FILTERS FOR WATER WELLS AND DRAIN PIPE

by

Norman A. Evans

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Filters for excluding sand and silt from wells or drains have been given some limited systematic study. In general such a filter must meet two specifications: (1) exclude sand and silt from entering the well or drain, and (2) permit unrestricted flow of water from the aquifer to the well or drain. If it performs these functions, a third is automatically met; namely, increased effective radius of the well or drain. The latter function is not under consideration in this paper.

Much ground water is developed from aquifers of uniform fine sands. Being practically cohesionless, these fine materials tend to be carried into a well by the drag of the water moving into the well. As a consequence, the impellers on the pump will likely be damaged, and if the sand pumping is great, the cavity so formed may cave in, with ultimate destruction of the well.

Filters for water wells, which are usually called "gravel packs", have been in use for at least 50 years. The rice industry in Arkansas and Kansas is said to have early adopted this practice, and the development of rotary and reverse circulation rotary drilling has fostered widespread use (1). Yet much of the use is on a guess-work basis as far as selection of materials to accomplish filtration is concerned. Some large organizations reportedly have been able to set up definite criteria for filters through extensive laboratory investigation and field observation. These criteria are, however, largely in the category of "trade secrets" and are not made available to the public.

The filtration process has been extensively used in sewerage and certain criteria evolved for this process. These criteria have not been applied to filtration of fine sand and silt however, and the fact that the sewage treatment

1 Asst. Prof. of Civil Engineering, and Asst. Irrigation Engineer, Colorado A & M College. Presented A S A E Winter meeting, Dec 8, 195 Chicago

case is entirely unlike the case at hand will account for this.

Various efforts to install filters for tile lines where fine sand or silt is encountered have been observed. The practice of wrapping joints with building paper or burlap has been used. Brush, straw or similar organic matter has also been used around the tile. Covering joints with a cap of fine gravel has also been done. Most common practice on irrigated lands at present is to construct an envelope of filter material around the tile line. This envelope is commonly two to four inches thick and usually a pit-run material which is thought to be suitable is used. Again, as in the case of "gravel-packs" for water wells, the criteria for selecting these filter materials are mainly convenience and low cost, with experience as a guide.

Screens for water wells have been developed to meet the need of a filter which at the same time possess structural rigidity. Often screens in combination with a filter of coarse material are used. Occasionally, if the aquifer is graded, it can be "developed" by vigorous surging or similar process to create a natural filter next to a screen. The fines are drawn out near the screen leaving a coarser envelope which acts as a filter. However if the aquifer is quite uniform, some artificial filter usually is desirable. A screen can be used with slot openings small enough to retain the sand, but such screens may not be hydraulically suitable.

Well Screen Investigations

Studies at Colorado A & M (2) have shown that water enters the well through screen openings as radial jets at fairly high velocities. The energy of these jets is dissipated and acceleration imparted to the water in the axial direction. The investigation showed that the following relationship between significant factors could be written,

$$\frac{\Delta h}{V^2/2g} = 2 \frac{\cosh \left(\frac{CL}{D} + 1\right)}{\cosh \left(\frac{CL}{D} - 1\right)} \quad \text{------------------------------} \quad (1)$$

where Δh is the hydraulic head loss through the screen, V is the average velocity inside the screen, (Q/A where Q is the well discharge and A the cross-sectional area of the screen), D is the diameter of the screen, L is the axial length of the screen, and C is defined as the "screen coefficient." This coefficient was found to be,

$$C = 11.31\ C_c A_p \text{ -- } (2)$$

in which C_c is the orifice coefficient of discharge for the screen openings and A_p is the ratio of total area of screen openings to total area of screen.

The loss coefficient, $\frac{\Delta h}{V^2/2g}$ in equation (1) approaches a minimum of 2, as the value of $\frac{CL}{D}$ exceeds about 6. Thus the screen losses are a minimum for all $\frac{CL}{D}$ greater than 6. For a given diameter screen with a certain screen coefficient, an increase in length beyond this amount would not result in appreciable decrease of screen losses. A corollary inferred is that a screen longer than necessary to achieve $\frac{CL}{D} = 6$ is unnecessary, at least from the standpoint of head loss in the screen. The fact that flow into the screen is mainly in the region where $\frac{CL}{D} = 6$ was confirmed by pigmy current meter observations in the experimental wells.

When gravels of various sizes were placed around screens, it was found that unless they decreased the effective open area in the screen, there was no increase in head loss at the screen. Since selection of a filter will depend upon the size and size distribution of aquifer sands, the selection of screen would then be governed by the size of filter in order that the slot openings will not permit the passing of filter material; and furthermore the filter-slot relationship should be such as to minimize reduction in effective open area of the screen. As far as the writer knows, there have been no published recommendations for slot size on this latter basis. On the basis of exclusion of the filter material from the well, the Corps of Engineers(3) recommends that $\frac{D_{65}\text{ (filter)}}{\text{Slot size}} \geq 1$. Smith (1) recommends that $\frac{D_{90}\text{ (filter)}}{\text{Slot size}} \geq 1$.

Terminology

An explanation of terminology is necessary at this point. The particle size distribution of a sample of granular material is generally presented in the form of a curve having the sieve size as abscissa and the percent by weight of the total sample which passes, or is finer than, the given sieve size as the ordinate. The ordinate scale thus runs from zero to 100 percent. If the range in particle sizes is not very great, it has been found (13) that the mean particle diameter is nearly the same as the size for which 50 percent is smaller. This size is written, D_{50}.

For two relatively uniform materials, the ratio of $\frac{D_{50}(A)}{D_{50}(B)}$ is sufficient to show the gradation of (A) with respect to (B), and this is frequently done. It does not however indicate the uniformity of the materials. Hazen (14) determined that uniformity can be expressed as a ratio of the 60 percent size to the 10 percent size, $\frac{D_{60}}{D_{10}}$. This ratio is called the coefficient of uniformity, C_u.

Experimental Criteria for Filters

The effectiveness of the filter in excluding fine particles is evidently a function of the gradation or uniformity of the filter, the uniformity of the aquifer, and the relationship between some characteristic size of filter and aquifer. Terzaghi and Peck (4) state that filters must: (1) increase the effective diameter of a well or drain, and (2) hold smaller particles from entering the drain. The filter must be fine enough to hold out the fines of the aquifer, but coarse enough so as not to enter the perforations or openings in the drain or well. Experiments by Terzaghi have shown that for filters to control piping due to seepage under a dam, the D_{15} should be at least four times as large as the D_{15} size of the coarsest layer in contact with the filter, and not more than four times as large as the D_{85} of the finest adjoining layer of soil. This can be stated, $\frac{D_{15}\text{ (filter)}}{D_{85}\text{ (aquifer)}} < 4 < \frac{D_{15}\text{ (filter)}}{D_{15}\text{ (aquifer)}}$. Figure 1 represents this criterion. It will be noted that uniformity of either filter or aquifer is not specified in this criterion, although the relationship between fines is well established. This criterion is quite well established for filter drains in connection with dams.

Bertram (5) made an extensive laboratory study of protective filters using uniform sands and crushed quartz. He found stable conditions to obtain when the ratio of D_{15} filter to D_{85} aquifer is less than 9. This was found to hold regardless of whether flow is upward or downward, and regardless of the magnitude of the hydraulic gradient. This extends the upper limit of the D_{15} of the filter considerably beyond that recommended by Terzaghi. The uniformity of filter or aquifer is not expressly included in Bertram's criterion.

The U. S. Waterways Experiment Station (6) studied the requirements for underdrains and applied these to drainage wells. The recommendation made is,

$$\frac{D_{15}\text{ filter}}{D_{85}\text{ aquifer}} \leq 4 - 5 \leq \frac{D_{15}\text{ filter}}{D_{15}\text{ aquifer}}$$

This is essentially the same criterion as that presented by Terzaghi (4). The application of this to drainage wells at the toe of a large dam field-tested the design and it was found suitable. In this criterion, the ratio of $\frac{D_{15}(\text{filter})}{D_{15}(\text{aquifer})}$ is established to limit uplift pressure in case of upward flow, or otherwise to insure greater intrinsic permeability in filter than in the aquifer.

In addition to the limit $\frac{D_{15}(\text{filter})}{D_{85}(\text{aquifer})} \leq 5$, the recommendation is made that the grain size distribution curves should not differ by more than 25 times at any point. This calls attention to the fact that some consideration should be given to the uniformity of the filter and aquifer, although no specific limit of uniformity was found or recommended. It is noted that the coefficient of uniformity for filters used in these studies ranged from about 2 to about 9, and for the aquifers from about 1.6 to 2.1.

This important study also points out that dense packing of the filter is desirable to reduce settling and also to reduce migration of small particles into the filter during initial operation.

The U. S. Bureau of Reclamation (7) made an extensive series of laboratory studies including both uniform and graded filters. These studies were directed toward establishing filter criteria for both earth dam protective filter drains, and other drains such as those for agricultural drainage. For uniform filters, a ratio of the D_{50}(filter) to the D_{50}(aquifer) of between 5 and 10 was found satisfactory. The limiting values for this ratio were confirmed by a rather complete series of experiments. There is no specific uniformity required by this criterion, although the coefficients of uniformity of the filters used in the tests were less than 1.67, while aquifer uniformity ranged from 1.4 to 6.5.

The following are among rules given by the U.S.B.R. to be applied in selecting a uniform filter:

1. $5 < \frac{D_{50}\text{ (filter)}}{D_{50}\text{ (aquifer)}} < 10$

2. A range of 1 to 3 log cycles between the mean grain size of filter and that of aquifer is permissible so long as the ratio $\frac{D_{50}\text{(filter)}}{D_{50}\text{(aquifer)}}$ is within limits specified.

3. Coarse material within narrow size limits (pea gravel and coarser) is not suitable for filtering fine aquifer materials.

4. The maximum size of slot or opening in the drain pipe should be one-half the D_{85} of the filter.[1]

The Soil Conservation Service (8) made a limited laboratory study of filter materials for a pump drainage project in which pumping from a shallow sump was tried. First attempts using "pea-gravel" and coarse grained filters proved unsuccessful in excluding sand. The conclusion was reached that a "sized"

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[1] As suggested by the War Department Engineering Manual, Ch XXI, Pt.2, 1943.

(uniform) sand only a little larger than the aquifer material was needed. The progress report referred to the fact that the greatest restriction to water flow in the region of the filter and aquifer occurs at the interface between filter and aquifer. Thus a filter sand size only slightly larger than the aquifer material should be suitable if it is possible to prevent fines of the aquifer from occupying the pores at the interface thus restricting flow.

Head loss at filter-aquifer interface.--Leatherwood (9) working at Colorado A & M found that the head loss at the filter-aquifer interface is indeed greater than the loss in either the filter, or the aquifer, and attributes this to the action of fines moving into voids at the interface. He considers that the more important variables describing the fluid, the flow and the geometry can be expressed as

$$f_1\,(\rho, \mu, D_\ell, D_s, \sigma_\ell, \sigma_s, \alpha_\ell, \alpha_s, h, V_\ell, V_s) = 0 \quad \text{----------(3)}$$

where

ρ = mass density of fluid

μ = dynamic viscosity of fluid

D_ℓ, D_s = mean diameter of filter and aquifer particles

σ_ℓ, σ_s = standard deviation from the mean of filter and aquifer particle size

α_ℓ, α_s = porosity of packing of the filter and aquifer

V_ℓ, V_s = bulk velosity of fluid in filter and aquifer

h = head loss at the interface of filter and aquifer

In these experiments the porosities were constant and $V_s = V_\ell = V$. (Bulk velocity V is the quotient of total discharge and cross-sectional area). The remaining variables were grouped by dimensional analysis to yield a functional relationship,

$$\frac{h}{D_s} = f_2\left(\frac{VD_s\rho}{\mu}, \frac{D_\ell}{D_s}, \frac{\sigma_e}{D_e}, \frac{\sigma_s}{D_s}\right) \quad \text{----------------------------(4)}$$

The experimental data are shown in figure 2. From the figure, it is seen that head loss at the interface varies directly with Reynolds Number up to $R_e = 25$.

Evidently the flow under these conditions and with the definition of Reynolds Number used was in the laminar range. It is interesting to note that a Reynolds Number which indicates change from laminar to turbulent flow in porous media is difficult to standardize because the proper length parameter is uncertain (10). In this case the value of 25 is higher than values commonly cited.

From figure 2 it can be seen that the head loss is a function of Reynolds Number, mean diameter of the aquifer particles, and a uniformity parameter

$\left(\frac{\sigma_s}{D_s} \quad \frac{\sigma_f}{D_f}\right)$, or

$$\frac{h}{D_s} = f_3 \left\{R_e, \left[\left(\frac{\sigma}{D}\right)_f \left(\frac{\sigma}{D}\right)_s\right]\right\} \qquad (5)$$

It is concluded that D_s was of considerable importance, but D_f was only of secondary importance to the uniformity of particle sizes in <u>both</u> filter and aquifer.

The functional relationship of equation 5 can be expressed as,

$$h = C\, R_e \left(\frac{\sigma_f}{D_e}\right)\left(\frac{\sigma_s}{D_s}\right) \qquad (6)$$

in which constant C is best expressed as a function of the uniformity parameter,

$$C = 1.02 \times 10^8 \left[\left(\frac{\sigma_e}{D_e}\right)\left(\frac{\sigma_s}{D_s}\right)\right]^{4.6} \qquad (7)$$

Equations 6 and 7 are believed to be valid in the range of grain sizes used in the experiment (0.0112 - 0.222 inch).

Stability (no movement of fines into the filter) was determined by plotting head loss at the interface as a function of average pore velocity as shown in Figure 3. Where the curves representing head loss for certain ratios of D_f/D_s decreased with increasing pore velocity, the sand was assumed to have moved through the interface leaving larger voids, and thus accounting for a decrease in head loss. A critical ratio of $\frac{D_{50}(\text{filter})}{D_{50}(\text{aquifer})}$ of less than 5.3 and for $\frac{D_{15}(\text{filter})}{D_{85}(\text{aquifer})}$ less than 4.1 was determined in this way. This method was believed to be more sensitive than visual observation of sand movement.

Bennison (11) pointed out the importance of uniformity in the filter for wells. A uniformity coefficient less than 2 is recommended. He also recommends that sands having a D_{10} size greater than 0.01 inch and a uniformity coefficient greater than 2 need not be filtered with a "gravel pack." It has been observed that frequently the uniformity coefficient C_u is too high, i.e., the filter is too well graded.

The thickness of the filter has not received special study so far as can be determined. Bennison (11) reports that 3 inches to 12 inches is best for water wells. Thicker filters tend to cause a reduced velocity in the filter such that sand which might be carried into the filter is deposited there, rather than being carried through.

On the other hand, information has been received from a large southwestern corporation that the size of the filter material is of less importance than its thickness, and that the diameter of a well filter should be such that the velocity of water leaving the aquifer at the interface is too low to move the sand. This organization also believes a uniform filter is preferable to a graded one.

Lockman (12) at Colorado A and M found that the uniformity of the aquifer was significant in design of a filter for a water well. His studies in the laboratory showed that although the aquifer materials were relatively uniform, the most consistent criterion for stability was achieved by using the product of $\left(\frac{D_{50}(\text{filter})}{D_{50}(\text{aquifer})} \times C_u(\text{aquifer})\right)$. This product should be between 5 and 8 for design purposes. Values greater than 8 proved unstable, while values less than 5 resulted in higher hydraulic head losses in the filter without any reduction in sand movement. It was also concluded that aquifers with C_u greater than 2 should not need to be filtered in so far as stabilizing sand is concerned.

Lockman found that the amount of sand moved into the filter varied with the magnitude of the hydraulic gradient in the sand. However as long as the ratio of $\frac{D_{50}(\text{filter})}{D_{50}(\text{aquifer})}$ is less than 7.5, the increase in sand movement with hydraulic gradient is not great. Figure 4 is a plot of some of his data.

Summary and Conclusions.

From the foregoing review and discussion of the published or freely available information on the requirements of filters for water wells and drains, it is apparent that no standardized criteria are yet available. Research is still needed to better establish the elements of a good design.

To review the existing thoughts on filters, it may be well to consider first the similarity between conditions requiring filters for water wells and those for drains.

Fine sands and silts are the soil materials giving rise to the need for a filter. Where these cohesionless fractions predominate we find problems of sand pumping in water wells. Pump impellers are damaged, and wells are ruined as a result. Pipe drains likewise meet the problem of "silting-up" in such materials. The problem seems to be greatest when these fine sands or silts are of uniform texture.

The force causing movement of the fine particles comes from the viscous shear of the moving water as it flows toward the openings in well or drain. This drag per unit volume is represented by the hydraulic gradient. Usually in the fine sands and silts, the hydraulic gradients are comparable for wells and drains, except very near the well, where turbulent flow may exist. In this respect the flow conditions may differ significantly. In the case of wells, accidental over-pumping may induce more severe flow conditions than those found near drains. In general the requirements imposed on filters for wells are similar to those imposed on drains, although possibly more severe.

Uniformity.--For nearly uniform aquifer materials it is fairly well agreed that a uniform filter is preferable to a graded filter, particularly if only one layer of filter is to be used.

In the first place, the fines in a graded filter will move through and into the well, unless slot openings are very small. Secondly it is difficult to place a graded filter about a well screen without segregation although with care and proper equipment it can be done.

To meet the requirement of having higher intrinsic permeability than the aquifer, the filter should preferably be uniform. Permeability of granular materials may be considered to be proportional to the $(D_{15})^2$. (14). Hence the permeability of a graded filter would be lower than that of a uniform filter having the same 50 percent size. It has also been found that the graded filter tends to permit greater movement of fines into the periphery of the filter creating a restricting zone of low permeability.

The primary argument favoring graded filters is that a pit-run material may be available which will greatly reduce the cost of the installation.

Thus, although there seems to be good agreement that uniform filters are best, the necessary degree of uniformity has not generally been established. Lockman (12) concluded that uniformity should be included in the criterion for a filter on the basis that the correlation between the ratio $\frac{D_{50}(\text{filter})}{D_{50}(\text{aquifer})}$ and stability was not good enough. He found that the product

$$\left[\frac{D_{50}(\text{filter})}{D_{50}(\text{aquifer})} \times C_u\ (\text{aquifer})\right]$$

gave a number more closely correlating with sand movement.

There is some evidence to indicate that aquifer materials having a uniformity coefficient greater than 2 need not be filtered. These materials can be "developed," or will create a natural filter.

<u>Thickness of Filter</u>.--Very little evidence has been collected on which to base a thickness recommendation. Authoritative opinions seem to be that thicknesses of 3 to 12 inches are suitable for wells and 3 to 6 inches are satisfactory for drains. From the standpoint of excluding sand, the filtering action should be confined to the interface, hence there is no need for a thick filter. The desirability of increasing the effective diameter of well or drain is yet another consideration however.

As a matter of interest it has been observed that the 36-inch and larger irrigation wells being constructed by the rotary and reverse rotary methods have been subject to less sand pumping difficulties than the smaller diameter wells. The fact that the velocity and hence the drag at the filter interface decreases directly with increase in diameter will account for this.

Proposed Filter Criteria.--The criteria proposed for materials which will effectively prevent sand and silt from entering a well or drain are tabulated below.

Authority	
Terzaghi	$\frac{D_{15}\text{ (filter)}}{D_{85}\text{ (aquifer)}} < 4$
U.S.B.R.	$5 < \frac{D_{50}\text{ (filter}}{D_{50}\text{ (aquifer)}} < 10$
Corps of Engineers	$\frac{D_{15}\text{ (filter)}}{D_{85}\text{ (aquifer)}} < 5$
Leatherwood	$\frac{D_{50}\text{ (filter)}}{D_{50}\text{ (aquifer)}} < 5.3$
	$\frac{D_{15}\text{ (filter)}}{D_{85}\text{ (aquifer)}} < 4.1$
Bertram	$\frac{D_{50}\text{ (filter)}}{D_{50}\text{ (aquifer)}} < 9$
Lockman	$\frac{D_{50}\text{ (filter)}}{D_{50}\text{ (aquifer)}} < 7.5$
	$5 < \left[\frac{D_{50}\text{ (filter)}}{D_{50}\text{ (aquifer)}} \times C_u\text{ (aquifer)}\right] < 8$

The results of several of the experiments reported are tabulated for the purpose of comparison in Table 1. Inspection of the data shows that the criterion of the Corps of Engineers is most closely associated with satisfactory experiments. All experiments which were satisfactory have a $\frac{D_{15}\text{ (filter)}}{D_{85}\text{ (aquifer)}} < 5$, with one exception. All except two of the experiments which failed have a ratio $\frac{D_{15}\text{ (filter)}}{D_{85}\text{ (aquifer)}} > 5$. There is essentially no difference between the uniformity of the filters or aquifer materials in the experiments which failed or were satisfactory.

It seems, however, that uniformity of the filter and aquifer should be in some way specified as part of any criterion. It is tacitly understood that the materials of the filter are relatively uniform, but selection of only one point on a grain size distribution curve does not assure any degree of uniformity of the material.

Finally it appears that more effort should be directed toward study of graded, or pit-run materials in regard to their suitability as filters, particularly for drain pipe in fine sand and silt.

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TABLE 1. SUMMARY OF SELECTED EXPERIMENTAL DATA

Identification	Filter D_{15}	Filter D_{50}	Filter D_{85}	Filter Mean Grain Size	Aquifer D_{15}	Aquifer D_{50}	Aquifer D_{85}	Aquifer Mean Grain Size	C_u Filter	C_u Aquifer	$\frac{D_{50}(\text{filter})}{D_{50}(\text{Aquifer})}$	$\frac{D_{50}(\text{Fil})}{D_{50}(\text{Aqu})} \times C_u$ (Aqu)	$\frac{D_{15}}{D_{85}}$ (Filter) (Aquifer)	Range of Head or Hydraulic Gradient*	Remarks
USBR EM-132 A 1	0.160	0.209		0.206	0.013	0.052	0.127	0.044	1.67	6.50	4.02	26.1	1.26	2-30	Satisfactory
A 2	0.317	0.368		0.368	0.013	0.052	0.127	0.044	1.12	6.50	7.07	46.0	2.50	2-30	Satisfactory
A 3	0.447	0.515		0.515	0.013	0.052	0.127	0.044	1.29	6.50	9.90	64.3	3.52	2-30	Satisfactory
A 4	0.656	0.822		0.812	0.013	0.052	0.127	0.044	1.50	6.50	15.81	103.0	5.17	2-30	Failed
A 5	1.300	1.660		1.627	0.013	0.052	0.127	0.044	1.41	6.50	31.92	207.5	10.23	2-30	Failed
B 1	0.447	0.515		0.515	0.082	0.106	0.141	0.103	1.2	1.50	4.86	7.28	3.17	2-30	Satisfactory
B 2	0.656	0.822		0.812	0.082	0.106	0.141	0.103	1.45	1.50	7.76	11.56	4.65	2-30	Satisfactory
B 3	1.300	1.660		1.627	0.082	0.106	0.141	0.103	1.30	1.50	15.68	23.50	9.21	2-30	Failed
C 1	1.300	1.660		1.627	0.336	0.435	0.553	0.435	1.38	1.40	3.82	5.34	2.35	2-30	Satisfactory
C 2	2.716	3.357		3.221	0.336	0.435	0.553	0.435	1.40	1.40	7.72	10.80	4.92	2-30	Satisfactory
C III	5.000	5.495		5.531	0.336	0.435	0.553	0.435	1.11	1.40	12.63	17.70	9.04	2-30	Failed
C 3	5.321	6.611		6.611	0.336	0.435	0.553	0.435	1.40	1.40	15.20	21.30	9.62	2-30	Failed
Corps of Engineers (Tech Memo No. 183-1) 3 B	2.00	5.50	6.70		0.13	0.19	0.25		3.53	2.10	28.4	59.5	8.7	2*	Failed
4	1.20	2.60	4.50		0.13	0.19	0.25		3.00	2.10	28.9	60.6	4.8	1.7*	Satisfactory
5	0.35	0.80	4.80		0.13	0.19	0.25		5.36	2.10	4.31	9.04	1.3	2*	Satisfactory
6	1.70	3.00	5.00		0.13	0.19	0.25		2.12	2.10	15.80	33.2	6.9	2*	Unstable
9	0.35	0.80	4.80		0.10	0.15	0.22		5.36	1.95	5.33	10.4	1.1	2*	Satisfactory
12	0.78	3.30	6.40		0.10	0.15	0.22		6.17	1.95	22.0	42.8	3.6	2*	Unstable
14	1.30	3.50	5.70		0.10	0.15	0.22		3.81	1.95	23.3	45.5	5.9	2*	Unstable
15	0.76	3.20	6.10		0.10	0.15	0.22		6.17	1.95	22.0	42.8	4.1	2*	Slightly Unst.
19	1.20	4.70	15.00		0.10	0.15	0.22		6.17	2.00	22.0	44.0	3.6	1.7*	Slightly Unst.
24	0.10	0.16	0.22		0.10	0.16	0.22		7.47	2.00	31.0	62.0	5.0	2*	Satisfactory
Corps of Engineers (Tech Memo No. 195-1) 1	0.60	2.80	4.60		0.46	0.65	0.85		9.14	1.63	4.3	7.00	0.70		Field Tests With Wells Using Recommended Filters of Tech. Memo No. 183-1 (All satisfactory)
2	0.60	2.80	4.60		0.25	0.38	0.62		9.14	2.05	7.37	15.15	1.00		
3	1.90	3.50	5.70		0.46	0.65	0.85		2.37	1.63	5.38	8.77	2.40		
4	1.90	3.50	5.70		0.25	0.38	0.62		2.37	2.05	9.22	18.90	3.30		
5	2.00	3.80	17.00		0.46	0.65	0.85		2.82	1.63	5.85	9.53	2.40		
6	2.00	3.80	17.00		0.25	0.38	0.62		2.82	2.05	10.00	20.50	3.30		
S.C.S. 1	1.00	2.10	4.60		0.054	0.088	0.097		4.00	3.60	23.8	85.6	10.3	2-14	Satisfactory
2	1.00	2.10	4.60		0.12	0.19	0.26		4.00	1.9	11.0	20.9	3.85	2-14	Unsatisfactory
Lockman Colo A&M	0.54	0.68	0.79		0.24	0.29	0.35		1.38	1.30	2.3	3.0	1.5	0.9 to 22*	Satisfactory
	1.22	1.30	1.38		0.24	0.29	0.35		1.08	1.30	4.5	5.8	3.5	0.9 to 22*	Satisfactory
	1.46	1.60	1.72		0.24	0.29	0.35		1.16	1.30	5.5	7.2	4.2	0.9 to 22*	Satisfactory
	2.06	2.20	2.33		0.24	0.29	0.35		1.10	1.30	7.6	9.9	5.9	0.9 to 22*	Failed
	2.73	3.40	3.68		0.24	0.29	0.35		1.32	1.30	11.7	15.2	7.8	0.9 to 22*	Failed
	1.22	1.30	1.38		0.30	0.435	0.54		1.08	1.66	3.0	5.0	2.3	0.9 to 22*	Satisfactory
	1.46	1.60	1.72		0.30	0.435	0.54		1.16	1.66	3.7	6.1	2.7	0.9 to 22*	Satisfactory
	2.06	2.20	2.33		0.30	0.435	0.54		1.10	1.66	5.1	8.5	3.8	0.9 to 22*	Satisfactory
	2.73	3.40	3.68		0.30	0.435	0.54		1.32	1.66	7.8	13.0	5.1	0.9 to 22*	Failed
	4.95	5.50	6.10		0.30	0.435	0.54		1.16	1.66	12.7	21.1	9.2	0.9 to 22*	Failed
	2.06	2.20	2.33		0.54	0.68	0.79		1.10	1.38	3.2	4.4	2.6	0.9 to 22*	Satisfactory
	2.73	3.40	3.68		0.54	0.68	0.79		1.32	1.38	5.0	6.9	3.5	0.9 to 22*	Satisfactory
	4.95	5.50	6.10		0.54	0.68	0.79		1.16	1.38	8.1	11.2	6.3	0.9 to 22*	Failed

SUMMARY OF PROPOSED FILTER CRITERIA

Authority	$\frac{D_{50}}{D_{50}}$	$\frac{D_{50}}{D_{50}} \times C_u$	$\frac{D_{15}}{D_{85}}$	Remarks
Terzaghi			< 4	
U.S.B.R.	$5 < \frac{D_{50}}{D_{50}} < 10$			Compacted
Corps of Engrs			< 5	
Rohwer-Leatherwood	< 5.3		< 4.1	
Bertram	< 9			Compacted
Lockman	< 7.5	5 to 8		

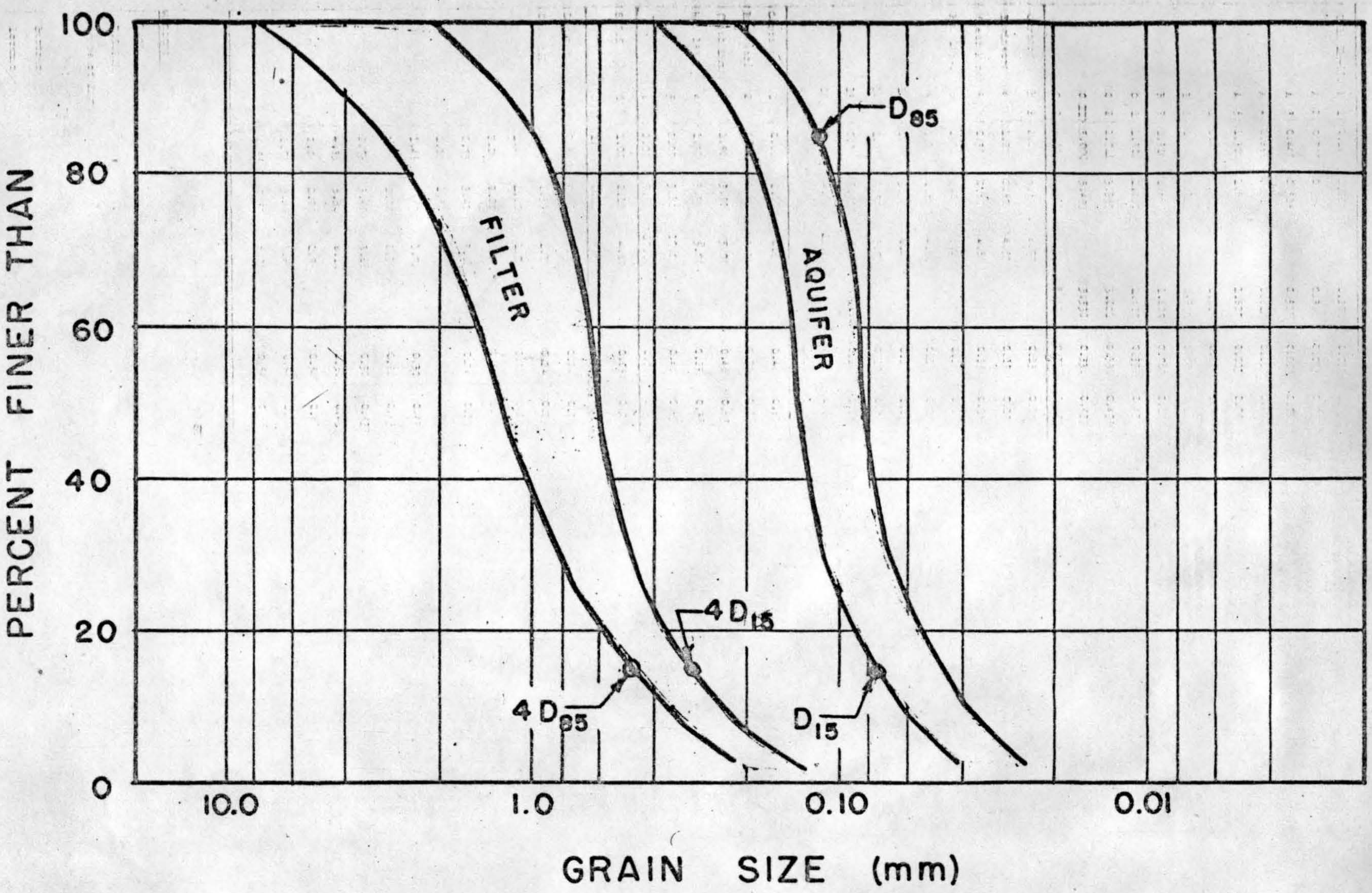

FIGURE I. FILTER CRITERIA (TERZAGHI)

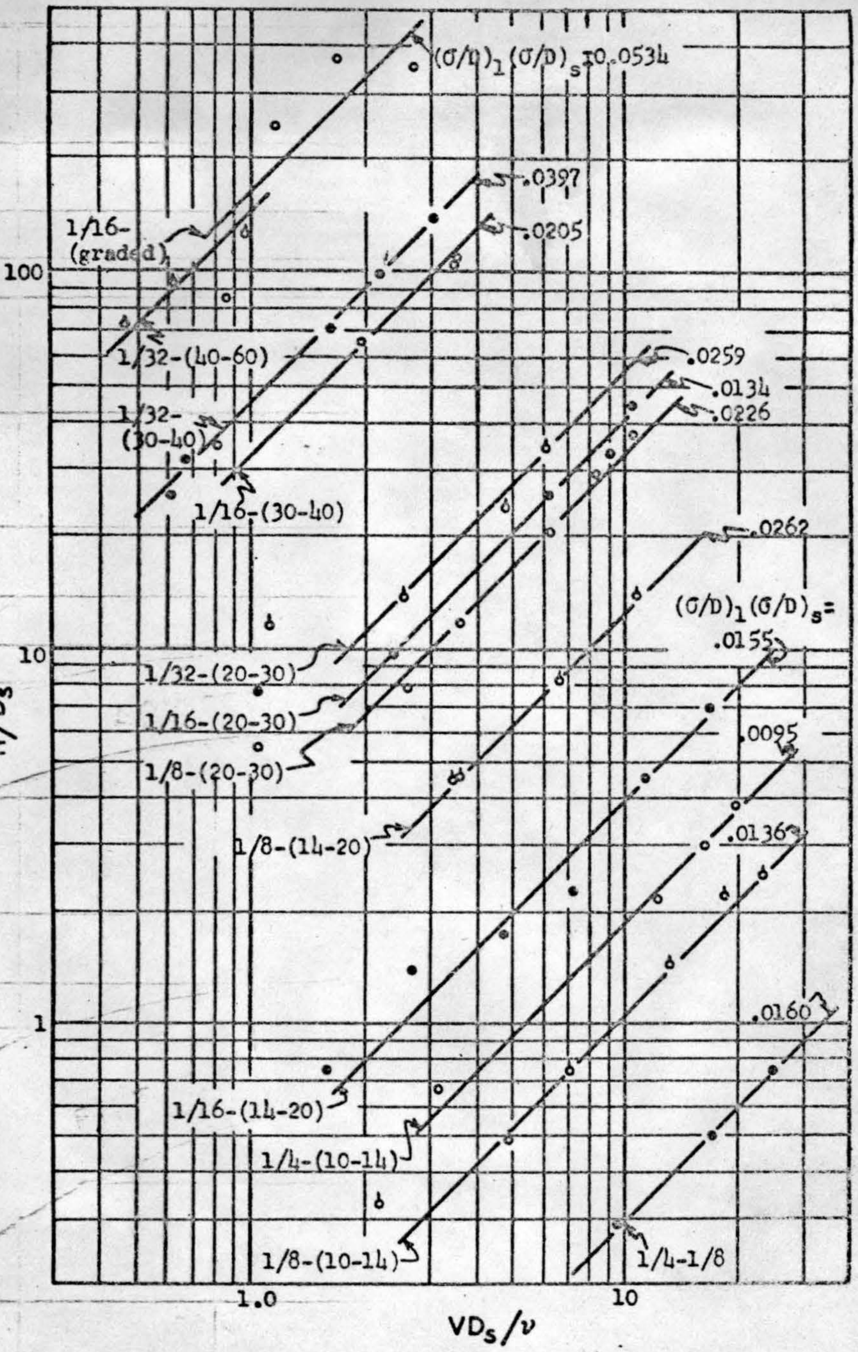

Fig. 2 -Head loss parameter as a function of the Reynolds number

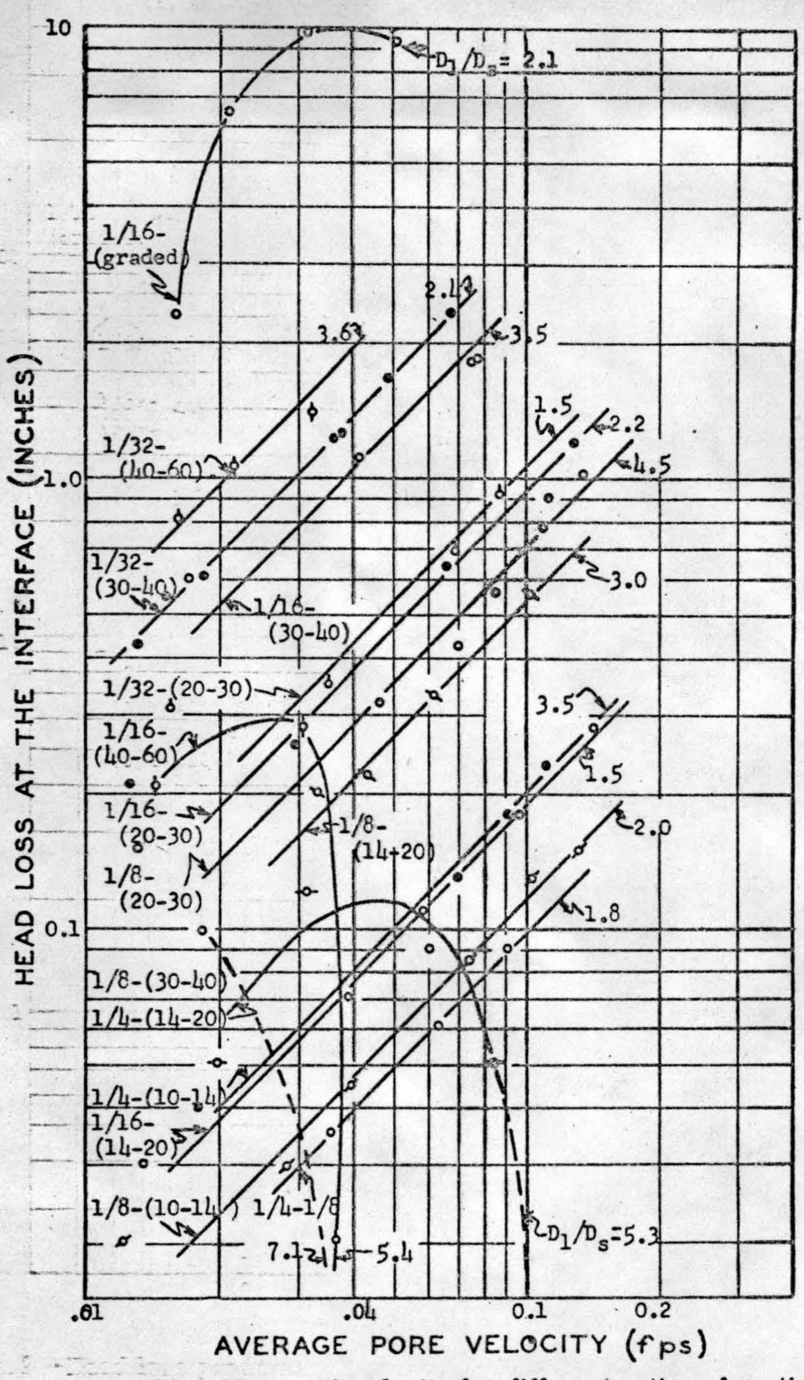

Fig. 3--Variation of head loss with velocity for different ratios of particle sizes

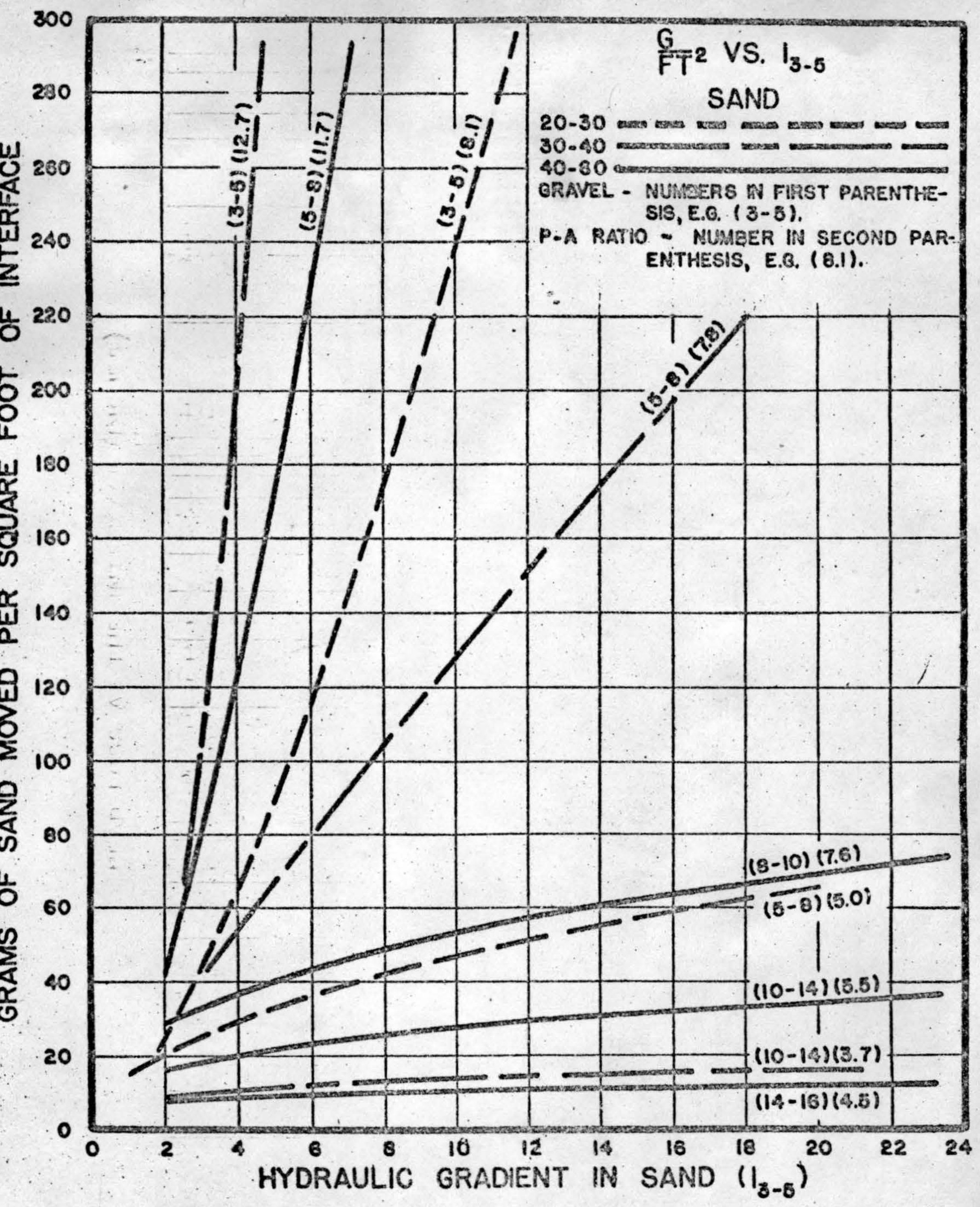

Figure 4. Relation of sand movement to hydraulic gradient in the sand for several filter-aquifer combinations.

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