

# A NEW MODEL FOR THE BEHAVIOUR OF GRANULAR FILTERS

Mark Locke<sup>1</sup> and Buddhima Indraratna<sup>2</sup>

<sup>1</sup>PhD Student, <sup>2</sup> Professor of Civil Engineering, University of Wollongong, NSW.

## ABSTRACT

Filters are used in Geotechnical Engineering to control seepage and to prevent erosion of soil due to the drag forces of seeping water. Filters act as barriers to retain the base soil while allowing seepage flows to exit without causing high hydraulic gradients or pore pressures which may damage the structure. This paper describes a new analytical model of filtration. The model is based on a three dimensional network model of the filter pores, and the equations of conservation of mass and momentum which govern the rate of particle transport. The model has application in the design of granular filters for protecting non-cohesive base soils in embankment dams, retaining walls, drainage wells or road pavements.

## 1 INTRODUCTION

Filters are used, in geotechnical engineering, where it is necessary to protect soils from erosion due to seepage and groundwater. As water flows through a soil, particles of the soil can be washed out, leading to internal erosion (or piping) and eventual failure. A correctly designed filter will retain the eroded soil particles while allowing seepage water to flow; thus preventing piping and avoiding a build up of high internal pore pressures. Filters are used in embankment dams, road pavements, behind retaining walls, coastal protection, in landfills and wastewater treatment, sand beds in oil wells and chemical engineering filtration. This study deals predominantly with the problem of granular filters for embankment dams.

Filters are used where water seeping out of fine grained soils may cause erosion of the soil, by removing particles under hydraulic forces. To function correctly, filters must be:

- 1 Fine enough that the pore spaces between the filter particles are able to capture some of the larger particles of the protected material (see Figure 1).
- 2 Coarse enough to allow seepage flow to pass through the filter, preventing the build up of high pore pressures and hydraulic gradients.
- 3 Non cohesive, so that no cavities or cracks can form within the filter.

Figure 1 shows a stable base - filter interface. Seepage forces have washed some base soil particles into the filter. Initially, some fine base particles may be washed completely through the filter, but in a stable filter the larger base particles will be trapped by the void constrictions of the filter material. The void constrictions are the smallest cross section between two voids, hence, particles smaller than the constriction are unable to pass through to the next void. These trapped particles will then form smaller voids, retaining smaller base particles and the entire interface becomes stable. This process is called "self filtration". If a filter is too coarse, the base soil particles will be able to move through the pores of the filter material and self filtration will not occur. If a filter too fine, it may not have sufficient permeability to allow the seepage flows to leave the base soil and high pore pressures can develop. Also, manufacturing a fine filter is often considerably more expensive than a coarse filter; hence, the economic benefits of correct filter design are significant.

There is an increasing push to replace granular filters with geotextiles which perform the same function. The advantages of geotextiles are numerous, often they are cheaper to install than granular filters and they are manufactured and placed under strict specifications, so the uncertainties involved with using natural materials are removed. However, there is still a concern that the long term performance of geotextiles (remembering a dam usually has a design life in excess of 50 years) may be unsatisfactory. A particular concern is that a geotextile may tear due to differential settlement within the structure, or earthquake motion. Because of these concerns, granular filters are more commonly used in important structures such as embankment dams. This study will focus solely on the performance of granular materials as filters.

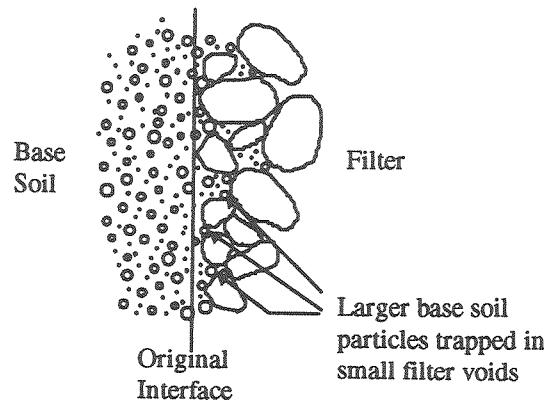


Figure 1 Stable Base-Filter Interface During Seepage (Indraratna and Locke, 1999).

## 2 EXISTING DESIGN METHODS

Terzaghi (1922) was the first to develop filter design requirements. He envisaged two requirements that must be fulfilled:

The filter should be many times more pervious than the base soil, to allow the free seepage of water, without causing excessive head loss (the permeability requirement). To ensure this he recommended:

$$D_{15F}/d_{15B} \geq 4 \quad (1)$$

The filter should be fine enough to prevent the washing through of the base soils and arrest piping (the retention requirement). To ensure this he recommended:

$$D_{15F}/d_{85B} \leq 4-5 \quad (2)$$

Where  $D_{15F}$  is the diameter of filter particles where 15% by pass of particles are smaller, and  $d_{85B}$  is the diameter of base particles with 85% of the particles, by mass, smaller. These requirements describe, basically, the conflicting requirements on grain size, of a suitable filter. Some engineers still use these criteria for designing granular filters.

Subsequent research into filter behaviour has been predominantly empirical; a series of experiments on sets of base soil - filter combinations, has lead the researcher to recommend an empirical relationship for a stable combination. Research has lead to empirical design criteria that provide simple to apply relations for stable base soil - filter combinations. The most widely accepted empirical criteria are those of Sherard and Dunnigan (1985). A review of the application of empirical methods can be found in Indraratna and Locke (1999). These empirical criteria are extensively used, in preference to other methods, for filter design. However, they are only applicable to the range of soils tested, and have certain laboratory bias due to different testing methods, definitions of failure etc. Applying empirical criteria does not provide an understanding of the mechanisms involved with base soil - filter interaction. Hence, these methods do not give the designer a clear picture of what may occur within the dam and the level of safety involved with design decisions.

Many researchers are now concentrating on numerical analysis of filtration, particularly modelling particle movement through filters. These approaches recognize that soil masses are made up of a random distribution of many sized particles. The most important part of base soil movement through a filter is the geometric requirement, that a base soil particle must be smaller than the pore void (and void constriction joining pores) through which it is passing (Silveira, 1965). Additionally, some researchers have considered the hydraulic conditions (seepage forces) necessary to carry soil particles through the filter (Indraratna and Vafai, 1997). The basis of the numerical analysis is:

to represent the filter by some form of a pore model, usually based on the particle size distribution of the filter material;  
to simulate the movement of base soil particles by an analysis of the movement of individual base soil particles through the pores of the filter, caused by seepage forces, up to a point where the particle passage is blocked by a pore constriction, or the seepage forces are insufficient to move the particle further.

There are two general approaches to modelling particle movement, either: geometric - probabilistic, where the expected depth of infiltration of a particle, into the filter, is determined by probabilistic analysis of particle and void sizes (Schuler, 1996); or mass transport equations using flow laws and conservation of mass and momentum to examine the

rate of particle movement (Indraratna and Vafai, 1997). Analytic methods provide detailed models of what may be occurring at a base soil - filter interface. They give an idea of the thickness of filter required and also can estimate a probability of failure. The assumptions used in developing the model are very important. Often the assumption of spherical particles or a certain particle size distribution curve shape etc. cannot be applied to a real soil. The models are often difficult to apply to real design situations because of their reliance on a number of empirical parameters or impractical mathematical models.

### 3 NEW ANALYTICAL FILTER MODEL

Existing numerical models of filtration have some limitations. They generally adopt simplified void models, and very few consider the time rate of formation of a stable filter interface. Indraratna and Vafai (1997) have developed a particle migration model, considering conservation of mass and momentum to model particle movement. This model is capable of showing the variation with time of particle size distribution, permeability and porosity of elements of the base soil and filter. Some criticism has been directed at the simplified void model adopted in this analysis. Hence there is some room for improvement and adaptation of this method. A new model for filtration is described below, based on the model of Indraratna and Vafai (1997), and a modified three dimensional pore void model, based on the work of Schuler (1996). The entire model includes:

**Filter void model** - based on a cubic network described by Schuler (1996). Void sizes are determined by an adaptation of the method described by Silveira (1965).

**Particle infiltration depth** - Schuler (1996) developed an equation, based on Monte Carlo simulation, for infiltration depth, dependent on particle size.

**Particle transport equations** - the equations of conservation of mass and momentum, developed by Indraratna and Vafai (1997), are used to determine the rate of particle transport.

#### 3.1 FILTER VOID MODEL

There are many models of filter voids which have been adopted in modelling filtration. The commonly used models include; parallel channels of varying diameter (Indraratna and Vafai (1997)), layers of filter voids perpendicular to the direction of flow (Silveira (1965)), or pore networks (Schuler (1996)). The three-dimensional, random arrangement of pores and constrictions in a natural soil is most accurately modelled by a regular three-dimensional network of pores interconnected by constrictions. Schuler (1996) suggests that after examination of the pore voids of a real soil, there are on average 5.7 constrictions from every pore. Based on this, Schuler (1996) developed a regular cubic network model of pores and constrictions, shown in Figure 2.

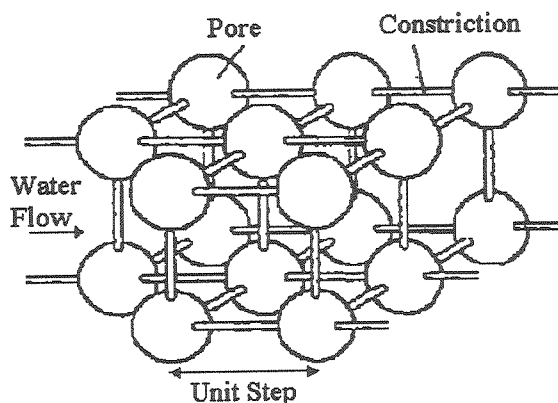


Figure 2 Cubic network void model (Schuler, 1996)

It remains then, to determine the size of the voids and void constrictions in the void model. The void constrictions, represented as bonds between the voids in Figure 2, form the smallest link between voids, capturing moving particles. Hence the important factor for modelling filtration is the void constriction size distribution, hereafter called the CSD. Schuler (1996) has examined the CSD of a soil at varying relative density and found that the CSD curves all have the same shape. Hence, if we find the CSD for most dense and least dense states, then the actual CSD will have the same shape and lie somewhere in between.

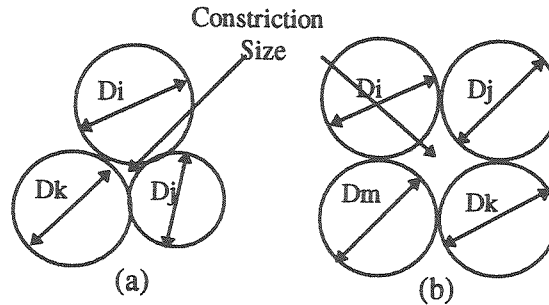


Figure 3 Void Constriction Size for a) Most Dense and b) Least Dense states (Indraratna and Locke, 2000).

The two geometric conditions to be considered, are shown in Figure 3. Humes (1996) presents a method to calculate the CSD for the most dense case (Figure 3a), based a method described by Silveira (1965) using the filter PSD. The PSD by mass (as determined by sieve analysis) tends to over-estimate the influence of larger particles, which form a large proportion of the mass of the soil, but are few in number and unlikely to meet to form large voids. Humes (1996) recommends using the PSD by surface area of grains, and has shown this to better represent the pore constriction sizes for well graded materials. Equation (3) can be used to convert the PSD by mass to a PSD by surface area, assuming all particles have the same specific gravity.

$$P_{i,SA} = \frac{P_{i,mass} / D_i}{\sum_{j=0}^n P_{j,mass} / D_j} \tag{3}$$

The PSD is divided into a number of discrete particle diameter intervals ( $D_0, D_{10}, D_{20}$ , etc.), so that it then represents the cumulative frequencies ( $P_0, P_{10}, P_{20}$  etc.) of the medians of these intervals. The theory of standard mean error can be used to find the void size,  $D_v$ , for the most dense particle packing (Equation 4). This is the case where the void is formed by three tangent spheres of diameter  $D_i, D_j$  and  $D_k$ , as shown in Figure 3a.

$$\left(\frac{2}{D_i}\right)^2 + \left(\frac{2}{D_j}\right)^2 + \left(\frac{2}{D_k}\right)^2 + \left(\frac{2}{D_v}\right)^2 = 0.5 \left[ \left(\frac{2}{D_i}\right) + \left(\frac{2}{D_j}\right) + \left(\frac{2}{D_k}\right) + \left(\frac{2}{D_v}\right) \right]^2 \tag{4}$$

The probability of occurrence,  $P_v$ , of void size  $D_v$ , is a function of the probability of occurrence of the three particles, taken from the discretised PSD.  $P_v$  is calculated using (5), where  $r_i, r_j$  and  $r_k$  represent the number of times particle diameters  $D_i, D_j$ , and  $D_k$  appear in the combination of three particles being considered. Hence  $r_i, r_j$  and  $r_k = 1, 2$  or  $3$  and  $r_i + r_j + r_k = 3$ .

$$P_v = \frac{3!}{r_i! r_j! r_k!} (P_i)^{r_i} \cdot (P_j)^{r_j} \cdot (P_k)^{r_k} \tag{5}$$

Silveira et al. (1975) present equations for the least dense packing of a granular material; where the void constrictions are formed by four tangent grains as shown in

Figure 3b. Silveira et al. (1975) note that the geometry of the problem is very difficult to solve directly. An easier method is to assume the void is equivalent to a circle with the same area as that formed by four tangent particles as shown in Figure 4b and c. The Silveira et al. (1975) equations for the diameter of the equivalent circle are presented in Indraratna and Locke (2000), and will not be repeated here.

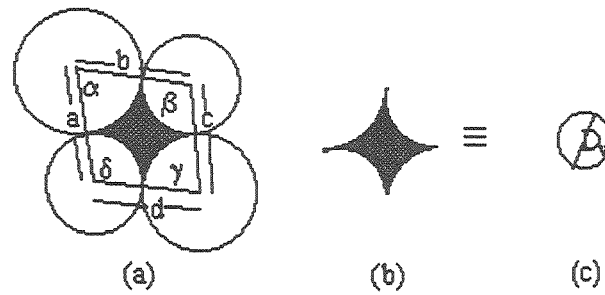


Figure 4a) Pore constriction formed by 4 particles b) Constriction Area formed by tangent particles c) Circle of equivalent area (after Silveira et al.,1975)

In the least dense packing arrangement, pore constrictions usually do not form on a plane through the centres of the four particles making up the constriction. Hence, it is suggested that the mean of all possible chords through the circular particle be used to represent the size of particles, rather than the diameter. Thus the particle diameter to be considered for determining constriction size,  $D_{model}$ , is given by Equation (6).

$$D_{model} = 0.82 D_{actual} \tag{6}$$

The CSD of a granular material, at different relative densities, will have the same shape as the most dense and least dense CSD (Schuler, 1996). The assumption is made that the difference between two constriction size distributions will be directly proportional to the difference in relative density. Hence, using relative density, defined in Equation (7), then the actual CSD can be calculated from Equation (8). The CSD is divided into  $n$  discrete portions. The integer  $i$  represents these discrete portions of the CSD such that  $\frac{i}{n}$  is the fraction of constrictions finer than constriction diameter  $D_{v,i}$ . We then have a pore void model, consisting of a 3D cubic network of pores with six constrictions connecting each pore to its neighbours, as shown in Figure 2. The size of each constriction is randomly generated from the CSD.

$$RD = \frac{e_{max} - e}{e_{max} - e_{min}} \tag{7}$$

$$D_{v,i} = D_{VMD,i} + \frac{i}{n}(1 - R_d)(D_{VLD,i} - D_{VMD,i}), i = 1, 2, \dots, n \tag{8}$$

where,  $D_{VMD,i}$  and  $D_{VLD,i}$  are the  $\frac{i}{n}\%$  coarsest constrictions from the most dense and least dense constriction size distributions respectively.

### 3.2 PARTICLE INFILTRATION DEPTH

Having defined a model of the filter voids and void constrictions, it remains to examine how far a base particle can infiltrate into the filter before being captured. Here a deterministic equation is described for the expected infiltration of base particles, based on a probabilistic analysis of particle and constriction sizes. For a base particle of diameter  $d$ , the probability,  $p$ , of the particle passing a single random constriction is the cumulative probability of larger void constrictions from the CSD (ie. the percent larger than  $d$  on the CSD). Based on the probability  $p$ , the probability of a particle passing one layer in the direction of water flow, through the three dimensional network is given by Equation (9). This equation is developed based on the combined probability of a forwards step, in the direction of flow, through the model, after any number of movements perpendicular to the flow direction.

$$P(F) = p + \sum_{i=0}^{\infty} [1 - (1-p)^4] (1-p) p^i [1 - (1-p)^3] (1-p)^i \tag{9}$$

Silveira (1965) has used an absorbing Markov chain process to determine the number of confrontations,  $n$ , with randomly generated pore constrictions, required to stop a particle moving forwards through the filter, with a confidence level  $\bar{P}$ . This equation can be adapted to consider the number of layers,  $n$ , a particle can move through the pore network model (Figure 2), based on the probability of passing one layer  $P(F)$ . The number of layers is given by

Equation (10). A confidence level of  $\bar{P}=95\%$  has been adopted in modelling, as this gives a conservative estimate of the depth a particle may infiltrate into the filter.

$$n = \frac{\ln(1 - \bar{P})}{\ln P(F)} \tag{10}$$

The spacing between layers in the network is the *unit step* between confrontations. A particle encounters a constriction, and then moves into the next pore, where it will encounter another constriction at the exit of the pore. Since particles will meet a constriction and then pass approximately two half diameters to the next constriction, it seems reasonable to adopt the mean filter particle diameter (determined by number of particles, not mass),  $D_{f,mean}$ , as the unit step. Hence, the length of infiltration,  $L$ , is given by:

$$L = \frac{\ln(1 - \bar{P})}{\ln P(F)} \cdot D_{f,mean} \tag{11}$$

### 3.3 PARTICLE MIGRATION MODEL

Indraratna and Vafai (1997) have developed a particle transport approach to model particle movement. They also consider the hydraulic forces required to mobilise the particles. If seepage forces exceed the critical hydraulic gradient and the particle is smaller than the pore constriction, it will move. Moving particles are controlled by governing differential equations of conservation of mass (12) and momentum (13).

$$\frac{d(\rho_m u)}{dz} = \frac{d\rho_m}{dt} \tag{12}$$

$$\sum F = \rho_m V_m \left( \frac{du}{dt} + u \frac{du}{dz} \right) \tag{13}$$

By considering a number of elements at the base - filter interface, the movement of particles can be modelled by a forward step, finite difference analysis. The rate of particle erosion and movement is governed by (12) and (13). The geometric constraint to movement is modelled by the depth of infiltration into the cubic network (11). If the predicted infiltration,  $L$ , of a particular particle size is equal the length from the filter interface to the end an element then particles smaller than that diameter can pass through the filter element; larger particles will be captured. The base and filter particle size distributions can be recalculated at each time step and the procedure repeated. This analysis predicts the gradual change in particle size distribution of the base and filter elements and hence describes what is occurring at the base - filter interface with time for the entire particle size range. Indraratna and Locke (2000) describe the procedure in greater detail, including a method to estimate the change in permeability and porosity of the base and filter materials during filtration. Hence, the model is able to describe the time dependent changes in particle size distribution, mass transfer, flow rate, permeability and porosity of the base and filter materials.

### 3.4 APPLICATION OF THE MODEL

The model presented in this paper is intended to predict the time rate of particle migration of a non-cohesive base soil through a granular filter. No laboratory data or alternative models are available to verify the particle migration equations proposed by Indraratna and Vafai (1997). However, the geometric model of filter voids can be compared with existing laboratory data and model predictions. A number of models have been proposed for particle infiltration depths. The models considered here are that of Schuler (1996), and Humes (1996). Previous laboratory and analytical research has shown that a filter has a controlling constriction size,  $d_c^*$  (Kenney et al., 1985). Base soil particles finer than  $d_c^*$  can pass through a filter of large thickness. As base particles larger than  $d_c^*$  are considered, their depth of infiltration into the filter decreases rapidly as the particle diameter increases. Witt (1993) also determined equations for the controlling constriction size. Hence, the particle infiltration models should predict a rapid increase in infiltration depth for particles finer than the controlling constriction size. The pore channel model adopted by Indraratna and Vafai (1997) predicts a minimum pore diameter,  $d_0$ . Particles smaller than  $d_0$  will pass through the filter element, while coarser particles are retained. This minimum diameter is included in the comparison as a single value. Hence,  $d_0$  can be compared directly

with the controlling constriction size. The previous models are compared with the newly developed model for two cases: a uniform sand, with  $C_u=2$  (Figure 5), and a well graded sand, with  $C_u=6$  (Figure 6).

The pore channel model of Indraratna & Vafai (1997) predicted a minimum pore channel diameter larger than other models for the well graded filter. Vafai (1996) has pointed out that the validity of 'd<sub>0</sub>' tends to decrease as the  $C_u$  value is increased above 6. The Indraratna & Vafai (1997) model assumes nearly spherical particles (shape factor  $\alpha=6$ ) which decreases accuracy when considering broadly graded filters. For broadly graded materials, the shape factor,  $\alpha$ , should be calibrated such that the minimum pore channel diameter is equivalent to the controlling constriction size predicted by Witt (1993) or Kenney et al. (1985). As can be seen, in both examples the model of Schuler (1996) predicts a rapid increase in particle infiltration at diameters slightly coarser the controlling constriction size of Kenney et al. (1985) and Witt (1993). The model of Humes (1996) predicts a significantly lower infiltration depth for the same particle diameters. The current model predicts a rapid increase in infiltration depth (log scale) at a diameter close to the controlling constriction size determined by Kenney et al. (1985) and Witt (1993). Hence, the new geometric model is suitable for modelling infiltration into granular filters.

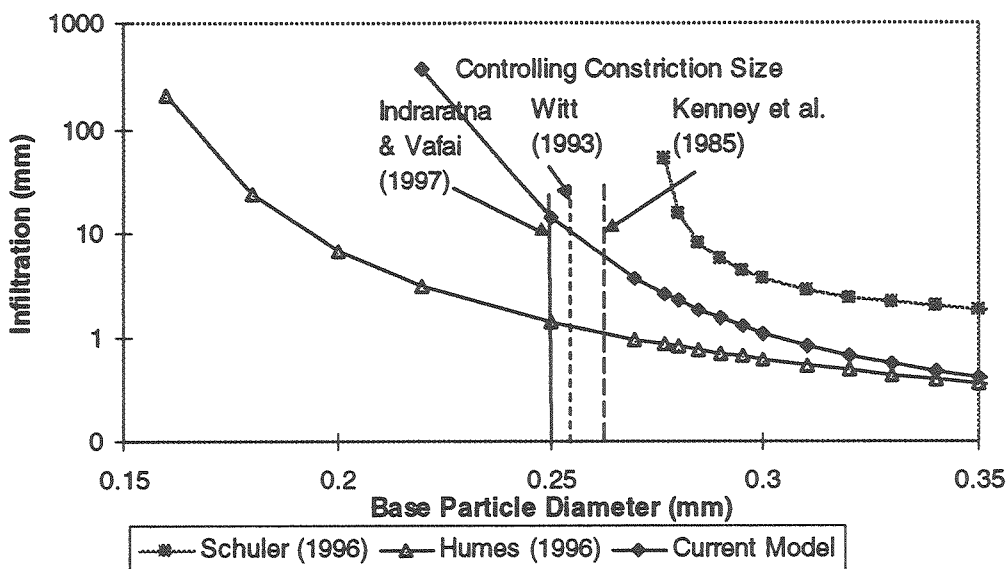


Figure 5 Comparison of Predicted Infiltration Depth of Base Particles into a Granular Filter - Uniform Sand,  $C_u=2$ ,  $D_{15}=1.3\text{mm}$  (Indraratna and Locke, 2000)

The model can be applied in practice to any geotechnical structure subject to seepage flow. First consider the steady state flow through a structure. Figure 7 shows the predicted flow through a simplified, rectangular (in two dimensions) earth structure with a hydraulic head difference across the structure.

Noting that flow occurs along flow paths, the filtration analysis can be simplified to a one dimensional flow problem. Along any seepage path, the corresponding core-filter system can be divided into a number of one dimensional elements with inclination matching the flow path. The hydraulic pressure and flow rate in each element are determined from the Laplace equation. Then the equations developed with the model described in this paper can be used to describe the movement and capture of particles. A finite difference procedure is used to predict the time dependent particle movements and flow rate, and changes in the base soil and filter permeability, porosity and particle size distribution. As the material permeabilities change due to particle loss and capture, the Laplace equation is applied again to the entire structure to re-calculate the flow rates and pressures.

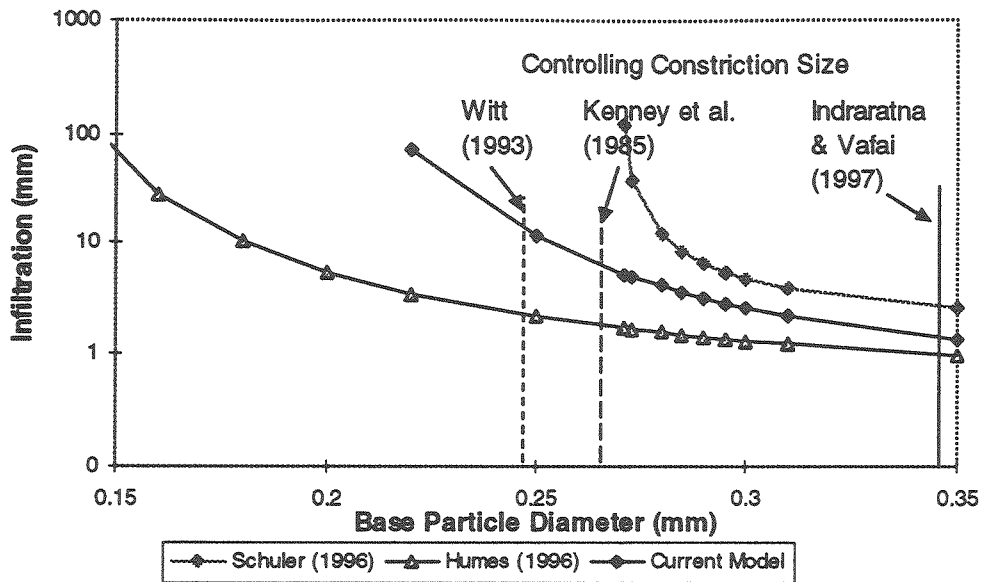


Figure 6 Comparison of Predicted Infiltration Depth of Base Particles into a Granular Filter - Well Graded Sand,  $C_u=6$ ,  $D_{1.5}=1.3\text{mm}$  (Indraratna and Locke, 2000)

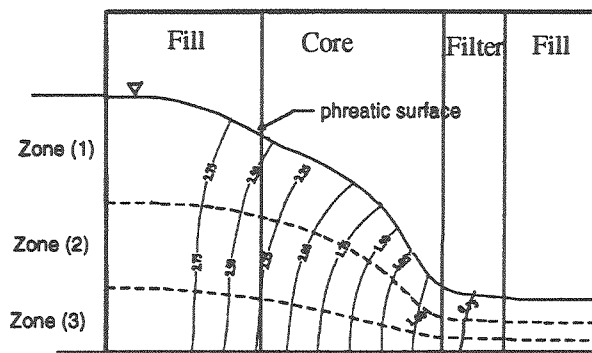


Figure 7 Flow net for a simplified earth structure (Vafai, 1996)

### 4 CONCLUSIONS

Granular filters are an essential element of earthfill dams, providing protection from erosion and piping to the dam core. The role of a filter is to retain any eroded particles, while allowing seepage water to drain from the base material. This requires careful selection of filter particle size; the pores of the filter must be small enough that the larger base soil particles are captured within the pore constrictions. A new analytic model has been presented which describes the time rate of infiltration of base soil into a filter. The filter pores are modelled by a three dimensional network of pores, connected by constrictions. The size of these constrictions is randomly generated from the constriction size distribution; which is determined from the filter particle size distribution and relative density. The rate of movement of particles is modelled by a finite difference approximation of the differential equations of conservation of mass and momentum. The model has been shown to predict infiltration depths of base soil particles similar to those determined by other researchers, from both experimental and theoretical work. The analytical model presented here has several advantages over previous models, including:

- A three dimensional pore model, more representative of real soil conditions than simple pore channel or layered void models.
- Description of the rate of particle movement. Hence, predicting the time to reach steady state or large scale piping of the base soil.

- Modelling of time dependent changes in the base soil and filter. As particles are eroded or captured they alter the particle size distribution of the soil or filter. By re-calculating the constriction size distribution, porosity and permeability of each element in the model at each time step, the time dependent changes are considered.

## 5 ACKNOWLEDGEMENTS

The authors would like to thank SMEC Victoria for their commitment to improving knowledge in dam engineering through sponsorship and advice throughout this Australian Research Council - SPIRT research project. In particular, Dr Gamini Adikari for his involvement with this project. A more detailed description of the model was presented as a keynote lecture to GeoFilters 2000, in Warsaw, Poland. This information can be found in Indraratna and Locke (2000). Permission has been granted by Balkema Publishing to reproduce the figures and text in this paper.

## 6 REFERENCES

- Humes C. (1996) "A New Approach to Compute the Void-Size Distribution Curves of Protective Filters", Proc. GeoFilters '96, Montreal, Canada, pp. 57-66.
- Indraratna B. and Locke M. (1999) "Design methods for granular filters - critical review", Proc. Instn. Civ. Engrs Geotech. Engng, Vol. 137, pp. 137-147.
- Indraratna B. and Locke M. (2000) "Analytical Modelling and Experimental Verification of Granular Filter Behaviour", Keynote Paper *Filters and Drainage in Geotechnical and Environmental Engineering*, Wolski and Mlynarek Eds., Balkema, Rotterdam, pp. 3-26.
- Indraratna B. and Vafai F. (1997) "Analytical Model for Particle Migration Within Base Soil - Filter System", Jour. Geotechnical and Geoenvironmental Engineering, ASCE, Vol 123, No. 2, pp. 100-109.
- Kenney T., Chahal R., Chiu E., Ofoegbu G., Orange G., Ume C. (1985) "Controlling Constriction Sizes of Granular Filters", Canadian Geotechnical Journal, Vol. 22, pp. 32-43.
- Schuler U. (1996) "Scattering of the Composition of Soil - An Aspect for the Stability of Granular Filters" Proc. GeoFilters '96, Montreal, Canada, pp. 21-34.
- Sherard J. and Dunnigan L. (1985) "Filters and Leakage Control in Embankment Dams" Proc. Symposium on Seepage and Leakage from Dams and Impoundments, R.L. Volpe and W.E. Kelly (eds.), ASCE, pp 1-30.
- Silveira A. (1965) "An Analysis of the Problem of Washing through in Protective Filters", Proc. 6<sup>th</sup> Int. Conf. Soil Mechanics and Foundation Engineering, Canada, Vol. 2, pp. 551-555.
- Silveira A., Peixoto T., Nogueira J. (1975) "On Void Size Distribution of Granular Materials", Proc. 5<sup>th</sup> Pan-American Conf. Soil Mechanics and Geotech. Engng., pp. 161-176.
- Terzaghi K. (1922) "Der Grundbruch an Stauwerken und Seine Verhütung" Forcheimer Nummer Der Wasserkraft, 17, pp. 445-449.
- Vafai F. (1996) "Analytical Modelling and Laboratory Studies of Particle Transport in Filter Media", PhD Thesis, University of Wollongong, NSW, Australia.
- Witt K. (1993) "Reliability Study of Granular Filters", in *Filters in Geotechnical and Hydraulic Engineering*, Brauns, Heibau & Schuler (eds.), Balkema, Rotterdam, pp.35-42.