Journal of the Faculty of Environmental Science and Technology.
Okayama University
Vol.13 No1, pp.63-66, March 2008

State of the Art on Filter Design and Particle Clogging; and Proposed New Numerical Approach to Redesign

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Filters are essential in the design of embankments/dams, drains and wells for water and oil supplies. As a result of these functions, filter use is increasing. In order to use the required filter, various empirical relations have been given based on mathematical and field experience. However, these guidelines have not worked to perfection considering the fact that clogging within the filter face is a serious challenge. A short review on filter design criteria is given in this script coupled with a numerical formulation to propose the design limits.

Key words: *filter, particle clogging, filter classification, numerical model equation, force of attraction*

1 INTRODUCTION

Flow through porous media has long been an area of much interest to scientists ever since the French scientist Henrry Darcy in 1906 discovered the famous flow equation using water and sand. The equation has been built upon and extended to cover many other porous media. Though the flow equation is useful, certain conditions have at times affected the smooth and continuous flow with time. It is believed that the flow occurs in the micro pores created by the interaction of the particles in the media. These pores are also the main controlling paths of contaminants and pollutants to subsurface environment. However, the micro pores may reduce in size or seal completely when other fine particles either slightly less than or equal to the pore sizes are transported during the flow. The result of these sealing pores is clogging, change in soil water retention property and in major water ways, flooding.

In order to reduce the effect of pore sealing, filters are normally required to sieve the fines. A state of the art is being collected on the water flow system through porous media such as soil, the filtering system and design.

The current research intends to collate information on filter design and propose a numerical model to predict particle clogging especially in the unsaturated soil based on mean diameter, and from which in-situ filters can be made.

2 STATE OF THE ART OF FILTER CLASSIFICATION

Filters are materials used for trapping unwanted material from in-flowing substances. They can therefore be classified as chemical, biological or physical filters. Chemical and biological filters are purposely for trapping chemicals/minerals in solution by using other chemicals or living micro-organisms. The latter may also be referred to as bio-filters. Physical filters otherwise known as geological filters are solid particles used to trap sediments from the inflow-outflow process. For the purpose of this research, the filters are limited to physical filtration process hence geological filters are considered.

Geological filters have been useful in the construction of embankments/dams, boreholes (wells) and drains. Their importance in geotechnical construction can therefore not be over emphasized. Since the early part of the 20^{th} century, research on the behavior of filters has been ongoing. Good geological filters are required to be permeable at the same time capable of trapping sediments from the base material. Terzaghi (1929) proposed an empirical relation that could be used to select good geological filters. In his relation, good filters need to satisfy the condition that $D_{15}/d_{85} <4$ which was later modified by US Corps of Engineers (1948) to $D_{15}/d_{85} \leq 5$, where D_{15} means 15% by mass of the filter particles are finer than that size and 85% of the particles are finer than d_{85} particle size of the base material. The shapes of the particle size distribution curve for both the base and filter material should also be similar in uniformity. Based on this relation, there has been more development after his research. Sherard at el. (1984) demonstrated with filter investigation that Terzaghi's relation was conservative and that filters with the ratio of D_{15}/d_{85} higher than 5 were successful. Also, the shapes of the particle size distribution curves of filter and base materials do not necessarily need to be similar. Lafleur, (1984) also found out that some nonuniform filters with D_{15}/d_{85} of less than 4 were found to be ineffective. These discoveries gave more room for more research works.

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Other researchers have argued that the particle based relation does not distinguish between uniform and well graded filter if they all have same D_{15} (Indraratna and Raut, 2006). Researchers such as Witmann, 1979; Sherard, 1984 and Kenney et al, (1985) are of the opinion that there are inherent discrepancies in the entire existing filter criterion and hence there is need for modification. Lafleur (1984) showed that the representative base material particle size in a well-graded base soil is finer than d_{85}, and therefore, the use of d_{85} sometimes makes the design unsafe. As a result of this, further research suggested that d_{50}-d_{85} be used (Lafleur et al 1989). Lone et al. (2005) made an attempt to explain the physical behavior of porous media of different packing patterns leading to non-uniform particles size. The conclusions drawn from their research include:(1) the controlling size of the flow channels of a filter mass is the minimum of the resulting pore (window) size of unit assembly of filter mass consisting of three primary spheres, intervening sphere and fillers. (2) The size D_{15} of filter mass alone was not adequate for ensuring filter behavior since the overall gradation of the filter was ignored. Indraratna and Raut (2006) and Indraratna et al. (2007) also used numerical models to demonstrate that filter selection should not be based on particle size of filter-base material but rather on the controlling constriction size of the voids created from self filtration. Although much research is still ongoing, the hydrodynamics of filter clogging is not well understood.

Particles in base soils are subject to hydrostatic forces and as a result, may cause instability. The end result of the unstable position is dislodging of the particles from their initial positions to other places which include the voids created within the filter particles. The mechanisms of particle dislodging due to hydrostatic forces are well explained in many literatures (eg. Bastra et al., 2001, Marmur, 1988, Visser, 1970, Cleaver and Yates, 1973, Herman et al., 1990). O'Neill (1968) used a mathematical model to show that the hydrodynamic force on a spherical particle resting on a plane surface is given by equation (1). Cleaver and Yates (1973) also used a numerical model to predict the adhesive and lift forces necessary to dislodge a particle from the matrix (equations 2 and3) respectively.

$$F_{Hydrodynamic} = 32aU\nu \quad (1)$$

$$F_D = 8\rho\nu^2(\frac{aU}{\nu})^2 \quad (2)$$

$$F_L = 0.076\rho\nu^2\left(\frac{aU}{\nu}\right)^3 \quad (3)$$

Zimon (1964) as stated in Cleaver and Yates (1973) mentioned that all types of adhesive forces are proportional to the particle diameter, so that if a particle is to be removed from the surface the ratio of lifting forces to adhesive forces must be greater than unity. Khilar and Fogler (1984) demonstrated with an experiment that particle release and settlement depends on the salt concentration in the fluid. They further mentioned that monovalent salts such as sodium chloride influence the particle release or settlement. However, as particle move, there is always an attraction between it and other surrounding ones. The main force of attraction during the movement is the van der Waal's forces existing between the particles (Cleaver and Yates, 1973, Khilar and Fogler, 1984, Lee-Desautels, 2005). Hamaker (1937) used the additive concept proposed by London (1936) to determine the van der Waal's force of attraction between two spherical particles (equation 4).

$$F_{PS} = \frac{Aar}{6H^2(a+r)} \quad (4)$$

ρ : fluid density, ν :kinematic viscosity, U:wall friction velocity, A: Hamaker constant, H: the shortest distance between any two spherical particles, a, r: radii of spherical particles.

The reviewed information on particle flow and deposition has shown that much research has been carried out. However, the filter criterion has still got some lapses and need to be reassessed. Classifying filters on specific diameter size might not be suitable since the hydrodynamic forces (equations 1-4) act on all particles. Also the available literature has failed to consider the combine effect of the pressure on the particles filling the pores created by filters. More so, the effect of the particles overlying the dislodged particle, and the internal movement of the dislodged particle leading to particles crushing and re-sizing is not well understood. This has made it difficult to predict the time taken for filters to get clogged and hence when to clean them.

3 PROPOSED NUMERICAL MODEL BASED ON DYNAMIC FORCES

Consider 3 or 4 primary spheres arranged to form pores which are being occupied by base material(**Fig. 1(a)**and **(b)**). Suppose the spheres are of an average radius of **a** and that of base sphere is **r**.
Then the surface area of the pore that can accept a filler sphere in the tetrahedral arrangement is given by

$$A_1 = \left(\frac{2\sqrt{3}-\pi}{2}\right)a^2 \quad (5)$$

The area of the filler sphere is given by

$$A_2 = 4\pi r^2 \quad (6)$$

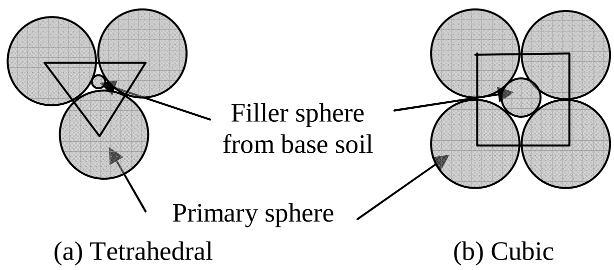

Fig. 1 Filter arrangement during filtration

Assuming that the force of attraction between primary sphere and primary sphere, and primary sphere and filler (base) sphere are solely van der Waal's forces, and the shortest distance between any two spheres remain the same, then, from Hamaker's relation the attraction between same spheres is given by

$$F_1 = \frac{Aa}{12H^2} \tag{7}$$

And the force of attraction between primary sphere and filler sphere is given by

$$F_2 = \frac{2Aar}{12H^2(r+a)} \tag{8}$$

Since the filler particle is held by the attractive forces, the hydrodynamic pressure and pressure due to overlying particles acting on the filler sphere is being transferred to the primary spheres which also share the stress among themselves. Hence the ratio of the force of attraction between the primary spheres to that between the primary-base spheres will be numerically equal to the ratio of the area of the pore to that of the base sphere. Therefore,

$$\frac{F_1}{F_2} = \frac{A_1}{A_2} \tag{9}$$

Substituting (5), (6), (7) and (8) in (9) and simplifying,

$$a = 40r \tag{10}$$

And the pore size radius b is given by

$$b = 0.23a \tag{11}$$

Suppose we consider the primary spheres arranged in the cubic form, the surface area of the pore that can accept a filler sphere is given by

$$A_1 = (4-\pi)a^2 \tag{12}$$

And the area of the filler sphere is given by equation (6). Substituting equation (6), (7), (8) and (12) into (9) and simplifying,

$$a = 8.21r \tag{13}$$

The pore size radius b is given by

$$b = 0.52a \tag{14}$$

A: Hamaker's constant
H: The shortest distance between two spheres.

4 DISCUSSION

It is apparently clear from the above review that filter use and problems of clogging keep increasing as the design of many dams, wells and drains are on the increase. The Terzaghi criterion has been agued by many researchers to be conservative. Furthermore, the filter design criteria in use is not fully satisfying purpose probably due to the fact that many parameters such as overburden pressure and international collision are not accounted for. The filter grain size distribution is not well represented in the D_{15}/d_{85} cases. It therefore gives room for more mathematical formulations taking in to consideration the average particle size. Also, the previous researchers have concentrated so much on particle movement in a saturated condition. However, when the soil becomes unsaturated, the attractive forces between particles increases leading to settlement and compaction.

The current proposed empirical equations (10 and 13) are derived based on the attractive forces proposed by Van der Waal. It is observed from these equations that the average filter size varies linearly with that of the base material. Sand has a particle size range between 0.2 and 2mm, equation (10) will require a filter diameter of 8 to 80 mm which does not look reasonable. It is therefore prudent to consider equation (10) suitable for clayey and very fine soils. The numerical ranges of equations (10) and (13) are within the limits proposed by earlier researchers such as Sherard et al (1984a, b) and the US Bureau of Reclamation (1955).

The pore size resulting from cubic arranged primary spheres are about 2 times the pore size generated from tetrahedral arrangement. The pore size radius for the cubic arranged filters also agree with pore size radius reported in Yanuka et al, (1986) using a three dimensional numerical model approach and verified with laboratory experiments.

5 CONCLUSIONS

The various ideas drawn from the available literature on filters show that the filter classification still has some challenges since clogging is still a major obstacle in filter performance. Besides that the argument that the classification should be based on D_{15}/d_{85} has raised a lot of questions among many researchers.

In view of the above reasons, the present research focuses on trying to reclassify filters with the mean diameters rather than the specific diameters.

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