurs before the time factor as defined by Equation (3) exceeds 0.15 then the final bleed is given by

$$\text{Bleed} = Q \times \text{time to set}$$

where Q , the rate of bleeding, is a constant as given by Equation (1) or (24) and the time to set is the time

from placement of the grout until it has sufficient strength to prevent further consolidation. Clearly the time to set may be a function of the stress level i.e. the height of the column. As a first approximation it may be assumed to be independent of the height of the grout column. This may seem a rather cavalier assumption but it should be remembered that hydrating cement shows an initial period of relative inactivity, but once set starts, strength gain is quite rapid. If set is independent of depth, and the coefficients of consolidation and compressibility are also reasonably insensitive to the stress level, then the maximum bleed, and not just the rate of bleeding, in any deep grout mass duct will be independent of the depth of the grout. A grout mass may be defined as 'deep' if

$$C_v t_s / h^2 < 0.15 \dots \dots \dots (4)$$

where t_s is the time to set (strictly this should be measured from grout placement rather than mixing but clearly measuring time from mixing will give a conservative result). For low water/cement ratio grouts (0.3–0.4) the minimum depth for constant bleed may be less than 200 mm and thus almost all practical grout masses will be 'deep'. For higher water/cement ratio grouts, provided there is no channelled bleed, the minimum depth for a 'deep' mass is typically less than 1 m though it will depend on the type of cement, the shear level during mixing, temperature, etc.

Thus to predict bleed in ducts over about 1 m high (and less for low water/cement ratio grouts) it is not necessary to carry out small-scale experiments and extract consolidation parameters. A reliable estimate of bleed can be obtained by casting a test specimen about 1 m high and measuring the actual final bleed. The test is very simple since it is not necessary to measure the rate of settlement, merely the final settlement. If there is uncertainty over the necessary height, for example if a slow setting cement is to be used or low temperatures are involved, then a series of samples can be cast. Because of the h^2 term in Equation (4), only a limited range of heights need be tested. For practical situations where the depth of grout is less than 1 m the full-scale depth can easily be modelled in the laboratory. The independence of bleed and duct height has been confirmed for ducts up to 6 m high and is reported in Reference (3).

SHRINKAGE

Bleed is not the only process which causes surface settlement in a grout. The cement hydration reactions will lead to an overall reduction in volume and the development of negative pore pressures. Often this leads to the re-absorption of all bleed water. With low water/cement ratio grouts (water/cement ratios typically less than about 0.4 though this will depend on the method of mixing, for example) shrinkage from hydration may be of the same order of magnitude as

bleeding. Shrinkage may not be fully manifested at the surface, as internal cracking may develop if the grout mass is restrained at the walls.

ALTERNATIVE DRAINAGE PATHS

It is important to note that for the analysis presented in the paper the top surface of the grout must be the only drainage surface. Other drainage situations can be analysed; for example, if there is leakage at the base of the duct consolidation will be significantly more rapid and hence more severe. If there is radial drainage, for example to an unsealed tendon bundle, in ducts over a few metres high, the bleed may be increased by orders of magnitude.

CONCRETE

The authors state that the results can be adapted for use by the concrete industry. In principle this may be the case but in practice the situation is much more difficult to investigate for concrete than for grouts. The presence of aggregate in concrete increases the permeability and reduces the coefficient of compressibility. Both these factors increase the coefficient of consolidation and hence the rate of consolidation. Furthermore the depth of a concrete pour may be quite small compared with the height of a prestressing duct. Thus for concrete, consolidation may be very rapid and as a further complication the effects of rate of placement can be highly significant. Harrison⁽⁴⁾ provides useful data on concrete.

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Reply by the authors

The authors would like to thank Dr Jefferis for his

discussion which raises a number of interesting points. His discussion also indicates a growing awareness that bleeding may be a consolidation process and not sedimentation as previously thought. That is the main thrust of the paper, and the experimental and analytical works reported in it were intended to clearly demonstrate the point.

Since viewing bleeding as a consolidation process is a new idea in cement technology, it was decided that a fundamental approach should be adopted in developing the theory. The reason for this is obvious. It is important to have as a basis for any future development a theory that is as general as possible. When solving a particular problem, a researcher can then examine the mechanics involved and make the necessary simplifying assumptions if possible. One of the assumptions that is normally made, if the amount of settlement expected is small, is infinitesimal strain. Then the theory developed in the paper would reduce to the classic Terzaghi's theory as mentioned by Dr Jefferis.

In the paper, the following relationship between permeability and void ratio was proposed:

$$k = K_0(1 + e) \dots \dots \dots (15)$$

and it was clearly stated that this relationship is valid for the range of void ratio that is commonly encountered during the bleeding process. Of course, if the void ratio does indeed approach zero, then Equation (15) has to be changed. However, during bleeding, it is impossible for the void ratio to approach zero. As permeability does change quite drastically with void ratio, it is more accurately to use Equation (15) than to just assume a constant permeability. This has been shown by various researchers in soil mechanics.

It is recognized that in order to predict the bleeding capacity accurately, the effect of setting has to be accounted for. There are a number of ways to do this. One of them is as suggested by Dr Jefferis. Alternatively, a more fundamental approach is to investigate the change in the permeability and compressibility due to setting. Once this can be determined, then the theory as developed can be used even to predict the bleeding capacity.

In conclusion, it is reiterated that the intention of the paper is to suggest that bleeding may be a consolidation process. The works reported in the paper and Dr Jefferis's experience seems to confirm this. As this is a relatively new concept in cement technology, much more work still needs to be done before it can be fruitfully applied to the industry.