A SIMULATION MODEL FOR THE INFILTRATION OF HETEROGENEOUS SEDIMENT INTO A STREAM BED

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ABSTRACT

Salmonid embryos depend on the adequate flow of oxygenated water to survive and interstitial passageways to emerge from the gravel bed. Spawning gravels are initially cleaned by the spawning female, but sediment transported during subsequent high-runoff events can nfiltrate the porous substrate. In many gravel-bed channels used for spawning, most of the infiltrating sediment consists of sand and fine gravel that fall by the force of gravity through the framework of bed particles once the sediment enters the streambed. The sediment comes to rest on the tops of large particles or lodges in pores created by bed particles in mutual contact.

We present a model that simulates the descent and deposition of heterogeneous spheres (sediment) into successive layers of a bed of heterogeneous spheres. Individual sedimentary particles may lodge or pass through a pore depending on its diameter relative to those of the bed particles creating the pore. As sediment lodges in each layer, the particle-size distribution of the layer is updated to give a new population of pores through which the next group of sedimentary particles attempts to infiltrate. Transformations of percentile-by-weight distributions are used in the simulation both to generate random sediment particles and to simulate pores in the bed.

Results using particle-size distributions from a natural channel show vertical variations in amount and particle size of infiltrating sediment. Top layers accumulate large amounts of relatively coarse sediment, middle layers accumulate little sediment, and bottom layers accumulate large amounts of fine sediment. This agrees qualitatively with direct measurements of sediment infiltration in this channel. Simulations using other arbitrary distributions show that the total volume, depth, and particle-size distribution of infiltrating sediment vary with the particle-size distribution of the sediment and streambed.

INTRODUCTION

Female salmonids have apparently evolved behavior to ensure that gravel nest sites (redds) are relatively free of sediment. By fanning bed gravel and sediment downstream, a female

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simultaneously cleans and digs a site for her eggs. She partially deposits and repeats the process just upstream. This covers the eggs while more suspendable sediment is carried beyond the site by fast moving water.

Once eggs are deposited, they are vulnerable to sediment infiltration. Too much sediment lodged around the eggs decreases their viability by reducing the supply of oxygenated water. Alternatively, dense sediment in top layers (Lisle, 1989) may create an impenetrable barrier for young fry.

We consider infiltration to be different from sediment transport. During transport, sediment particles move over the surface of static bed material. Infiltration, considers the penetration of sediment particles into the bed framework. Gravity moves sediment particles through comparatively low velocity water in the interstitial spaces of the bed matrix until they eventually lodge. The purpose of this model is to produce the accumulation of sediment in bed material as a function of initial sediment and bed particle distributions, bed depth, time, and sediment deposition rate.

THE MODEL

Previous work, has motivated development in several directions. Sphere packing is understood for regular arrangements of uniform spheres (Graton and Fraser 1935). Infiltration and transport of sediment has been studied experimentally by Einstein (1968) and Sakthivadivel and Einstein (1970) but the infiltration studies were limited to beds consisting of uniform spheres in a regular arrangement. Simulation has been used to study heterogeneous non uniform sphere packing. See Visscher and Bolsterli (1972) for an early example of this approach. Sowers and Sowers (1970) describe rules of thumb for the design of sand and gravel filters.

We recognize the need for simulation because variation in the diameter of bed and sediment material can span two or three orders of magnitude. The complexity involved with irregular packing of this material seems to defy a simpler modeling approach although we remain hopeful in this regard. Experiments with infiltration in actual stream channels were conducted by Lisle (1989). He observed that the sediment load stratified in the bed material. This suggests the use of layers in the simulation process. Kondolf (1990) observes that typical measure statistics used to describe a distribution of sediment or bed material have been inadequate. Thus, for the simulation, approximate distributions are used to describe the evolution of the system.

Initial Assumptions

1. Sediment lodges in the bed material primarily because it cannot fit through the intersticial spaces created by the bed matrix.
2. The median diameter of a particle or stone can be used to estimate the weight and surface area of the particle.
3. The bed material can be divided into layers in which the particles are more or less randomly distributed throughout the layer volume.
4. As particles lodge in the bed material, the bed material continues to be randomly distributed.
5. The sediment particle size distribution is stationary (not changing in time).
6. The sediment is considered to be raining down from above with no change in frequency of encounters with the bed surface either up or downstream.

The Model Components

Inputs to the model include the particle distributions of the sediment, armour layer, and initial bed material. As time passes, sediment drops into the bed material. This is simulated by generating random variables representing particles from the sediment distribution. The first layer that sediment particles encounter is the armour layer. If sediment does not pass through this layer the model assumes it washes away down stream. A decision function based on randomly constructed pore openings is used to decide whether or not a particle passes through a given layer. The next layer that particles encounter is the first layer of bed material directly below the armour layer. If it passes through this layer but not the next, it is considered to be lodged in the next layer. In a similar manner, the particle may pass through or lodge among succeeding lower layers. The exception to this is the last layer whose base is impervious to further penetration. If a particle passes into the last layer, it automatically lodges in that layer. After some particles have lodged in a layer, the distribution describing the layer of bed material is updated to include the new particles. Layers have a finite volume and can be filled with particles. When the top layer of bed material fills, the process is over. If any other layer fills, it effectively blocks particles from that layer down, and the layer above traps all particles that enter it. The other possible situation is that the top bed layer never fills. In this case some maximum sediment load is exhausted.

How Particle Distributions are Assessed

The method of particle sieving is widely used for developing an approximation to the particle distribution. The particle sample is gathered and run through a series of successively finer mesh sizes or sieves. A plot of the cumulative weight percentile versus a log plot of the sieve size characterizes the particle distribution. Nearly all the measure and descriptive statistics are derived from this method. Inputs to the model are conveniently sieve sizes and weight fractions of sediment and bed distributions. Model outputs are also represented by such distributions.

Transformations of Percentile-by-Weight Distributions

Both the simulation of random particles from sediment distributions and the simulation of pore distributions of bed material require transformations of the percentile-by-weight distribution described above. We develop a general transformation which can be used in both cases.

For this discussion $G(\mathrm{o})$ represents the percentile-by-weight distribution, $w(\mathrm{o})$ is the weight of a single particle in terms of its sieve diameter, $F_X(\mathrm{o})$ represents the frequency distribution. $F_B(\mathrm{o})$ and $f_B(\mathrm{o})$ represent a biased distribution and density function, and $h(\mathrm{o})$ represents an arbitrary functional bias of the frequency.

Suppose $x_1 < x_2 < x_3 < \ldots < x_{n-1} < x_n$ are ordered sieve (median) diameters from distribution F_X. Assume G is defined on $[x_{min}, x_{max}]$. Thus up to the particle of (median) diameter x_i,

$$WG(x_i) = \sum_{j=1}^{j=i} w(x_j) \qquad (1)$$

where W is the total weight. Consider a piecewise defined truncated weight function g(o) where $g = w$ for $X \le x_i$ but $g = 0$ for $X > x_i$. Then the sample mean of $g(X)$ motivates the following approximations:

$$W\,G(x_i) = \sum_{j=1}^{n} g(x_j) \approx n\,E(g(X)) = n\int_0^{x_{\max}} g(u)\,dF(u). \tag{2}$$

$$G(x) \approx \frac{n}{W}\int_0^x w(u)\,dF_X(u) \tag{3}$$

We introduce bias by multiplying the bias factor by the probability of occurrence i.e. $dF_B(x) = h(x)\,dF_X(x)$. Thus

$$G(x) \approx \frac{n}{W}\int_0^x \frac{w(u)}{h(u)}\,dF_B(u), \tag{4}$$

$$G'(x) \approx \frac{n\,w(x)}{W\,h(x)}\,f_B(x) \qquad \text{and} \tag{5}$$

$$f_B(x) \approx \frac{W\,h(x)\,G'(x)}{n\,w(x)} \tag{6}$$

With any continuous piecewise differentiable approximation to $G(x)$ such as linear or spline interpolation, F_B can be recovered by integration. Either f_B or F_B can be used to generate random variables as described in Bratley et. al. *(1983)*. If $h(x) = 1$ then we have the frequency distribution F_X. This distribution can be used to generate random sediment particles. Bias is used to randomly generate pore sizes compensating for dimensional effects of packing. Limiting pore sizes are generated by adjacent particles within the bed framework. Generating three contacting random particles (spheres) from the bed framework distribution, and computing an associated pore opening clearly will not represent a random sample of a pore within the framework. However, by considering biasing the frequency of the bed framework particles in this process, we can come much closer. As an example, we might reason that particles would have contacts proportional to surface area, thus we should bias the frequency in proportion to x^2. Or we might consider the effect of layer thickness in the model concluding that particles would appear within a bed layer inversely proportional to their diameter. Other dimensionally related packing effects that could be considered are particle shape, or the fact that not all critical pores are generated by touching particles. For these simulations we conveniently lump these considerations into a single parameter and consider an arbitrary bias of x^d where d *is* a parameter to be determined. Pores sizes generated with a selected d provide the basis for deciding whether sediment will ingress to deeper layers or lodge in the current one. This technique can be considered somewhat analogous to dimensional analysis for fitting power functions commonly used in engineering practice. The difference is that instead of lumping a number of variables together, a number of random variables is being lumped together by assumptions being made about their dependence. In so doing the model becomes partially deterministic and partially stochastic.

Choosing different values of the parameter d will affect the pore size distribution. Figure 1 shows the results of generating 1000 holes while varying the dimensional bias of a typical

bed material distribution As the parameter *d* changes, the pore size distribution shifts while retaining some characteristic features.

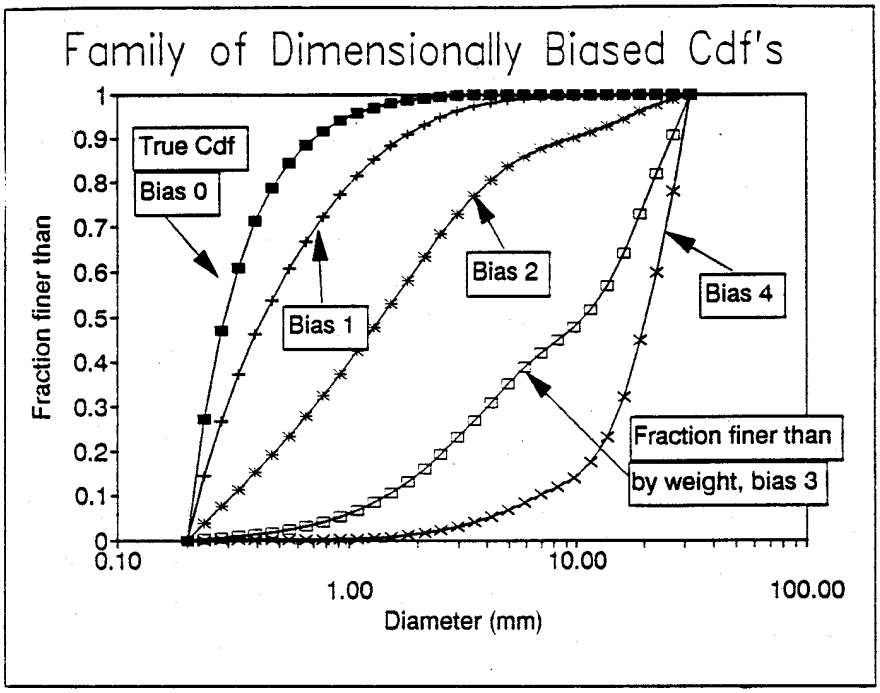

figure 1: Effect of bias on hole distributions

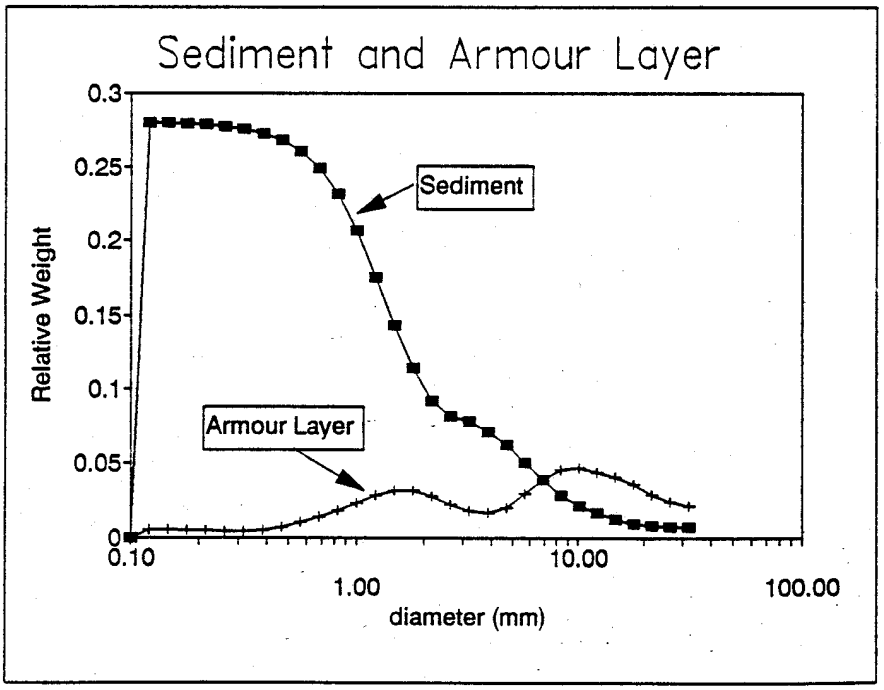

figure 2: Sediment and armour layers

SAMPLE OF SIMULATION RESULTS

This example represents a typical simulation. The sediment distribution (figure 2) consists of a heavy load of fines while the armour layer (figure 2) tends to have larger material in it than either the sediment distribution or the distributions representing layers of bed material (figure 3).

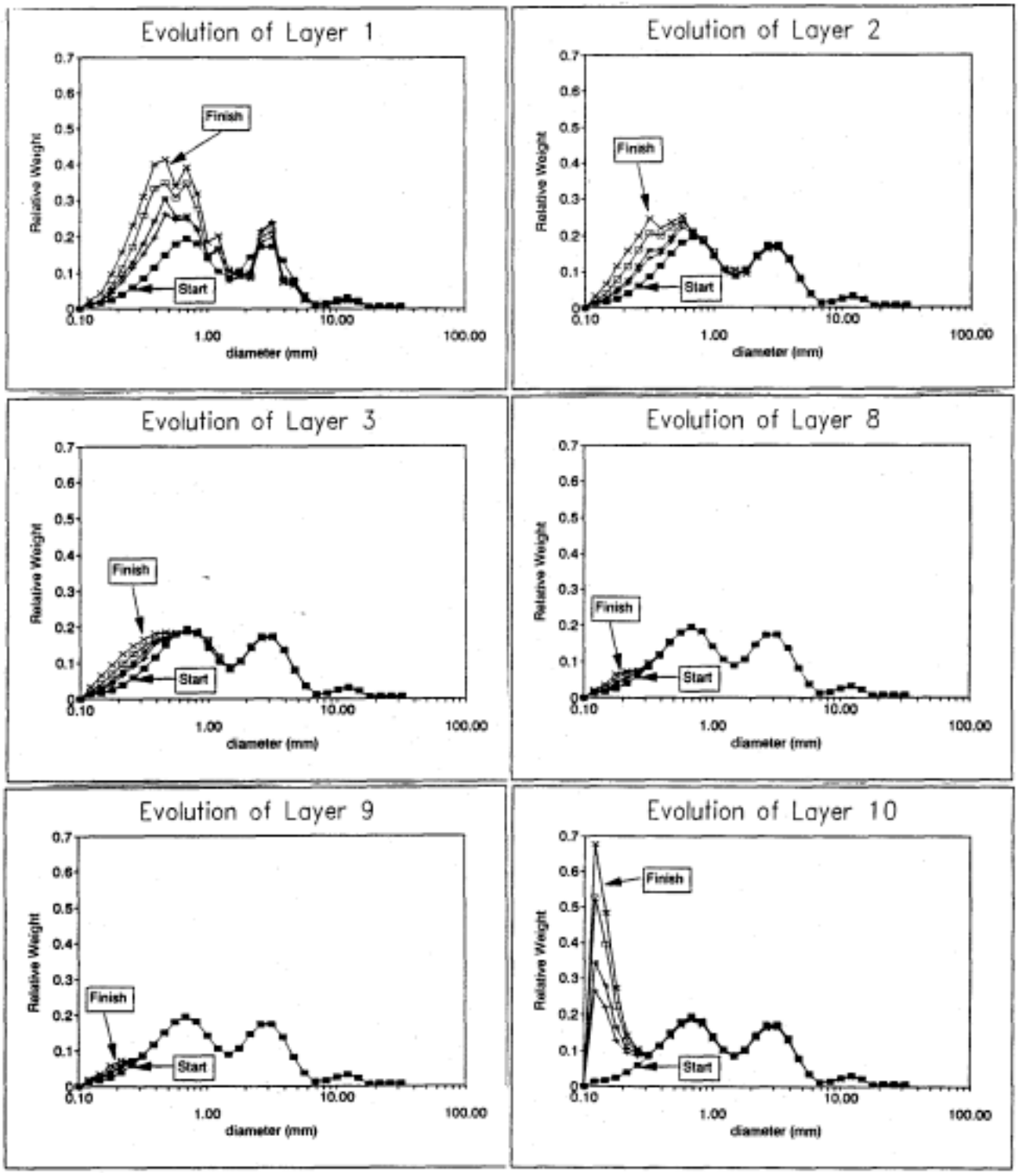

figure 3
relative time: Start=0, 12, 16, 26, 37=Finish

Variables representing initial and final packing were set to 60% and 85% of layer volume for bed material. Dimensional bias is set to 1.0 for each run. The relative packing percent provides a stopping criteria for any bed layer, and filling the first layer stops the simulation. For each layer shown in figure 3, the distributions were updated as sediment penetrated and

lodged in the bed. Figure 3 shows the distribution for all bed layers at the time when 60% and 85% of top layer volume is used up as well as three intermediate fill levels 66.25%, 72.5% and 78.75% of top layer volume. Relative time to reach each of these fill levels can be approximated by the number of outer loop iterations and is listed below figure 3.

DISCUSSION

For this sample run, we note that the algorithm stopped when the top layer filled, and this occurred before any other layer filled completely. While this is fairly typical, it is possible to have fill from the bottom up when there is a very fine sediment load relative to the bed matrix. It is also possible that top layers will fill while bottom layers will remain untouched by sediment. For further details, and more sample runs see Lauck (1991). For top layers, the first layer accumulated the most sediment with layer two containing a lighter load of finer sediment. The finest particles passed completely through the bed matrix and lodged in the bottom layer.

A weakness of the model is that without the stopping criteria of 85% of total layer volume, the first layer will just keep filling beyond its 100% volume. The problem is that as particles infiltrate, particles are not really randomly distributed, but sorted to some extent (Jullien and Meakin, 1990). In fact, every interstice may have a small particle lodged within it. The assumption of randomly distributed bed material means that some random combination of large particles, will occur giving rise to a large hole when actually they were all plugged. Although this event occurs with less and less frequency as the simulation is run because more and more small particles are dominating the frequency distribution, the accumulative process guarantees increasing fill. To model the sorting effects, we could exclude larger particles based on the weight fraction of larger particles and the 'tightness' of packing within the layer. If the packing is 'tight' at a weight *k%* of a solid layer weight then we exclude larger particles from the distribution on the basis that smaller particles form a 'tight' packing around the larger ones. In the simulation, the distribution evolves not only by the possible incursion of small particles but by the exclusion of large particles. Such an addition requires two parameters *k* and *d* to fit instead of one but may clarify packing phenomenon.

Results of this model agree at least qualitatively with field observations of Lisle (1989). If initial bed distributions are relatively free of fine sediment, then coarser sediment is found to accumulate in the top few layers of bed material and finer sediment accumulates at the bottom. Further, if sediment is very fine, then it will pass through and fill from the bottom up.

For each particle distribution of bed material there is an implicit pore distribution. The mechanism which drives the model is the comparison between the implicit pore distribution and the size of the infiltrating sediment. If the sediment distribution does not significantly overlap the pore distribution then the sediment will fill the bed from the bottom up. When there is some overlap, smaller particles descend to the bottom unimpeded while slightly larger particles begin to lodge in the top bed layers. As layers fill, the overlap between sediment and the implicit pore distribution increases indicating an increase in interaction. Finer sediment lodges in the bed and yet finer material passes through to lower layers. If there is significant overlap between sediment and pore distributions then some sediment may penetrate the top few layers of bed material. However, probability is low that it will reach bottom.

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REFERENCES

Bratley, P., Fox, B. L. and Schrage, L. E. (1983) A Guide to Simulation, Springer-Verlag, New York.

Einstein, H. A., (1968) "Deposition of suspended particles in a gravel Bed", Journal of the Hydraulics Division, Proceedings of the ASCE, Vol. 94, pp. 1197-1205.

Frostick, L. E., Lucas, P. M. and Reid. I. (1984) "The infiltration of fine matrices in course grained alluvial sediments and its implications for stratigraphical interpretation", Journal of the Geological Society of London, Vol. 141, pp. 955-965.

Graton, L.C., and Fraser. H. J. (1935) "Systematic Packing of Spheres with Particular Relation to Porosity and Permeability", The Journal of Geology, Vol. 43, pp. 785-823.

Jullien, R. and Meakin, P. (1990) "A mechanism for particle size segregation in three dimensions", Nature, Vol. 344, pp. 425-427.

Kondolf, M. G., (1988) Salmonid Spawning Gravels: A Geomorphic Perspective on Their Size Distribution, Modification by Spawning Fish, and Criteria for Gravel (duality, Ph.D. dissertation for John Hopkins University.

Lauck, T. J., (1991) A Simulation Model for the Infiltration of Sediment into Spawning Gravel, M.S. thesis for Humboldt State University.

Lisle, Thomas E., (1988) "Sediment Transport and Resulting Deposition in Spawning Gravels of North Coastal California", Water Res. Research, Vol. 25, No. 6, pp. 1303-1319.

Ottaway, E. M., Carling, P. A., Clarke, A. and Reader, N. A. (1981) "Observations on the structure of Brown Trout, *Salmo Trutta Linnaeus,* redds", Journal of Fish Biology, Vol. 19 , pp. 593-607

Sakthivadivel, R. and Einstein, H. A. (1970) "Clogging of a Porous Column of Spheres by Sediment", Journal of the Hydraulics Division, proceedings of the ASCE, Vol. 96, No. 2, pp. 461-472.

Silveira, A., (1965) "An Analysis of the Problem of Washing Through in Protective Filters", Proceedings of the 6th International Conference on Soil Mechanics, Foundation Engineering, Montreal, Vol. 2, pp. 551-555

Sowers, G. B. and Sowers, G. F. (1970) Introductory Soil Mechanics and Foundations, Macmillian, New York.

Visscher, W. M. and Bolsterli, M. (1972) "Random Packing of Equal and Unequal Spheres in Two and Three Dimensions", Nature, Vol. 239, pp. 504-507.