Optimization of particle detachment by collapse-pulsing during air scour
by Margaret Mary Regan

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Environmental Health Engineering
Montana State University

Abstract:
The effectiveness of backwashing of granular media filters is directly related to the ability of the backwash system to provide abrasion and/or collisions between individual media grains. During these interactions the grain surfaces may slip and slide at their contact points actively removing attached particles. Two-phase, water fluidized, backwash systems provide only hydrodynamic shear mechanisms for particle removal. Alternately, three-phase systems utilizing simultaneous air scour and subfluidization water backwash provide the abrasion mechanism for aggressive particle detachment. Cleaning is significantly improved over particulate fluidization.

A condition can be induced in a fixed bed subjected to specific backwash flow combinations of simultaneous air and water in which the bed behavior is characterized by the formation and collapse of air cavities throughout its depth. This phenomenon, termed Collapse-Pulsing, maximizes the probability of abrasion/collisions between the grains implying optimum particle detachment. An original equation has been developed to predict Collapse-Pulsing behavior by equating the air pressure inside the cavity with the soil stresses in an active Rankine state plus the pore water pressure. Hence, the objectives of this research were: (1) to determine the combination(s) of air and simultaneous sub fluidization water flows which optimize particle detachment in a granular media filter, (2) to experimentally validate or nullify the implication that Collapse-Pulsing behavior is accompanied by optimized particle detachment, and (3) to establish design guidelines for filter backwashing which can be applied to improve filter performance.

Fifty pilot-scale studies were conducted on a small-scale filtration plant. Alum sol suspensions composed of uniformly distributed 1.0-µm particles were prepared by hydrothermal aging. A predetermined quantity of particles in one liter of influent were attached to glass beads of d90 size equal to 0.78-mm during gravity filtration. Subsequently, the filter was backwashed utilizing water flows from 20 to 225 percent of minimum fluidization with simultaneous air flows ranging from 3.44 to 7.39 scfm/ft^2. The three-phase backwash was followed by fluidization at 30-percent expansion with water alone. The backwash water was collected and analyzed to determine particle removal. Particles were sized and counted using a Bausch and Lomb Omnimet Image Analyzer and a Each Turbidimeter.

The results of the experimental investigation indicate: (1) Flow combinations promoting Collapse-Pulsing behavior in a granular media filter provide the optimum condition for particle detachment by abrasion. (2) The fundamental theoretical equation developed to predict Collapse-Pulsing is also valid in predicting optimum particle detachment, i.e., optimum cleaning in a granular media filter. It can, therefore, be applied during design to improve filter performance. (3) The theory is applicable for air flowrates greater than approximately 4.0 scfm/ft2 and seems to have a lower boundary of application.

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NOTATION

(The following is a list of symbols which appear in the thesis.)

b	=	coefficient corresponding to the y-intercept of the $\%V/V_{mf}$ versus Q_a^2 line
d	=	media grain diameter
d_{10}	=	10 percent finer size of media grains from a probability plot
d_{60}	=	60 percent finer size of media grains from a probability plot
d_{90}	=	90 percent finer size of media grains from a probability plot
$\frac{dh}{dZ}$	=	head loss gradient over the bed depth
D	=	diameter of filtration column
F_D	=	fluid drag force
g	=	acceleration due to gravity
Ga	=	$\frac{(d_{90})^3 \rho_w(\rho_d - \rho_w)g}{\mu^2}$ = Galileo number
h	=	head loss over the media
H_1	=	height of the column of water above the media
k	=	coefficient relative to Q_a
l	=	length of column of air in the closed U-tube manometer
m	=	coefficient corresponding to the slope of the $\%V/V_{mf}$ versus Q_a^2 line
N_O	=	horizontal force normal to contact area of grains
P_1	=	pressure below the air inlet orifice in psig
P_A	=	pressure at point A in the closed manometer
P_B	=	pressure at point B in the closed manometer
Q_a	=	air flowater in $scfm/ft^2$
r	=	radius of the menisci of the pores

Rmf	=	Reynolds number at minimum fluidization velocity
Sg	=	specific gravity of the media
T	=	surface tension due to the menisci in the pores
u	=	pore water pressure
U.C.	=	Uniformity Coefficient = ratio of d_{60} to d_{10} grain sizes
V	=	water flowrate in gpm/ft^2
V_{mf}	=	minimum fluidization velocity in gpm/ft^2
$\frac{\%V}{V_{mf}}$	=	the relationship in percent between the applied backwash flowrate and the calculated minimum fluidization velocity
Vb	=	Volume of the bulb on the closed end manometer
Wa	=	mass of flask plus water in Sg test
Wb	=	mass of flash plus water plus sample in Sg test
Ws	=	mass of media sample in Sg test
Z	=	depth of the media
Δy	=	difference between water levels in the legs of the closed end manometer
ϵ_o	=	static bed porosity
γ_b	=	buoyant unit weight of media
γ_d	=	unit weight of dry media
γ_s	=	saturated unit weight of media
γ_w	=	unit weight of water
μ	=	viscosity of water
ϕ	=	friction angle of the media
ρ_d	=	density of dry media
ρ_w	=	density of water
σ_h	=	horizontal intergranular stress

σ_v = vertical intergranular stress

τ_f = shear strength of media at failure

ABSTRACT

The effectiveness of backwashing of granular media filters is directly related to the ability of the backwash system to provide abrasion and/or collisions between individual media grains. During these interactions the grain surfaces may slip and slide at their contact points actively removing attached particles. Two-phase, water fluidized, backwash systems provide only hydrodynamic shear mechanisms for particle removal. Alternately, three-phase systems utilizing simultaneous air scour and subfluidization water backwash provide the abrasion mechanism for aggressive particle detachment. Cleaning is significantly improved over particulate fluidization.

A condition can be induced in a fixed bed subjected to specific backwash flow combinations of simultaneous air and water in which the bed behavior is characterized by the formation and collapse of air cavities throughout its depth. This phenomenon, termed Collapse-Pulsing, maximizes the probability of abrasion/collisions between the grains implying optimum particle detachment. An original equation has been developed to predict Collapse-Pulsing behavior by equating the air pressure inside the cavity with the soil stresses in an active Rankine state plus the pore water pressure. Hence, the objectives of this research were: (1) to determine the combination(s) of air and simultaneous subfluidization water flows which optimize particle detachment in a granular media filter, (2) to experimentally validate or nullify the implication that Collapse-Pulsing behavior is accompanied by optimized particle detachment, and (3) to establish design guidelines for filter backwashing which can be applied to improve filter performance.

Fifty pilot-scale studies were conducted on a small-scale filtration plant. Alum sol suspensions composed of uniformly distributed 1.0-μm particles were prepared by hydrothermal aging. A predetermined quantity of particles in one liter of influent were attached to glass beads of d_{90} size equal to 0.78-mm during gravity filtration. Subsequently, the filter was backwashed utilizing water flows from 20 to 225 percent of minimum fluidization with simultaneous air flows ranging from 3.44 to 7.39 scfm/ft^2. The three-phase backwash was followed by fluidization at 30-percent expansion with water alone. The backwash water was collected and analyzed to determine particle removal. Particles were sized and counted using a Bausch and Lomb Omnimet Image Analyzer and a Hach Turbidimeter.

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CHAPTER 1

INTRODUCTION

Long term filtration efficiency for turbidity removal is dependent on the effectiveness of the backwash system employed. In order to provide water of consistently acceptable quality to subsequent usage it is necessary to devise an efficient method by which the filter grains can be repeatedly cleaned. In a backwash system, cleaning is most effective when the mechanisms which promote collisions and abrasions between the grains are enhanced, so that attached material is actively removed throughout the depth of the bed. Research has shown that particulate fluidization does not function aggressively to remove attached particles, since it only provides the hydrodynamic shear mechanism in which few, if any, collisions occur [2].

In contrast to particulate fluidization, a condition can be induced in a fixed bed subjected to specific backwash flow combinations of simultaneous air and water in which the bed behavior is characterized by the formation and collapse of air cavities throughout its depth. The surrounding media grains are slipping and sliding against one another at their contact points. This phenomenon, termed Collapse-Pulsing [20,21], is theorized conceptually to provide better cleaning than fluidization mechanisms. In fact, the collapse-pulsing condition is anticipated to provide optimum particle detachment, i.e., cleaning, in a filter subjected to simultaneous air scour plus subfluidization water backwash flows.

A quantitative theory which will predict the condition of collapse-pulsing has been developed by Amirtharajah [3]. The flow combinations which are obtained from the theory are dependent on the components of the filtration system, i.e., column dimensions, media characteristics, and inlet configuration. The systemic components provide a series of coefficients which are either easily measurable or have characteristic values which can be inserted into the theoretical expression. Subsequently, the simultaneous air/water flow combination to provide collapse-pulsing in the three-phase system can be calculated.

A pilot-scale gravity filtration apparatus was designed with three objective in mind: (1) to determine the combination(s) of air and simultaneous subfluidization water flows which optimize particle detachment in a granular media filter, (2) to experimentally validate or nullify the implication that the Collapse-Pulsing phenomenon optimizes particle detachment during backwash, and (3) to establish design guidelines for filter backwashing which can be applied to improve filter performance.

A total of 50 experimental runs were conducted on the filtration plant. Alum sol suspensions containing uniformly distributed 1.0-micrometer particles were prepared by hydrothermal aging. A predetermined quantity of the particles were attached to the media grains during gravity filtration. During backwash the filter was cleaned utilizing typical air flowrates, from 3.44 to 7.39 scfm/ft^2, and simultaneous water flows varying from 20 to 225 percent of minimum fluidization, V_{mf}, were completed. The backwash water was collected and analyzed to determine the number of particles removed.

In order to address the subject of particle detachment by Collapse-Pulsing behavior in a granular media filter bed the thesis is organized in the following manner: Chapter 2 presents a review of the literature pertinent to the development of the Collapse-Pulsing theory. Chapter 3 summarizes the theoretical development relative to the tri-phasic mechanics of the system. Chapter 4, Experimental Methodology, includes an explanation of the experimental apparatus, experimental procedures, and sample calculations. Finally, Chapters 5 and 6 discuss the results and present the conclusions obtained during the experimental investigation.

CHAPTER 2

LITERATURE REVIEW

Both potable and wastewater treatment facilities can include a filtration step in the treatment process. Granular media filters are used as a final polishing step prior to distribution of potable water or as a means of reducing the concentration of suspended material prior to chemical addition in the wastewater industry. The ability of the filter to provide effluent of suitable quality, i.e., suitable to subsequent processing whether it be distribution standards or a suspended solids concentration which does not interfere with chemical treatment, is a function of the applied design criteria. In order to accurately predict the behavior of an on-line filter, the design must reflect a fundamental knowledge of the mechanics of a granular media filter. It is not only necessary to establish a definition of filtration mechanics, but backwash mechanics as well.

A granular media filter which has been repeatedly loaded and cleaned displays poor initial effluent quality. Amirtharajah and Wetstein [6] have shown that the poor effluent quality occurs as a result of two phenomena: (1) backwash water remnants remaining in the filter system and (2) the initial characteristics of filtration. One means available to improve the initial quality of filter effluent is to improve backwash efficacy.

Backwashing is defined herein as a solid-fluid contact system where the backwash fluid follows a path through the filter bed reverse of the influent water path. Any cleaning system which does not encompass the entire depth of the bed is not considered backwash, rather it is considered auxiliary wash. In backwash the solid-phase, media grains, are contacted by the fluid-phase, backwash liquid, which flows through the pores of the filter bed in an effort to remove attached particles in the fluid stream. Water used alone represents a two-phase, solid-fluid, system. When air and water flow simultaneously through the pores of the filter bed a three-phase, solid-fluid-fluid, system is present.

Typically, filtration plants in the United States employ water, two-phase backwash, at flowrates well above the minimum fluidization velocity, V_{mf}, with substantial bed expansion (20 to 50%) [13,30,31]. Fluidization alone, however, is an inherently weak cleaning process. Amirtharajah [2] has established that particle abrasion in a fluidized bed is limited; hydrodynamic shear forces represent the principal cleaning mechanism. Recent research [6,11,14,15] has shown that air scour either alone or with subfluidization water velocities, promotes collisions between the media grains which significantly improves cleaning. Air scour provides increased backwash effectiveness both as a backwash fluid and as an auxiliary wash. While auxiliary air wash provides limited improvement in particle detachment, the most effective particle detachment is obtained through simultaneous air and subfluidization water backwash [6,11,14,15]. All future references to simultaneous air and subfluidization water flows will be denoted as air/water backwash.

Although the air/water backwash system has been recommended, there is little fundamental understanding of the mechanics of particle detachment in a three-phase system composed of air and water flowing up through the pores of a fixed bed. Design parameters have not been based on established theory. Filter failure due to blowup of undergrain systems and media loss cause engineers to be wary of air scour designs. In fact, filters employing air scour disappeared from U.S. water treatment circa 1900 as a result of these problems. Some resurgence of an air/water backwash system has been generated in the wastewater industry [16]. The application of an air/water backwash system, however, was primarily focused on developing a means of destratifying the bed in preparation for a filter run, rather than as a particle detachment mechanism.

The use of small media in high level suspended solids removal in the wastewater industry results in undesirably short filter runs. Head loss builds up rapidly in the filter bed due to clogging of the pores. The use of larger diameter grain sizes, 2-4-mm, provides increased filter run-time [11]. The large diameter grains, however, would require prohibitive backwash flows to provide even minimum fluidization of the filter bed. Dahab and Young [16] applied simultaneous air scour and subfluidization water flows as the backwash mechanism in a wastewater filter having an effective size in the 1.0-mm range. The application of air/water backwash destratifies the bed. Smaller grains are not preferentially distributed to the top of the filter bed. High surface capture of suspended solids is no longer a problem. Filter run-time is increased. The air/water combinations which were applied, however, resulted in large amounts of media loss prompting design of an air-water baffle used to reduce media loss.

Most studies concerning particle behavior in a granular media filter have dealt with conditions leading to their adhesion on various substrates [1,8,25,27]. By comparison, only a few investigations [10,29] involve the detachment of attached particles. As a rule, these measurements were restricted to determining the amount of removed solids as a function of chemically varied parameters, i.e., solution chemistry is altered to cause particle detachment. In certain cases [1,8,10,23,25,27] attached particles could be released once the composition of the solution surrounding the particles was altered to the point where the system favored particle detachment. Matijevic and coworkers [23,25] conducted investigations where they simulated a fixed bed system with laminar flow, i.e., low Reynolds number, and the desorption phenomena were interpreted in terms of classical Double-Layer Theory.

Recent particle detachment studies at Montana State University have shifted the focus from solution chemistry to the mechanics of fluidized and fixed beds [29]. The results show that even under optimal conditions, complete removal of attached particles by fluidization is not possible. A preliminary study conducted by Morrison [28] deals with the formation and motion of air bubbles throughout the filter media. These findings prompted development of a modified mathematical theory predicting bubble motion.

Further investigations [20] dealing with simultaneous air and water flow through granular media resulted in an empirical equation to predict the combination of air/water flows which causes the media to display circular and downward motion:

$$\%(V/V_{mf}) + 3.64Q_a = 49.0 \tag{1}$$

Where $\%(V/V_{mf})$ represents backwash water flowrates as the percentage of minimum fluidization velocity, and Q_a equals the air flowrate in standard cubic feet per minute per foot squared. The downward and circular behavior exemplified by a granular media filter which is subjected to simultaneous air and subfluidization water flow combination predicted by the above empirical formula was termed Collapse-Pulsing [20,21].

A parallel study [5] addressed the problem of media loss in a system using simultaneous air scour and subfluidization water flows. Prior work by Holnbeck [22] indicated that the primary mechanism by which media is carried above the static surface of the bed is a result of the media grains being caught in the turbulent wake of an air bubble. Larger bubbles and co-current air and water flows both tend toward higher media losses. Test results [5] showed that the optimum combination of bubble size and water flow to minimize media loss are present during collapse-pulsing conditions. Media loss is minimized since bubble size is favorable, i.e., air bubble motion during collapse-pulsing does not result in turbulent wake formation.

Visual studies [20] indicated that air movement through the fixed bed, and hence, media movement, occurs in four distinct patterns depending on the air/water flow combination. It was also evident by studies of three separate sand sizes (d_{60} = 0.62-mm, 0.86-mm, 1.54-mm) that the characteristics of air motion change at water flows very close to the same percentage of the V_{mf}. Independent investigations conducted by Cleasby and

Lorence [14] utilizing a much larger sand size (d_{60} = 3.20-mm) also showed similar patterns of media behavior. Figures 1-8 illustrate the typical air and media movement patterns described by Hewitt [20].

Air scour alone. At zero water flow and low air flow rates (1-3 scfm/ft^2) the air moves up through the bed without any motion of the media. Air travels up through the pores of the bed as small bubbles which are completely surrounded by water. Small bubbles are characterized by a high surface to volume ratio. The radius of the bubble is small; therefore, the surface tension pressures are high. As the bubbles rise in the column, the static water pressure, ρ gh, decreases. As a result of the reduction in external pressure, the bubble expands, increasing the radius, effectively reducing the surface tension pressure. When the bubble diameter becomes much greater than the pore size, air flow converts from flow as bubbles to flow through a tubular channel. Figure 1 depicts a filter bed characterized by channel formation in the top layers of the media. A small section of the bed has been enlarged to show both forms of air flow.

At shallow depths, i.e., just below the media surface, the effective stresses between the media grains tend toward zero. Consequently, the uppermost portion of the channel displays a noticeable enlargement. The media grains are pushed apart. At the surface of the bed where the intergranular stresses are zero, the media behaves like a liquid. The air flow is no longer constricted by the presence of the media grains into characteristic tubular formation. Hence, the bubble will regain spherical shape to maintain minimum surface energy. Albeit, the bubble size at exit is much greater than the pore size (see Figure 1).

Given an inlet configuration which supplies multiple small bubbles, it may seem reasonable to assume that the random movement of the air bubbles through the filter bed

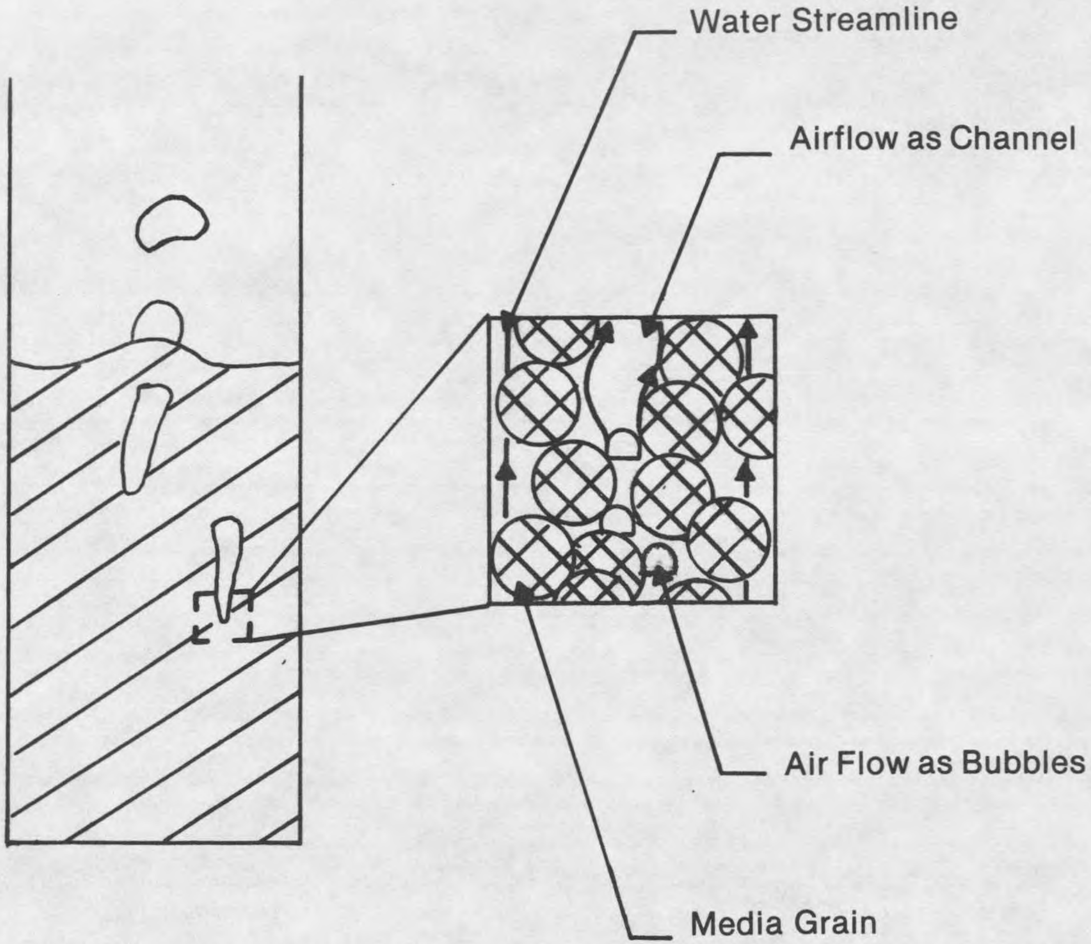

Figure 1. Channel formation in top layers of media.

would cause a sufficient number of collisions between the grains to provide effective cleaning. Cleaning, however, is not significant since the bubbles are smaller than the voids in the pores. The media grains are not actively abrading, i.e., the media grains are not forced into contact. The only apparent cleaning is limited to the top layer of the media where the channels form and collapse. In this region, the air flow is larger than the void spaces in the pores. The grains, however, are merely pushed out of their original position while air flows through the channel. The grains regain their original position once the air flow exits the channel through the surface of the media. Some turbulence develops in the wake of the bubbles above the bed where they exit the media surface. Media is carried above the bed surface in the turbulent wakes. Cleasby and his coworkers [11,15] have shown that the combined turbulence and minimal media movement may be enough to alleviate mudball formation, but air scour alone does little else.

As water flow is increased to low subfluidization flows: the pore water pressure is increased due to the head loss gradient in a flowing system. As water flow is increased the effective stresses decrease throughout the depth of the bed. The head loss increases to a maximum, and the effective stress between the grains reduce to a limit of zero where the media grains are suspended in the liquid stream. This point is defined as the minimum fluidization velocity, V_{mf}.

For fixed bed phenomena the limiting water flowrate of the system is the V_{mf}. In an ideal case where the bed is composed of unisize, spherical grains, the effective stresses would change uniformly over the depth of the bed as the water flow approaches V_{mf}. Channel formation does not occur at the same instant at every depth within the bed. Rather, as the flow increases from zero to low subfluidization water flows, the air channels which initially formed in the surface layers of the media subjected to air scour alone begin to extend deeper into the bed. Consider that a reference line or datum is established at the media surface as in Figure 2. As the distance, y, from the datum increases the pressure exerted by the media above y also increases. Hence, channels 'grow' from the surface to the base of the bed as the water flowrate is increased. At a specific air/water combination channels will extend from the surface to the base of the bed. Additionally, once channels form, they maintain a fixed position in the bed.

Less abrasion occurs between the media grains in a bed which displays channelling throughout its depth than the case where air scour is used alone. Bear in mind that the air/water flow combination defines the behavior of the bed. Backwash cycles which utilize a constant combination of air and water flowrates will maintain channels which extend from the surface to the base of the bed for the duration of the cycle. Air flow is no longer random. The grains are not moving into and out of position by the formation and collapse of channels. Air channelling behavior in a three-phase fixed bed system resembles that of water flow through channels in a two-phase, water fluidized system described by Leva [26]. Air travels preferentially through an existing channel rather than expend the energy to form a new one. Once a channel extends from the surface to the base of the bed it maintains a fixed position throughout the simultaneous air/subfluidization water backwash cycle.

<u>As water flow is increased to the transition phase from channelling to collapse-pulsing:</u> channelling is still evident in the top layer of media while air cavities begin forming in the bottom layer of media. Figure 3 shows the transition phase. The air cavities form when a favorable quantitative relationship between the air pressure and the soil stresses is reached.

Since the intergranular stresses are greater in the vertical direction than in the horizontal direction the air cavities tend to grow horizontally first, forming a lens shape. Cavity size increases until it reaches a point where the diameter of the cavity is much greater than the diameter of the pores. It causes local rearrangement and compression of the grains. Figure 3 shows a lens-shaped air cavity which is growing in the filter column. Figures 4 and 5 illustrate the isolated section of the filter column outlined in Figure 3 which has been

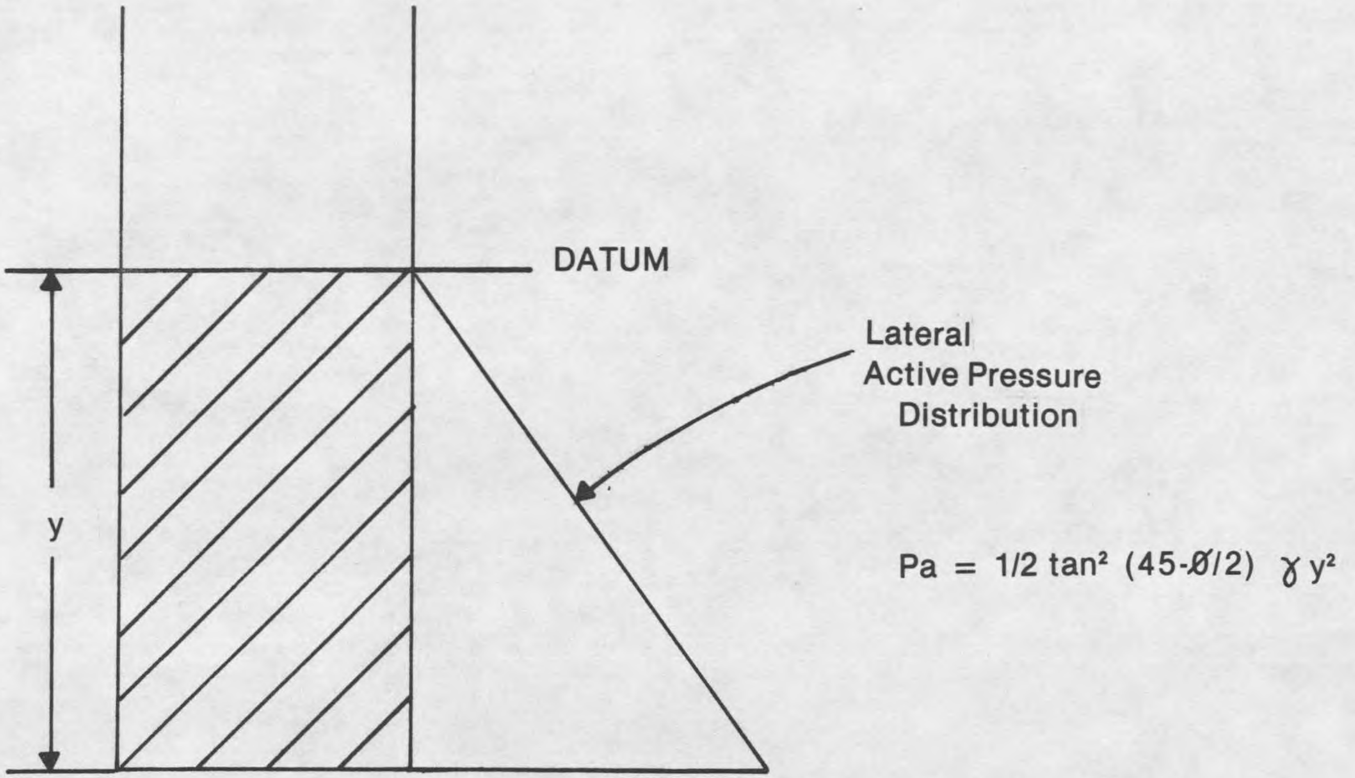

Figure 2. Lateral pressure distribution in a media column.

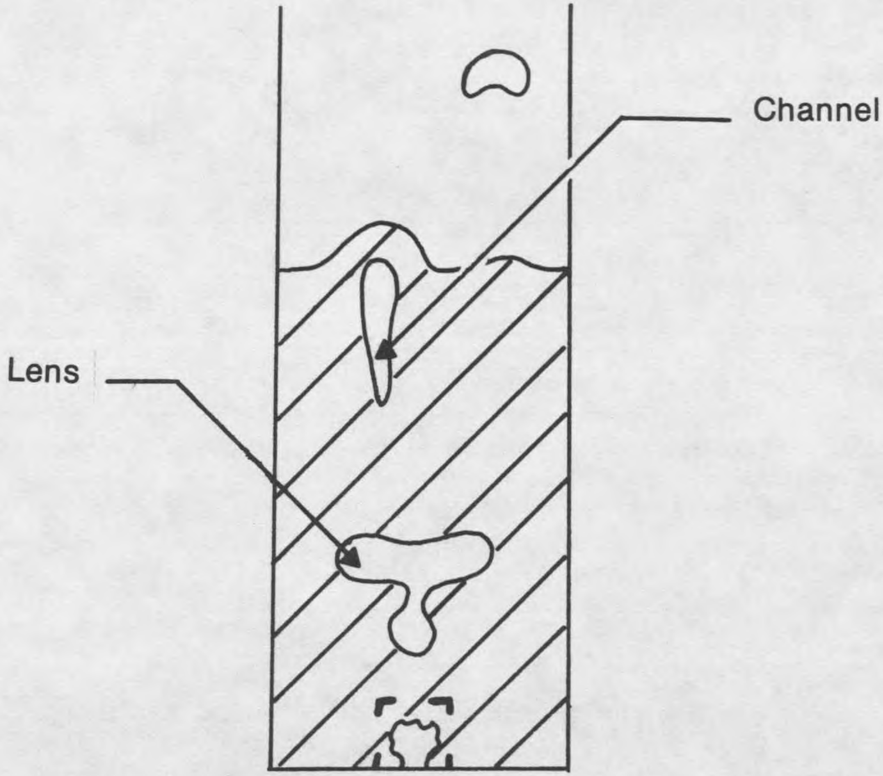

Figure 3. Transition phase from channeling to collapse-pulsing.

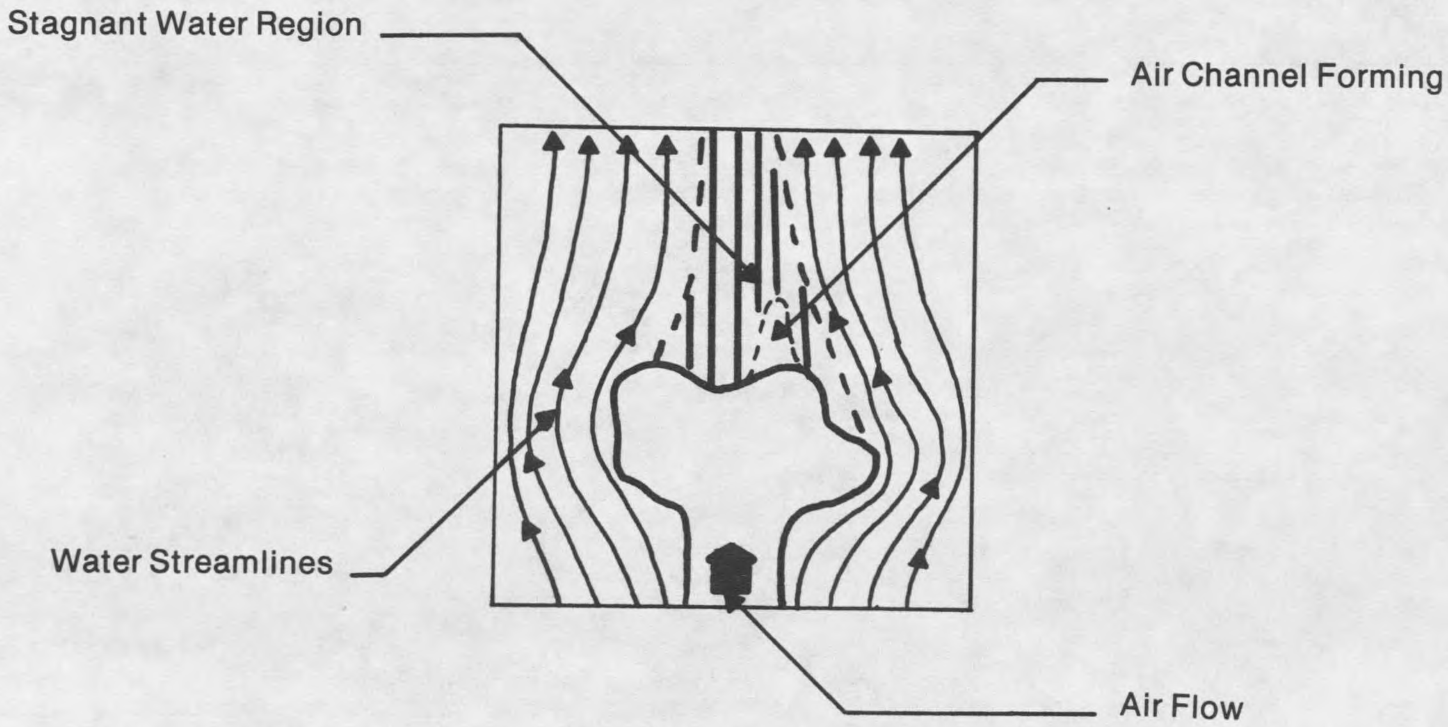

Figure 4. Schematic representation of air/water flows.

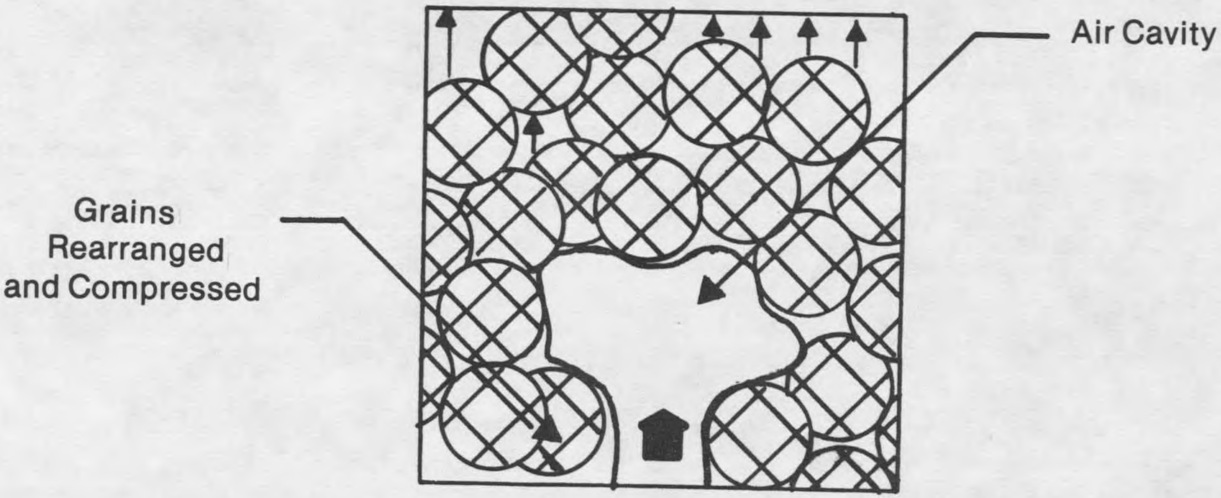

Figure 5. Schematic representation of local grain compression.

enlarged to show, respectively: (1) the air cavity with respect to the surrounding water streamlines and (2) the air cavity with surrounding grains under compression.

Under conditions of simultaneous air and subfluidization water flows, as the cavity grows horizontally (see Figure 4) the water streamlines tend to bend around the cavity resulting in a region of stagnant water, i.e., where the water flow tends toward zero, at the top of the air cavity. The pore water pressure approaches its lower limit, i.e., the effective stresses increase. The horizontal growth of the cavity reaches a limit defined by a pressure equilibrium. Once the internal pressure of the cavity becomes equal to the external pressure exerted by the media grains and the flowing water, horizontal growth stops. A tubular channel begins forming. Figure 4 shows a channel forming near the forward stagnation point of the collapsing cavity.

Air flows rapidly out through the channel and into a newly forming cavity above the first. As the cavity collapses the horizontal stress between the surrounding media grains is reduced. The media grains which are relieved of compressive forces will fail into the space evacuated by the air flow. At the instant of collapse, the shape of the air cavity is indefinite. The stresses cannot be easily quantified in an undefined system. Near the end of collapse, however, the cavity size approaches the grain size and can be quantified. The system resembles an active Rankine failure state. The media grains are slipping into the space once occupied by the air cavity along lines which are assumed to be defined by the Mohr-Coulomb failure law. Figure 6 shows the media circulation pattern during collapse. The grains slip along the lines which are defined by an angle $(45 - \phi/2)^\circ$ and a 90 degree rotation or $(45 + \phi/2)^\circ$ in which ϕ is the friction angle. The media circulation pattern with respect to the friction angle is shown in Figure 7. Note that the media grains follow the slipping planes down and into the center of the collapsing cavity. Following collapse, the cavity will reform and collapse cyclically.