Advancements in Well Design Techniques and Well Screen Hydraulics

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The classic approach to water well design has been to develop a conceptual design intended to deliver the desired quantity at a specified rate. In the well design process, it has become common practice to view the intake section as being the single-most important factor in achieving that goal. Although the screen interval is a significant contributor, other factors contribute to the overall productivity and efficiency of the well. In the case of gravel envelope wells, the grain size gradation of the pack and its hydraulic conductivity also contribute significantly to the well's efficiency. Research has been undertaken to examine the impacts of the filter/gravel pack in conjunction with the screen to determine what factors contribute to near-well turbulence resulting in head loss and lower efficiency. Understanding the mechanisms that create turbulence and taking proper measures to reduce them will result in a more efficient well that will operate at a lower cost over its intended service life.

One such study was conducted by Christopher J. Harich as part of his doctoral dissertation. In 2009, he published his thesis "Field and Laboratory Analysis of Water Design Parameters". The objective of Harich's research was to develop well design principles for four different types of aquifers: very coarse, coarse, medium, and fine-grained. He conducted extensive testing utilizing the world's largest sand tank aquifer model located at the University of Southern California's Geohydrology Laboratory and combined the findings with field data collected from over 100 wells accompanied by sieve analysis from over 400 aquifer samples. The Aquifer Model tests involved 12 wells screens: 5 shutter (louver) and 7 wire wrap screens, each with a range of similar slot sizes ranging from .040 to .125". The wire wrap screens had two additional screens with .010" and .020" slot. All screens were tested using the same coarse-grained aquifer material with no additional filter packs. Constant rate and step-pumping tests were performed on each screen and the data collected was used to calculate the efficiency value for each screen with its associated slot size.

Data derived from the step tests were used to calculate efficiency. Well efficiency can simply be described as the ratio of aquifer losses to the total drawdown of the well. The total drawdown in a pumping well is the sum of the aquifer losses and the well losses. Aquifer losses are associated with the amount of drawdown due to the pressure decrease and transmission of ground water through the aquifer toward the screen section of the pumping well. Ground water flow is generally considered to be laminar in the subsurface environment. Well losses are associated with the near well turbulence related to gravel pack conductivity, screen slot size, and degree of development of the pack and near well zone. The distance from the center of the well to the transition point from laminar to turbulent flow is referred to as the "critical radius" (Williams, 1985). The ideal condition is to maintain the critical radius to a minimum thus confining the turbulence to the vicinity of the screen. Properly applied and thorough well development techniques remove residual drilling fluid and aquifer fines reducing turbulence and the critical radius.

A sample of results from the pumping Step-Drawdown Tests conducted on the screens of similar slot size are summarized in the table below:

Table 1 – Well Efficiency via Step-Drawdown Test

Pumping Rate (gpm)	*Wire Wrap .040 slot*	*Louver .040 slot*		*Wire Wrap .080 slot*	*Louver .080 slot*		*Wire Wrap .125 slot*	*Louver .125 slot*
100	50.10%	50.30%		55.10%	56.20%		58.50%	58.50%
150	40.10%	40.30%		45.00%	46.10%		48.50%	48.40%
200	33.40%	33.60%		38.00%	39.10%		41.40%	41.30%

A comparison of the calculated efficiency values reveals little difference between wire wrap screens with calculated open areas ranging from 21 to 46% and louver screens with open areas between 2 and 6%. Similar findings have been reported from several independent studies where different screen types were tested; Williams 1981, Clark and Turner 1983, Jackson, Bikis, and Ahmad 1984. Conclusions from these studies demonstrate that screens with open areas of 3 to 5 % can achieve similar results to screens with open areas of over 40%.

Harich also examined current filter pack design guidelines and compared those with the reported values from actual wells. In this effort, he collected data from 100 production wells and examined 400 sieve analyses. A major objective was to determine if the current guidelines were prioritizing mitigation of sand migration at the expense of overall well efficiency. Filter/gravel pack gradation selection has been often referred to as more art than science. This statement has credence because of understanding and acceptance of the heterogeneous nature of the water-bearing formations the pack is intended to stabilize as well as the variability in the quality, texture, and physical and chemical properties of the pack itself. All too often a conservative approach has been used in the selection process for fear of passing fines from the formation. This leads to a finer than necessary filter pack blend and subsequently finer than the required screen slot size. Both actions result in increased well losses and reduce the overall efficiency of the well. These losses cannot be recovered once the well has been constructed.

Following the hydraulic tests using the Aquifer model and examination of data from field tests and well construction and sieve analysis records, Harich developed a series of design criteria for fine, medium, coarse, and very coarse aquifers. The following table is a partial list of criteria developed by Harich for different types of aquifers.

Table 2. Average Design Criteria for Different Types of Aquifers

Aquifer Type	*Filter Pack / Aquifer Ratio (D50/d50)*	*Uniformity Coefficient (d60/d10)*	*% Filter Pack Passing*	*Slot Size*
Fine	11.2	5.7	14.4	.060”
Medium	8.1	7.9	16.2	.070”
Coarse	6.3	8.9	15	.080”
Very Coarse	2.3	7.6	15.5	.080”
AVG. DESIGN RECOMMENDATION	10-Apr	1.3 – 12	<25	.050” - .125”

By applying these design criteria, a larger than expected filter pack gradation can be selected with an appropriately larger screen slot size, thereby increasing hydraulic conductivity around the screen, facilitating more effective well development and rehabilitation efforts, and reducing well losses.

The conclusions of the studies by Harich and others did not fully explain how or why the open area had little impact on the efficiency values and it became evident that advanced research beyond laboratory and field studies needed to be conducted to better understand screen hydraulics and head losses associated with the gravel pack and gravel pack/screen interface.

In 2019 the challenge to provide answers to these issues was undertaken by Amphos 21; a consulting firm commissioned by Roscoe Moss Company to develop conceptual and numerical models to simulate groundwater flow into a well through a filter pack and a set of different well screens. This study, “Numerical Modeling of Head Losses in Water Well Screens” focused on the small interphase zone between screen opening and gravel pack, and employed a numerical tool to explicitly model fluid dynamics from the well bore through the porous media (gravel pack and aquifer) and across different screen slot geometries. This methodology allows the calculation of well screen head losses using numerical simulation of ground water flow in porous media coupled with turbulent flow through well screens. It was a noteworthy achievement to couple the movement of ground water from laminar to turbulent flow through the well screen and within the screen open space. This multi-physics approach opens a door to quantify pressure distribution and screen head loss by analyzing the process at sub-millimetric scales for any well configuration (well diameter, type of screen, slot opening, gravel/filter pack thickness, and hydraulic conductivity, aquifer hydraulic conductivity, and pumping rate, etc.) for both pumping and injection wells.

Screen geometry types included mill slot, wire-wrapped, and downward-facing louvers. For this study slot sizes for the louvered, wire wrap, and bridge slot screens were .040 in, .060 in, and .080 in. Slot size for mill slot screen was .060 in. Pumping rates ranged from .5 l/m/s to 10 l/m/s. The Amphos model generated velocity profiles and streamline geometries for each screen type over the range of pumping rates. Examples of these are illustrated in Figures 1 through 4.

To determine head loss values, model runs were made for each screen type under a range of pumping rates. Examples of screen entrance velocity and related screen head loss values for louver and wire wrap screen of .060 in slot size are provided in Table 3. It should be noted the head losses reported only apply to water passing through the screen openings and do not include upflow losses inside the screen.

Table 3. Screen Performance Comparison, *Amphos 21*

Screen	*Pumping Rate Qp*		*Screen Velocity Vsc*		*Screen Head Loss Δh*	
	(l/m/s)	*(gpm)*	*(m/s)*	*(ft/sec)*	*(mm)*	*(ft)*
Louver *.060 slot* *3.15% open area*	0.1	2.4	0.0031	.0101	0.483	.001
	0.5	12.1	0.016	.052	3.11	.010
	1	24.1	0.031	.101	7.96	.026
	5	120.8	0.156	.512	109.95	.361
Wire Wrap *.060 slot* *26.6% open area*	0.5	12.1	0.0018	.0059	0.0857	.0003
	1	24.1	0.0037	.012	0.184	.0006
	5	120.8	0.018	.059	1.48	.005
	10	241.6	0.037	.121	4.48	.015

Velocity and head loss results vary between the screen types however the magnitude of velocity and screen head loss is inconsequential when compared to the total drawdown in a pumping well. Concerning well losses attributed to screen, these results correlate closely with the studies conducted by Williams, Clark and Turner, Jackson Bikis, and Ahmad, et al. where it was determined initial head losses across any engineered well screen types are negligible. This point is further exemplified when wells of similar design but different screen types are constructed close to one another and their performance is evaluated following pump testing. Los Angeles Department of Water and Power (LADWP) conducted a comparison study of wells constructed with louver and wire wrap screens. The data from those tests are summarized in the table below.

Table 4. LADWP Well Comparison Study Results

Screen	*GPM*	*Total Drawdown (ft)*	*Specific Capacity (gpm/ft)*	*Well Efficiency (%)*
Louver *.080 slot*	880	19.1	46.3	94
	1800	42.5	43.6	88
	2050	46.6	43.7	87
	2600	63.1	41.3	84
Wire Wrap *.080 slot*	880	17.2	50.8	91
	1800	38.7	46.6	83
	2050	45.5	45.7	81
	2600	60.6	43.3	77

The Amphos study identified a phenomenon common for all screen types which is the convergence of the flow at the screen opening and the initiation of turbulence as the water passes through the slot. The turbulence is further magnified as the flow enters the screen body. The model identified the formation of eddies inside the screen body which contributes to head loss. The model also allowed a view of the jet geometry formed as flow moves through the screen and upwards towards the pump intake. What the model provided was perhaps the first-ever view of the flow orientation and transition from horizontal to vertical inside the well screen. Using louver and wire wrap screen for comparison one can easily see how the flow through the downward-facing louver opening creates a vastly different internal flow regime than the sideward-facing openings of the wire wrap screen.

The figure below illustrates the jet geometry and degree of turbulence generated with .060 in louver and wire wrap screens under pumping conditions inducing entrance velocities of .018 m/s and .016 m/s respectively. The model-generated image reveals the upward trending flow jet for louvered screen versus the horizontal flow jets for the wire wrap screen. Readily apparent is the degree of turbulence inside the wire wrap screen where the transition from horizontal to vertical flow results in a far higher degree of turbulence when compared to the upward orientation of the flow within the louver screen.

Figure 1. Comparison of Jet Geometry for Louver and Wire Wrap Screen

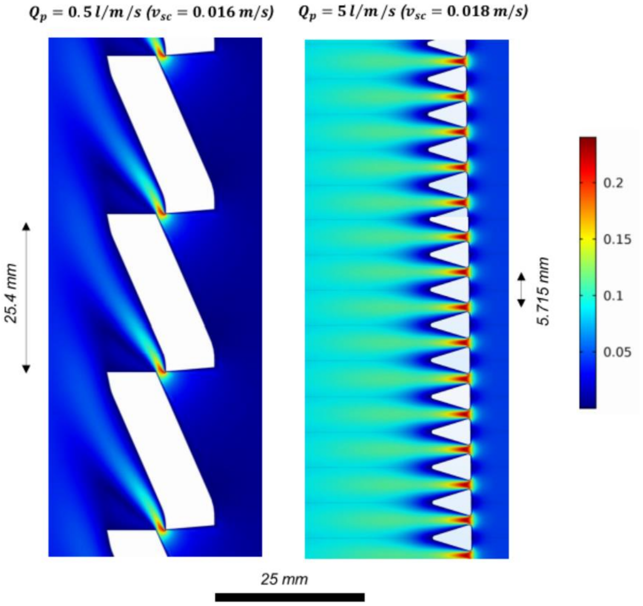


Figure 5.8: Comparison of jet geometry for 0.06”. Left: Louver screen. Right: Wire screen.

Head losses associated with internal turbulence and vertical water movement within the screen have been recognized by other researchers who have identified such losses as contributing to the majority of the well losses. One study of 17 wells with a variety of screen types concluded that the largest contribution to the head loss coefficient is the upflow head loss in the screen (63%) and the screen entrance losses are negligible (0.4%) (Misstear, et al. 2017)

Conclusions

The Amphos study showed well losses in the near-well zone are far more significant than screen losses and that open area and entrance velocity have negligible effects on well efficiency. Near well losses occurring before the water enters the well are the most important contributors to head loss and well efficiency and these losses can be minimized by utilizing proper gravel pack and design criteria.

The study authors concluded that screen head loss cannot be isolated from porous media based on the geometrical considerations of the screen. Recognizing this, one must consider the sum of the contributors well head losses and endeavor to reduce their impact to the greatest degree possible. Such contributors include; screen slot size, filter pack gradation, filter pack/screen interface, filter pack/aquifer interface, and thoroughness of well development.

The emphasis on proper screen design should not be underestimated and their selection should be made with all project objectives in mind. Long-term goals of maximum well efficiency, capacity, and durability cannot be achieved if screens clog or have inherent construction limitations with regard to initial development and future rehabilitation during the entire operational life of the well.

References

Bayer, M. and Jordana, S. (2019) Numerical Modelling to Assess Head Losses in Water Well Screens. Amphos 21 Consulting Final Report, v. n02, June 2019

Clark, L. and Turner, P.A. (1983) Experiments to Assess the Hydraulic Efficiency of Well Screens, Groundwater. Vol 21. No. 3. May-June 1983

Harich, C. R., (2009) Field and Laboratory Analysis of Water Well Design Parameters. Dissertation. Faculty of the Viterbi School of Engineering University of Southern California

Jackson, P. A., Bikis, E. A., and Ahmad, M. U., (1984) Laboratory and Field Studies of Well Design and Efficiency

Misstear, B., Banks, B., and Clark, L., (2017) Water Wells and Boreholes, Second Edition, Wiley Blackwell

Williams, D. E. (1981) The Well/Aquifer Model. Initial Test Results. Roscoe Moss Company

Figures

Velocity Profiles and Streamline Geometries for Screens Modelled in Amphos 21 Study

Figure 2. Jet geometry and flow lines for Louver screen

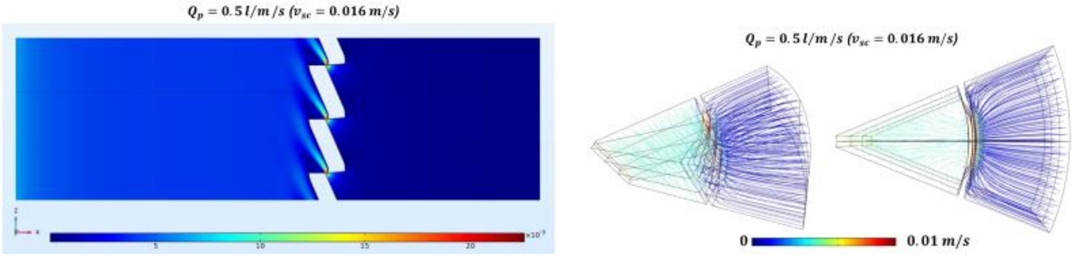
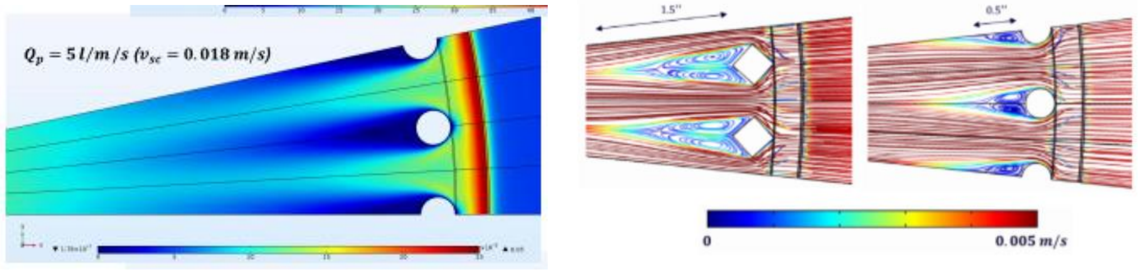
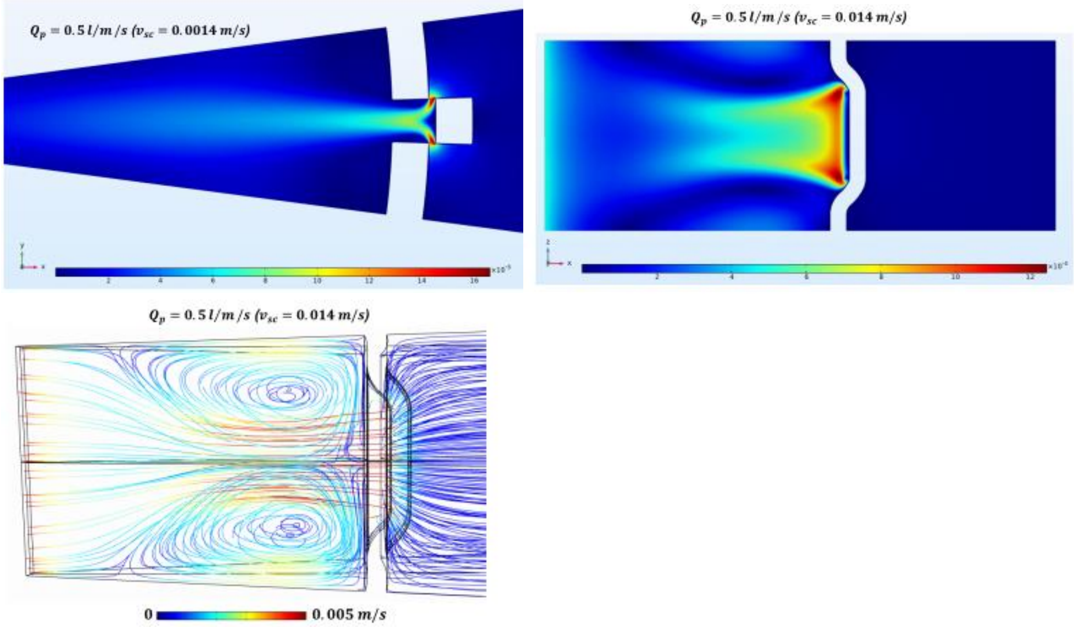


Figure 3. Jet geometry and flow lines for Wire Wrap Screen



Square rod on left, round rod on right

Figure 4. Jet Geometry and Flow Fines for Bridge Slot Screen



$Q_p = 0.5\, l/m/s\ (v_{sc} = 0.0014\, m/s)$

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Figure 5. Jet Geometry and Flow Lines for Mill Slotted Screen

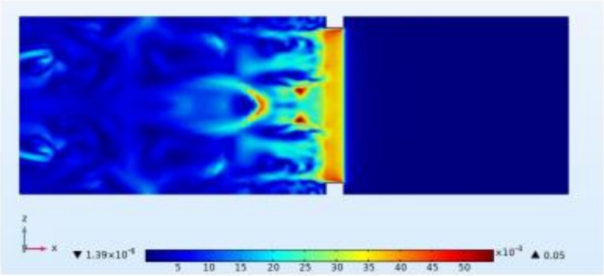
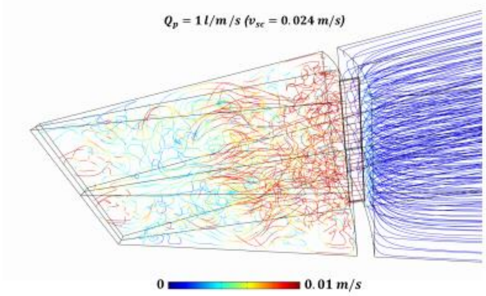


Figure 8.19: *Slotted 06: Velocity magnitude in a vertical cross section for* $Q_p = 0.5\, l/m/s\ (v_{sc} = 0.024\, m/s)$.



$Q_p = 1\, l/m/s\ (v_{sc} = 0.024\, m/s)$

Figure 6. Head Loss v. Distance to Center of Well with Louver Screen

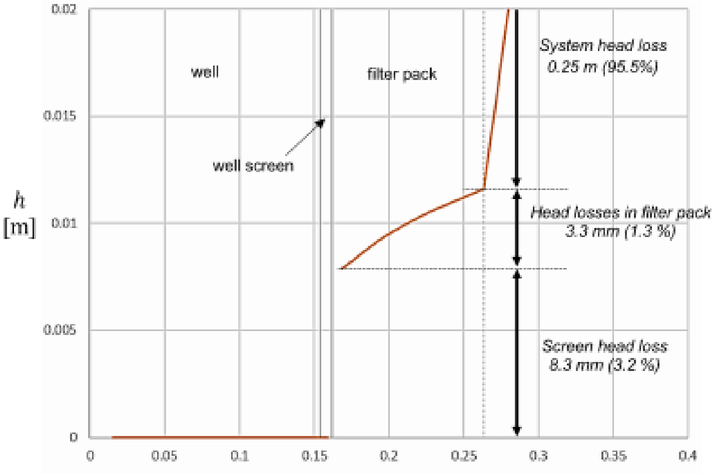


Figure 4.16: *Hydraulic head vs the well distance: head loss in gravel/filter pack and in screen. Louver 06 screen and flow rate* $Q_p = 1\, l/m/s$.

Figure 7. Screen Head Loss v. Screen Velocity for all Screen Types and Slot Sizes

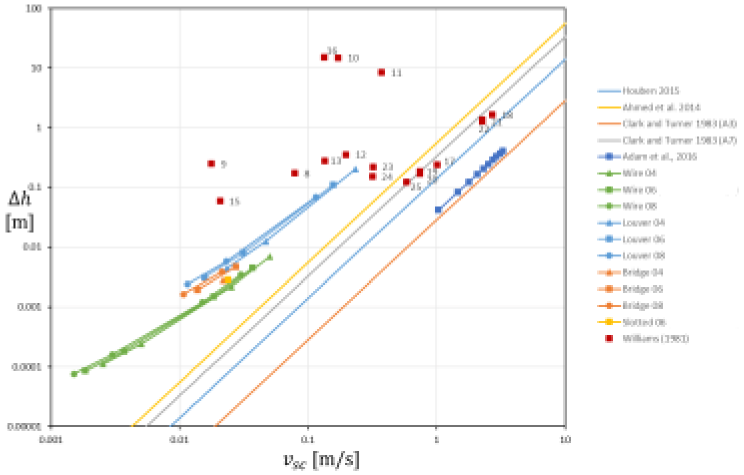
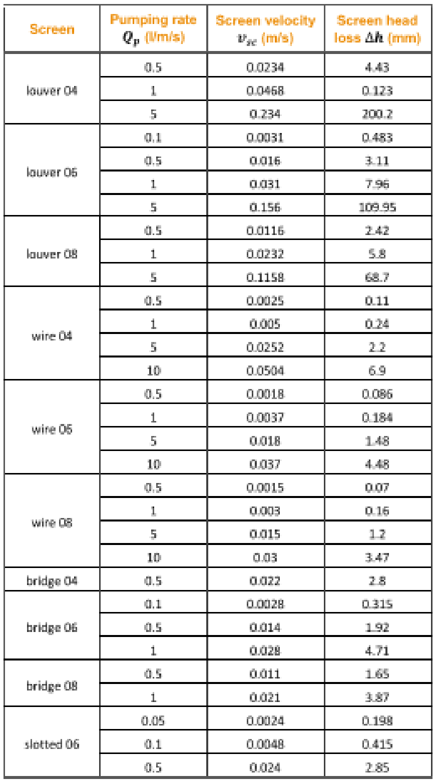


Figure 5.7: *Screen head loss* Δh *vs screen velocity* v_{sc} *for all screen types and slot apertures and fixed* $K_{filter} = 2000\ m/d$.

Figure 8. Summary of Screen Velocity and Head Losses for All Screen Types and Slot Sizes

Table 5-2: *Pumping rates Q_p, screen velocities v_{sc} and screen head loss Δh for 0.04", 0.06"and 0.08" apertures and fixed $K_{filter} = 2000\ m/d$.*



Screen	Pumping rate Q_p (l/m/s)	Screen velocity v_{sc} (m/s)	Screen head loss Δh (mm)
louver 04	0.5	0.0234	4.43
	1	0.0468	0.123
	5	0.234	200.2
louver 06	0.1	0.0031	0.483
	0.5	0.016	3.11
	1	0.031	7.96
	5	0.156	109.95
louver 08	0.5	0.0116	2.42
	1	0.0232	5.8
	5	0.1158	68.7
wire 04	0.5	0.0025	0.11
	1	0.005	0.24
	5	0.0252	2.2
	10	0.0504	6.9
wire 06	0.5	0.0018	0.086
	1	0.0037	0.184
	5	0.018	1.48
	10	0.037	4.48
wire 08	0.5	0.0015	0.07
	1	0.003	0.16
	5	0.015	1.2
	10	0.03	3.47
bridge 04	0.5	0.022	2.8
bridge 06	0.1	0.0028	0.315
	0.5	0.014	1.92
	1	0.028	4.71
bridge 08	0.5	0.011	1.65
	1	0.021	3.87
slotted 06	0.05	0.0024	0.198
	0.1	0.0048	0.415
	0.5	0.024	2.85