Estimating K_{sat} for Infiltration Assessment – WSDOT Approach

TONY ALLEN, State Geotechnical Engineer

May 16, 2017

Presentation Overview

- Infiltration rate estimation concepts
- Advantages and disadvantages of infiltration field testing methods
- Typical WSDOT approach for estimating infiltration rate
- Research to improve K_{sat} estimation using grain size data
- Quantifying the reliability of infiltration design
- On-going research to develop methodology to estimate infiltration rate in embankment side slopes

Infiltration Rate Estimation Concepts

Infiltration Rate Estimation

- Infiltration rate (*f(t)*) is a function of soil hydraulic conductivity (K) and hydraulic gradient (i)
- Based on Darcy's Law for saturated systems
- Approximated using the Green-Ampt Equation (Chin 2000) for unsaturated infiltration conditions and deep water table
- $f(t) = K_{sat}\left[\frac{H_0+L+h_{wf}}{L}\right]$

  where,
  - *f(t)* = infiltration rate at time t
  - K_{sat} = saturated hydraulic conductivity
  - H_o = depth of water in pond or infiltration facility
  - *L* = depth of wetting front below the pond bottom
  - h_{wf} = average capillary head at the wetting front
- Assuming saturated conditions is usually conservative for *f(t)*

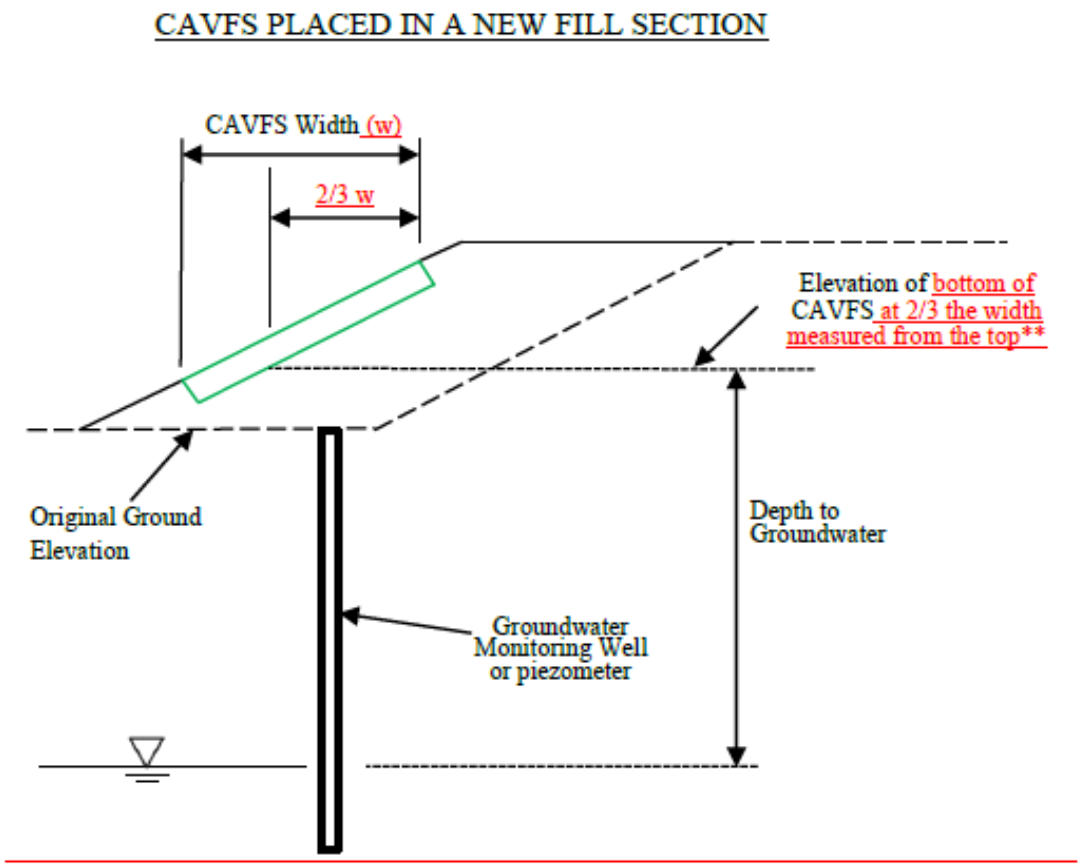
Infiltration Rate Estimation

- For deep water table sites, i = 1.0 is usually conservative, or can use Green-Ampt equation
- For shallow groundwater sites or where low permeability layer is present at shallow depths, i < 1.0 is likely
- For shallow water table conditions where groundwater mounding is possible, Massman (2003) recommended the following to calculate the hydraulic gradient for ponds:
  - $i \approx \left[0.73 A_{pond}{}^{-0.76}\right] \frac{D_{wt}+D_{pond}}{138.62 K_{sat}^{0.1}}$

    where,
    - D_{wt} = depth to water table or first low permeability layer (i.e., aquiclude) (ft)
    - D_{pond} = depth of water in pond (ft)
    - K_{sat} = saturated hydraulic conductivity (ft/day)
  - Targeted for typical conditions in western WA
  - An approximation to account for the reduction in hydraulic gradient due to ground water mounding
  - This is a steady state hydraulic gradient

Infiltration Rate Estimation

- These gradient approximations may not apply to infiltration in highway embankment slopes
- Currently approximated as a very shallow pond or trench using equations in HRM (e.g., for CAVFS)
- Current research may provide an update to this



Infiltration Rate Estimation

- K_{sat} value used is harmonic mean if soil is layered:

$$K_{equiv} = \frac{d}{\sum \frac{d_i}{K_i}}$$

  where,

  - d = total depth of soil column (limit to 20 times BMP depth, but not less than $2.5d_{pond}$)
  - d_i = thickness of layer i in the soil column
  - $K_i = K_{sat}$ for each soil layer
- For ponds, siltation and biofouling reduction factors usually needed (ranges from 0.2 to 0.9)
- Also consider aspect ratio of pond: $CF_{aspect} = 0.02(L_{pond}/W_{pond}) + 0.98$
- WSDOT HRM says siltation and biofouling reduction factors not applicable to slope treatments (e.g., CAFVS), but compaction factor applied to K_{sat} does apply (ranges from 0.067 to 0.2)
- $f_{corr} = CF_{silt/bio} CF_{aspect} K_{equiv} i$

Infiltration Field Tests

Infiltration Rates from Field Tests
Double-ring Infiltrometer Test

- 2 to 3 ft diameter cylinder inserted in ground with a second larger diameter cylinder inserted around the first cylinder
- Water is poured into inner ring, keeping water level constant by continuously adding water
- Quantity of water added during specified time is recorded
- Correction factors are often applied to measured infiltration rate to address the test scale, site variability, and potential for clogging in the full scale infiltration facility
- Test tends to significantly over-estimate the infiltration due to:
  - Gradient that is too high relative to the full scale infiltration gradient
  - Only the surficial soils are tested
  - Localized variability in the soil and moisture conditions
  - Does not address long-term effects due to bio-fouling and siltation

Infiltration Rates from Field Tests
Pilot Infiltration Test (PIT)

- Test pit is excavated with backhoe
- Enough water is added to pit to keep water level approximately 1 to 2 ft deep ft above pit bottom for a minimum of 6 hrs but more typically 17 hrs
- Test tends to over-estimate the infiltration due to:
  - Gradient that is too high relative to the full scale infiltration gradient, especially depending on time of year test is conducted (winter versus summer)
  - Model to estimate infiltration rate assumes one-dimensional flow, whereas the flow is in three directions; therefore Q and infiltration rate are too high
  - Only the surficial soils are tested, but significantly deeper than double-ring infiltrometer
  - Localized variability in the soil and moisture conditions
  - Does not address long-term effects due to bio-fouling and siltation
- Test is often not practical due to large volume of water required and long length of test

Infiltration Rates from Field Tests
Guelph Permeameter

- Focus of test is to estimate K_{sat} in-situ
- Essentially a reduced scale constant head borehole permeameter that can be applied to unsaturated conditions
- WSDOT currently limits its use to natural dispersion of runoff into the highway embankment side slopes
- Limited to eastern WA (i.e., drier conditions and relatively deep water table)
- Multiple tests conducted to account for site variability
- Generally used for depths of 3 ft or less, but can be used a few feet deeper if needed

Infiltration Rates from Field Tests
Borehole Tests

- Borehole tests (e.g., a Slug Test, Seepage Test, or Packer Permeability Test) can be used to obtain K_{sat} for deeper strata
- In general, these tests obtain K_{sat} in the horizontal direction, or possibly a bulk K_{sat}
- Should be isolated to single soil layer making sure that the hole is screened and sealed properly to accomplish this
- Can be conducted above or below the water table, depending on the type of test (e.g., seepage test – above the water table; slug test – below the water table)
- The hydraulic gradient is usually difficult to determine with certainty for any of these tests
- Strongly affected by near well conditions such as gravel pack, poor well development, skin effects, etc.
- Full scale aquifer pumping tests could also be conducted to get a more accurate determination of the bulk hydraulic conductivity, but very expensive and generally not used for infiltration design

Estimating Infiltration Rates
Conclusions Regarding Field Tests

- Full scale flood tests or long-term full scale infiltration studies are most accurate field test for estimating infiltration, but often not practical to do, other than for research
- Smaller scale tests have the disadvantage of only addressing the surficial soils, having too high a hydraulic gradient which may be difficult to quantify, and being susceptible to localized soil property variation
- Have relied on estimating K_{sat} from gradation parameters or laboratory hydraulic conductivity testing
- Further investment to improve K_{sat} predictions based on grain size characteristics is warranted

Summary of WSDOT Approach for Estimating Infiltration Rate

- Estimate K_{sat} for each soil layer using grain size analysis (currently using equation from Massman 2003 which is in WSDOT HRM and also DOE Stormwater manual)
- Estimate hydraulic gradient as summarized earlier in presentation
- Reduce K_{sat}/infiltration rate to address long-term maintenance and/or degree of compaction
- Alternatively, estimate K_{sat}/infiltration rate through Pilot Infiltration Test per DOE Manual, though this approach is rarely used by WSDOT
- No additional reduction/safety factors are applied

WSDOT Research Results Regarding Estimation of K_{sat} Considering Compaction

Current Research: Purpose and Scope

- Hydraulic conductivity (K_{sat}) is key parameter to estimate infiltration rate
- Research focus
  - Infiltration of storm water into embankment side slopes, but could also apply to other applications where K_{sat} needed
  - Effect of compaction (or density) on K_{sat}
- Research scope
  - Saturated, non-cohesive soils
  - Testing included soil grain size, density, and large diameter rigid and flex-wall permeameter tests
    - Mostly on specimens reconstituted in lab
    - Specimens in a loose and compacted state

Review of Previous Work

- To estimate K_{sat}, d_{10} (in mm) commonly used, as well as porosity, η, or void ratio, e
- Hazen (1892): $K_{sat} = Cd_{10}^2$
  where,
  - C = 0.4 to 1.5,
  - usually set equal to 1.0
- Slichter (1898): $K_{sat} = 10.2\eta^{3.287}d_{10}^2$
- Terzaghi (1925): $K\ (\text{cm/s}) = C_0 \frac{\mu_{10}}{\mu_t}\left(\frac{\eta - 0.13}{\sqrt[3]{1-\eta}}\right)^2 d_{10}^2$

  where,
  - C_0 = 8 for smooth grains and 4.6 for grains of irregular shape
  - μ_{10} = water viscosity at 10° C
  - μ_t = water viscosity at the soil temperature "t" (usually 20° C)
  - μ_{10}/μ_t usually taken as 1.30

Review of Previous Work

- Chapuis (2004): $K = 2.4622\left[d_{10}^2 \frac{e^3}{1+e}\right]^{0.7825}$
- More recently, equation developed by Massman (2003):
  - $Log_{10}(K_{sat}) = -1.57+1.90d_{10}+0.015d_{60}-0.013d_{90}-2.08F_{fines}$
  - This equation is currently in DOE Stormwater Management Manual and WSDOT Highway Runoff Manual (HRM)
- Most of these equations were developed for loose soils (not compacted)
- Most K_{sat} equations are purely empirical in nature
- Equations which include porosity or void ratio have the best chance of addressing compaction effects
- There are many K_{sat} equations

Laboratory Test Program
Materials Tested

- Natural soils used to meet WSDOT borrow specifications for embankments
- Soils reconstituted from natural soils to make gradations needed
- Mostly glacial in origin and angular in nature
- Nonplastic soils used

Laboratory Test Program
Specimen Preparation

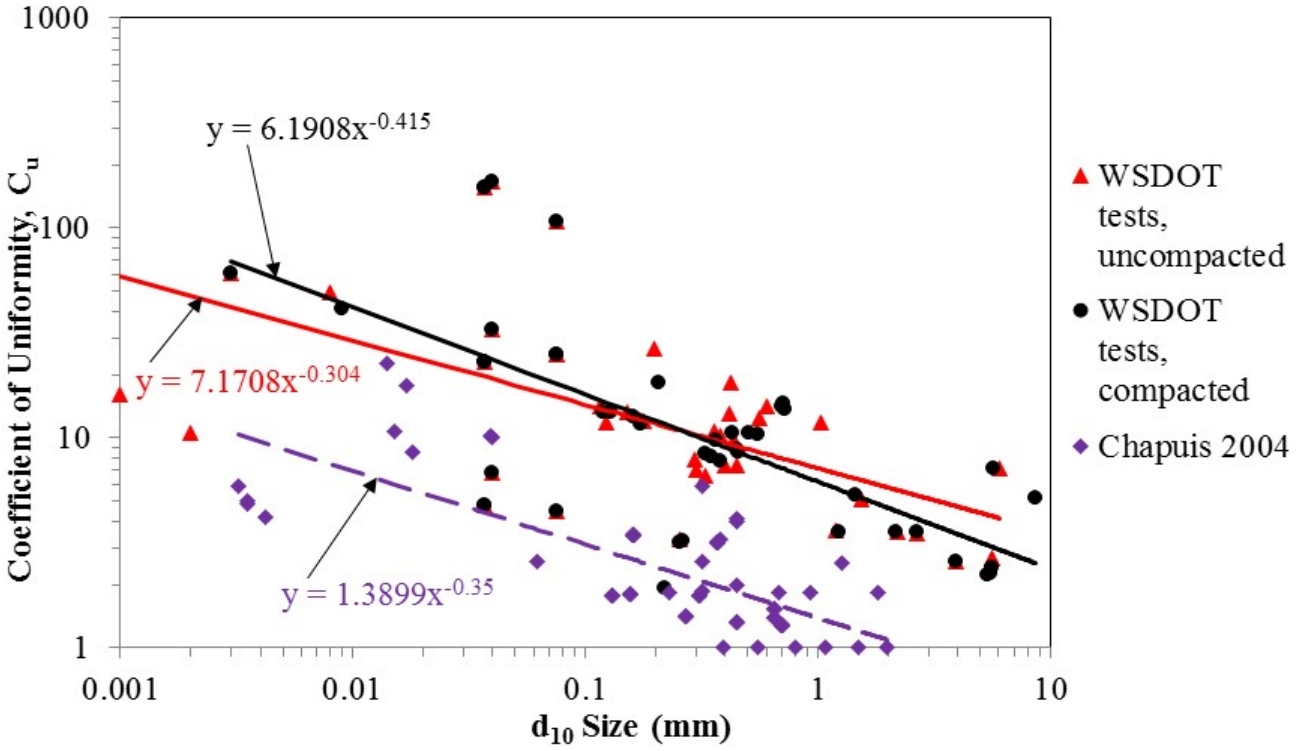
- Two levels of compaction used
  - Uncompacted – placed moist and lightly tamped by hand using 2 in. dia. circular tamping foot (only for uniform placement)
  - Compacted – placed moist using same tamping foot, but with 2.25 lbs weight and 12 in. drop
  - Achieved approx. 95% compaction or more for compacted specimens
  - Had approx. 80 to 85% compaction for uncompacted specimens

Laboratory Test Program
Test Procedures

- Rigid wall permeameter – AASHTO T215, 6 in. dia., except 9 in. dia. for coarsest soils, constant head, and used if soil $d_{10} \geq 0.1$ mm
- Flex wall permeameter – ASTM D5084, 6 in. dia., falling head, and used if soil $d_{10} < 0.1$ mm
- Testing was conducted such that the common mistakes in laboratory K_{sat} testing identified by Chapuis (2012) were avoided

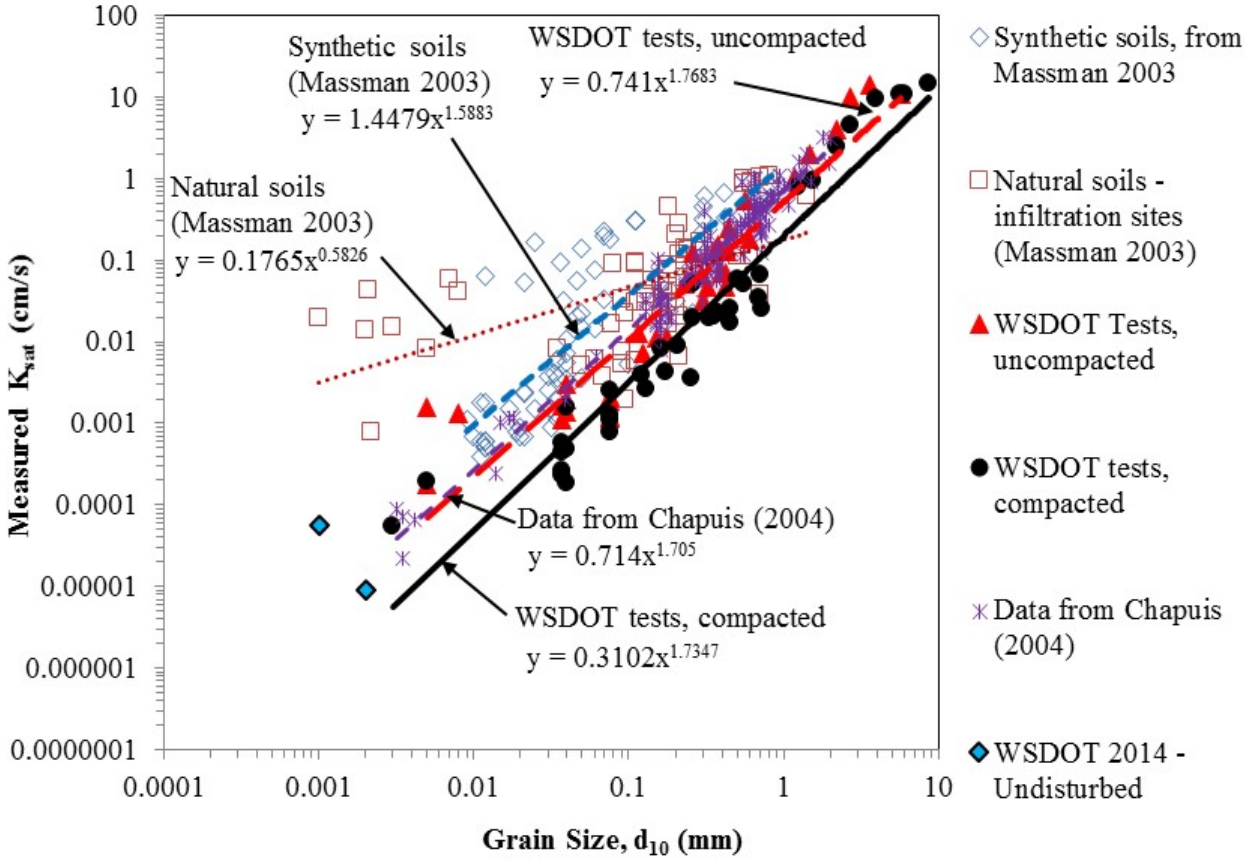
Gradation Characteristics of Soils Tested or Included in Database

- WSDOT Testing included 36 uncompacted and 37 compacted tests
- Gathered data from Chapuis (2004) as comparison, which included 137 tests, all not specifically compacted, and mostly rounded soil particles
- Outliers were removed based on criteria in in TRB Circular E-C079 (Allen et al. 2005) - a total of 11 points, mostly at very coarse end



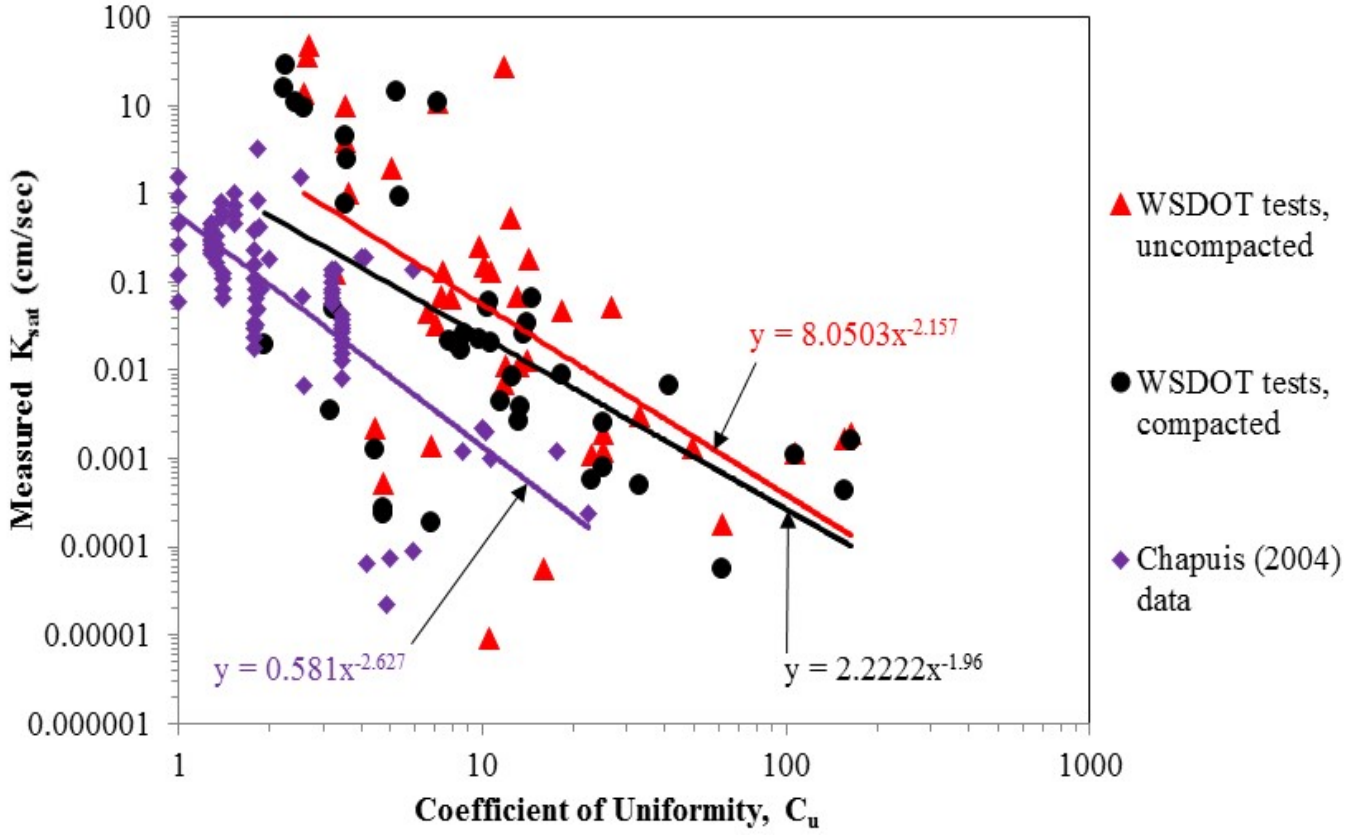
Relationship between Measured K_{sat} and Soil d_{10}

- All WSDOT and Chapuis data based on saturated hydraulic conductivity (K_{sat}) tests
- Massman (2003) data are air permeability tests converted to K_{sat}

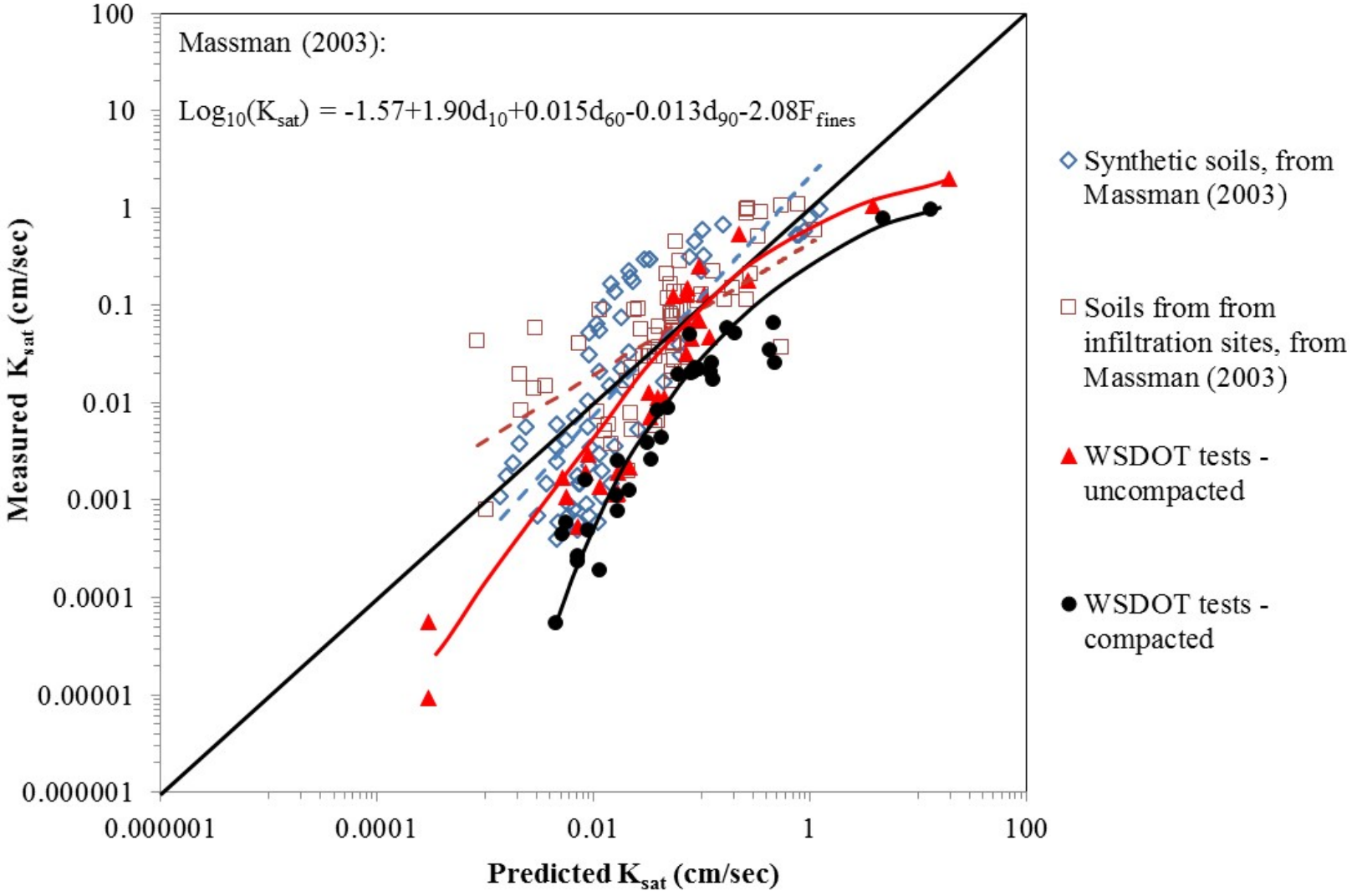


Relationship between Measured K_{sat} and Soil C_u

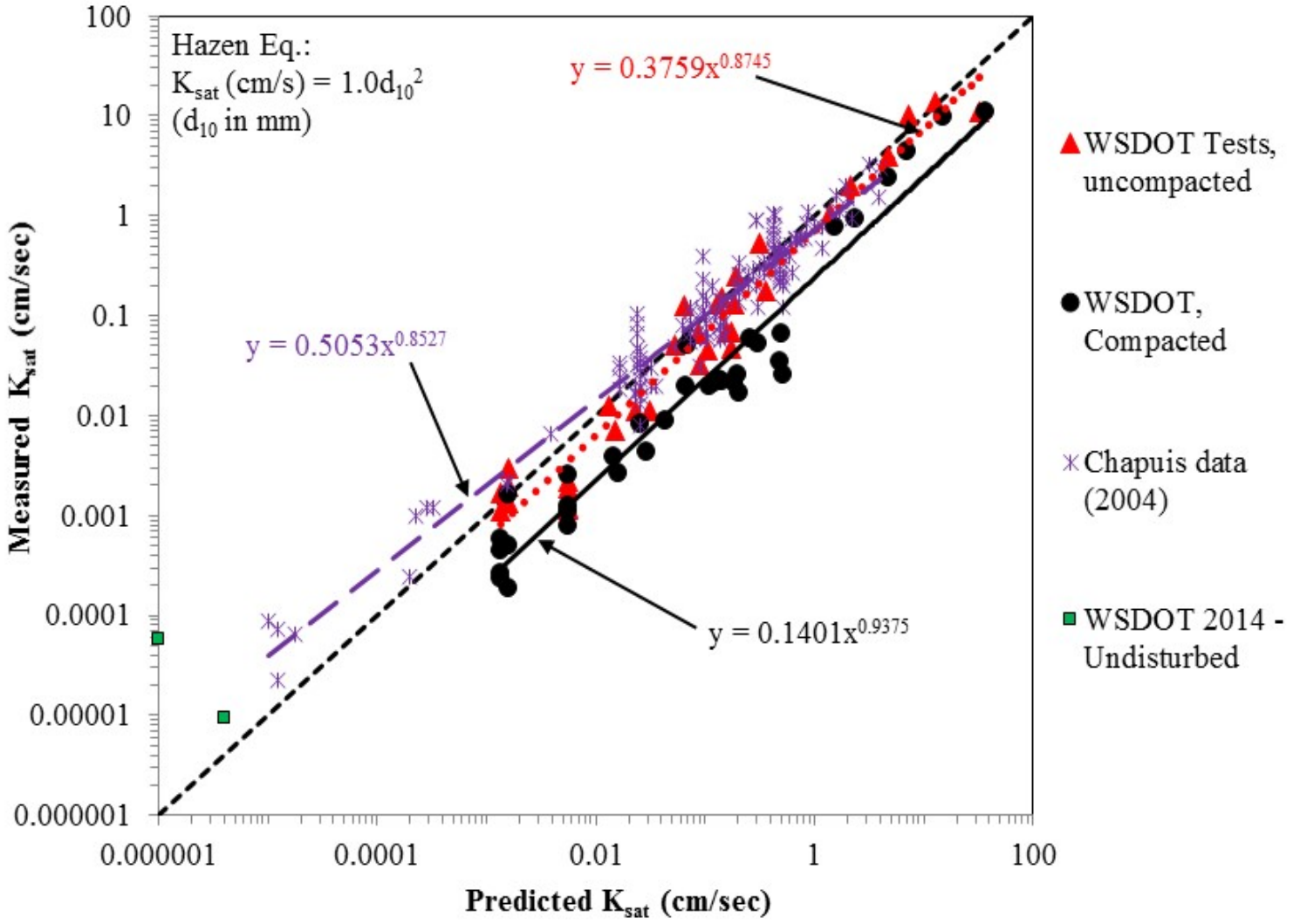
- Fairly strong relationship – as C_u increases, K_{sat} decreases
- Not all of the Chapuis data could be shown, as some cases did not have a d_{60} value reported



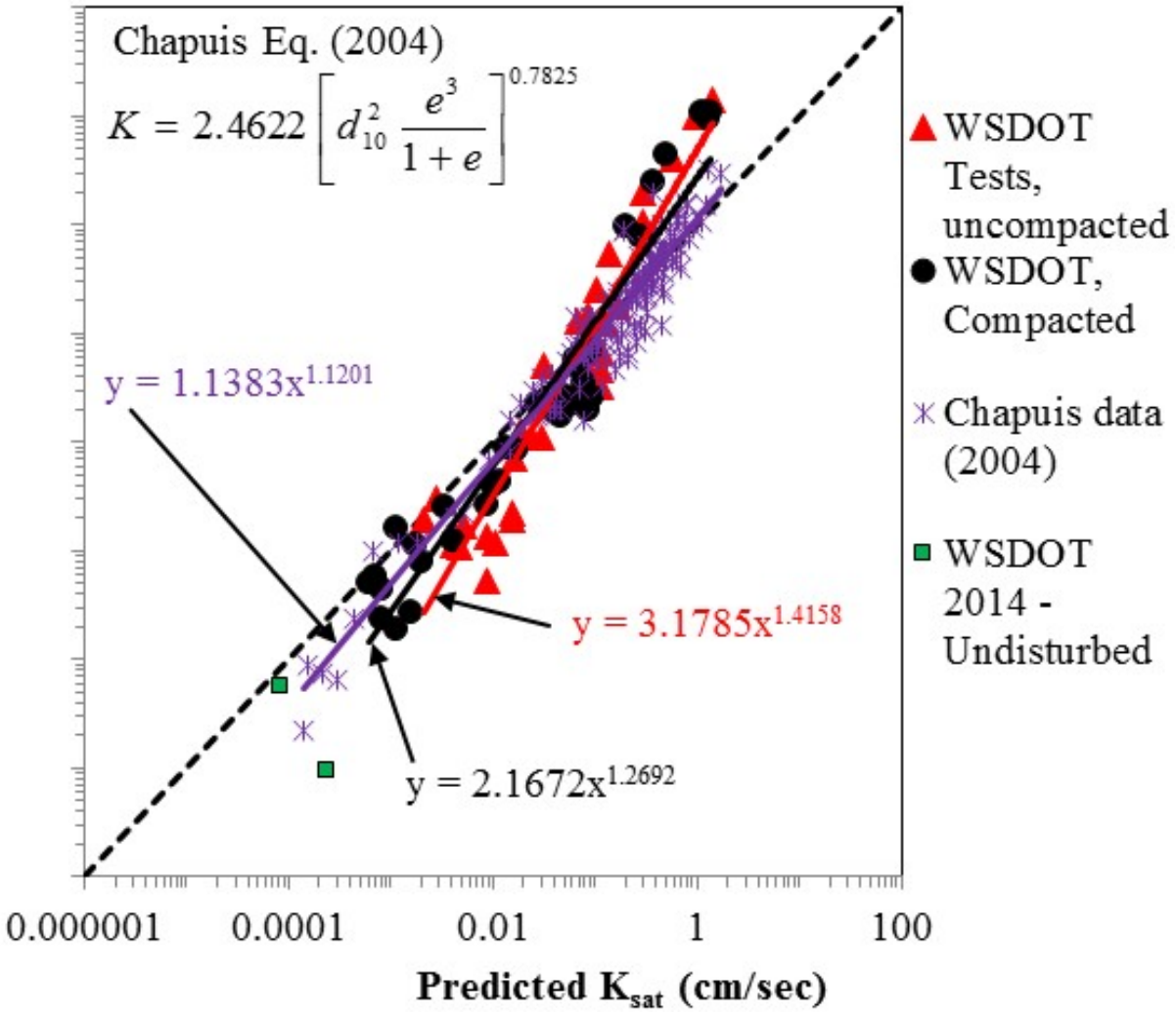
Massman (2003) Equation



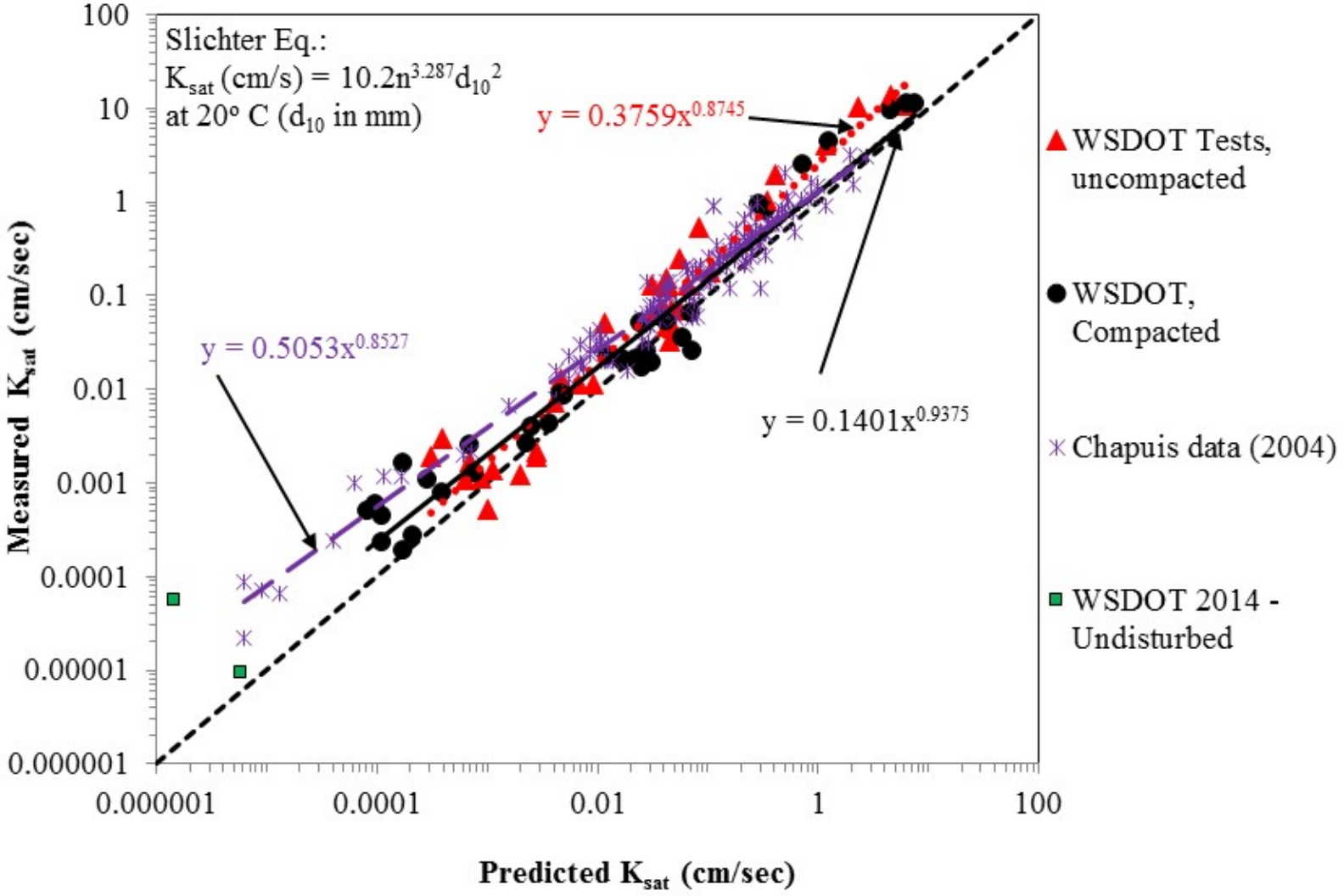
Hazen (1892) Equation



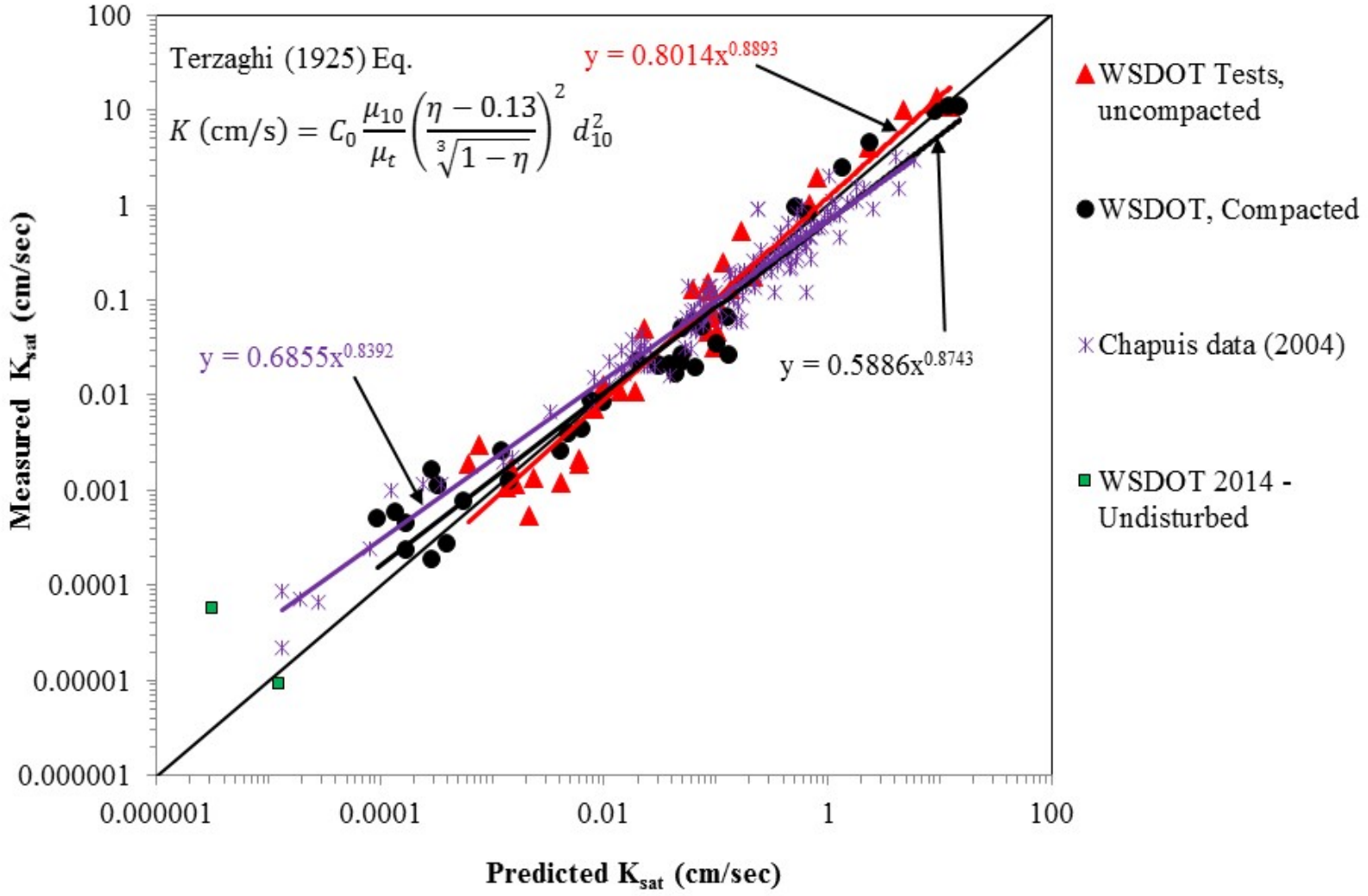
Chapuis (2004) Equation



Slichter (1898) Equation



Terzaghi (1925) Equation



Improving Method Accuracy

- Focused on “tweaking” coefficients and exponents
- Used SOLVER in Excel, then made final adjustments by hand
- Optimization approach
  - Lowest COV with mean as close to 1.0 as possible
  - Used K_{sat} method prediction bias (i.e., measured/predicted value) for statistics
  - Method accuracy as a function of key variables addressed (i.e., no hidden dependencies)
  - Considered differences between data sets, e.g., the WSDOT uncompacted sample data, the WSDOT compacted sample data, and the data gathered by Chapuis (2004)
  - Only considered saturated hydraulic conductivity test data
  - Did not consider air permeability test results by Massman (2003)

Optimized Methods

- Optimized Slichter Method: $K_{sat} = 21.2\eta^{3.5} d_{10}^{1.75}$
  - Original: $K_{sat} = 10.2\eta^{3.287} d_{10}^{2}$
- Optimized Terzaghi Method:

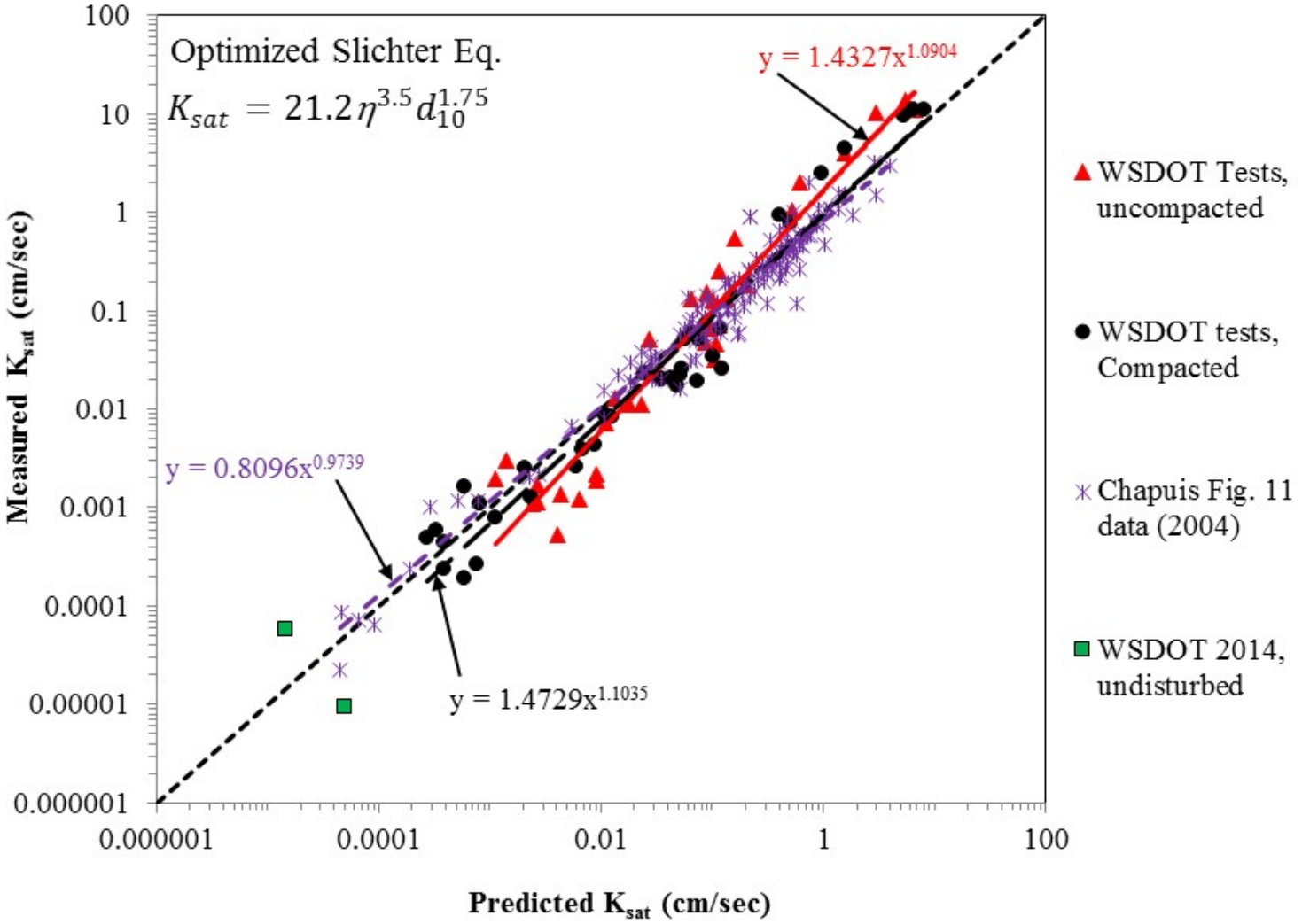
$$K\ (\text{cm/s}) = C_0 \frac{\mu_{10}}{\mu_t} \left(\frac{\eta - 0.13}{\sqrt[3]{1-\eta}} \right)^{1.7} d_{10}^{1.75}$$

  - Where, C_0 = 4.6 for all soils
  - Original: $K\ (\text{cm/s}) = C_0 \frac{\mu_{10}}{\mu_t} \left(\frac{\eta - 0.13}{\sqrt[3]{1-\eta}} \right)^{2} d_{10}^{2}$
  - Original: C_0 = 8 for smooth grains and 4.6 for grains of irregular shape
- Optimized Chapuis Method:

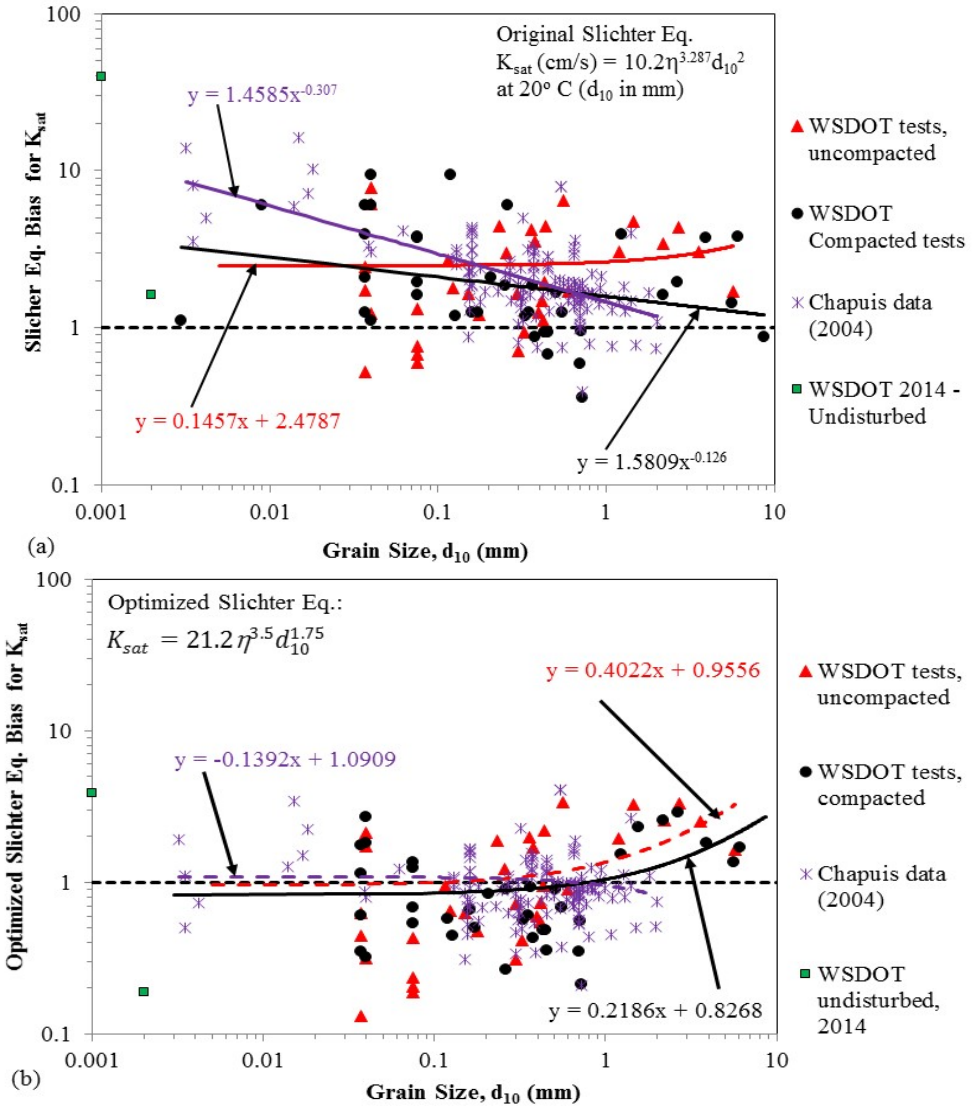
$$K_{sat} = 2.1 \left[d_{10}^{2.24} \frac{e^2}{1+e} \right]^{0.7825}$$

  - Original: $K = 2.4622 \left[d_{10}^{2} \frac{e^3}{1+e} \right]^{0.7825}$
- Optimized Hazen Method: $K_{sat} = 0.65 d_{10}^{1.65}$
  - Original: $K = 1.0 d_{10}^{2}$

Example: Optimized Slichter Equation



Example: Optimized Slichter Equation



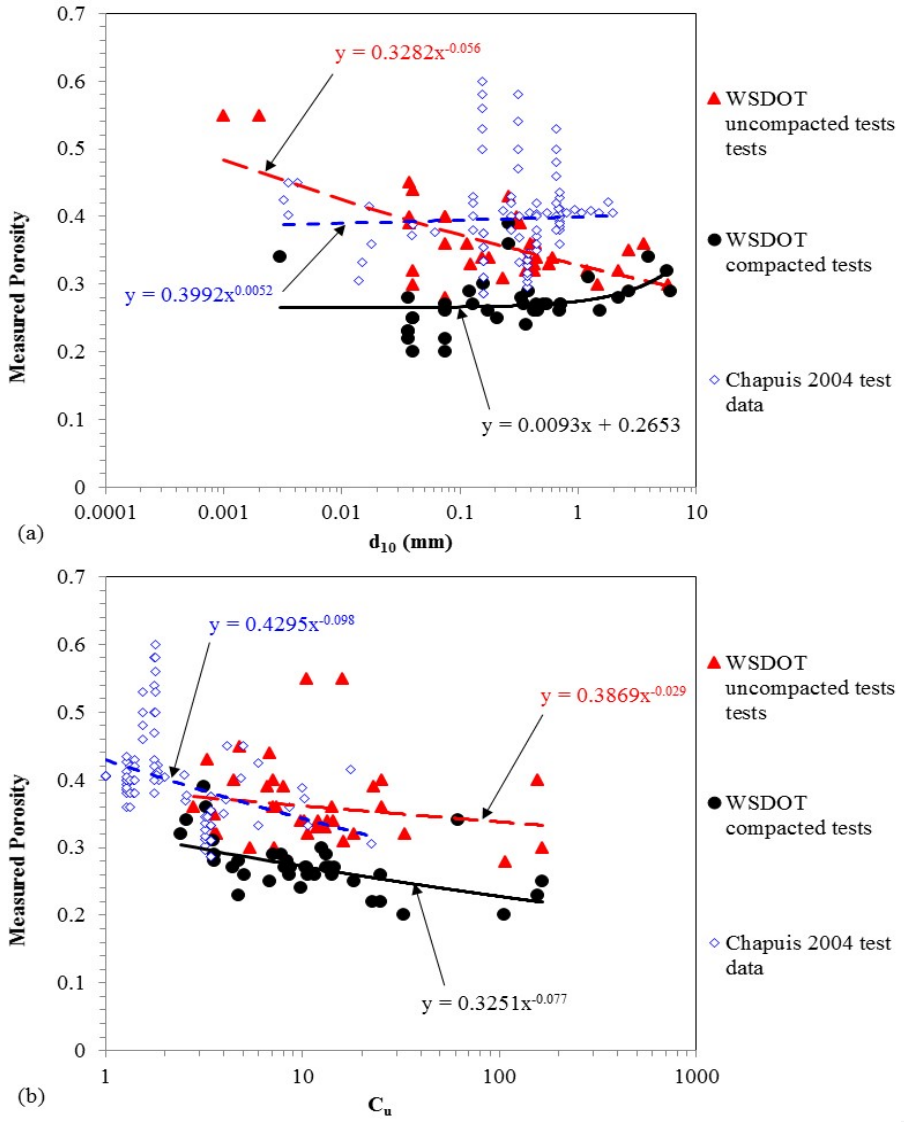
Summary of Observations Regarding Improvements

- Focused on methods that could account for compaction/density effects on K_{sat}
- Improved Slichter and Terzaghi methods provided similar accuracy and were best overall
- Improvements were not as effective for Chapuis Method (also true of Cozeny-Carmen Method)
- Hazen Method could also be improved, but still does not address compaction effects
- For Slichter and Terzaghi methods, need soil porosity – how to obtain?

Obtaining the Soil Porosity

- Can measure directly (e.g., from undisturbed specimens of natural soil, from soil compaction records, etc.)
- Past η prediction efforts focused on grain size parameters (e.g., C_u), but not relative density or degree of compaction
- Proposed equation: $\eta = P \times d_{10}^{a} \times C_u^{b} \times (F_{cp})$ where,
  - P = empirical porosity coefficient (P = 0.4)
  - a = empirical d_{10} exponent (a = -0.08)
  - b = empirical coefficient for C_u (b = -0.1)
  - F_{cp} = compaction factor for porosity (set equal to 1.0 if not compacted)

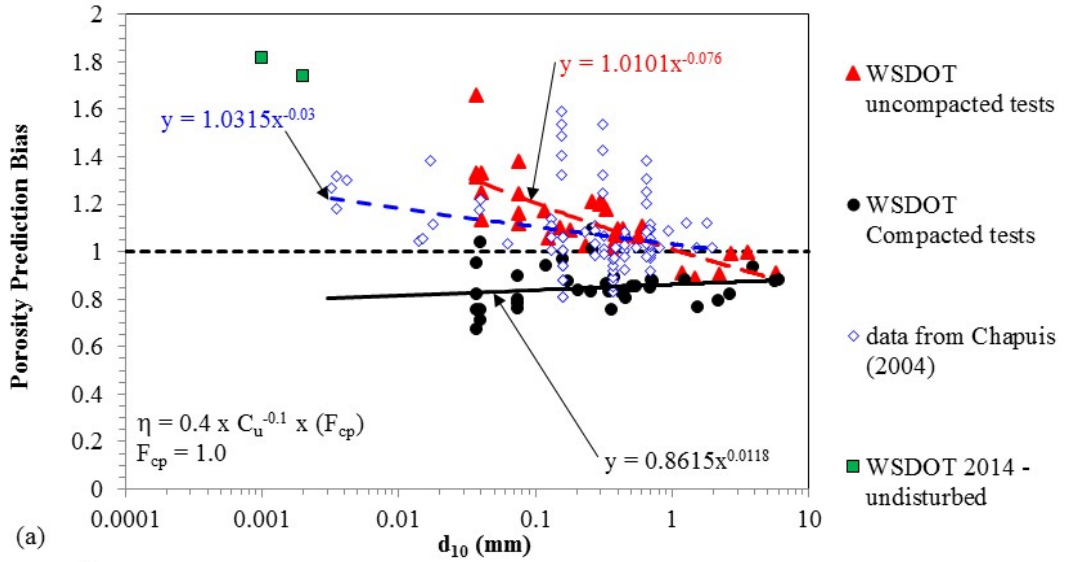
Compaction Effect on Porosity



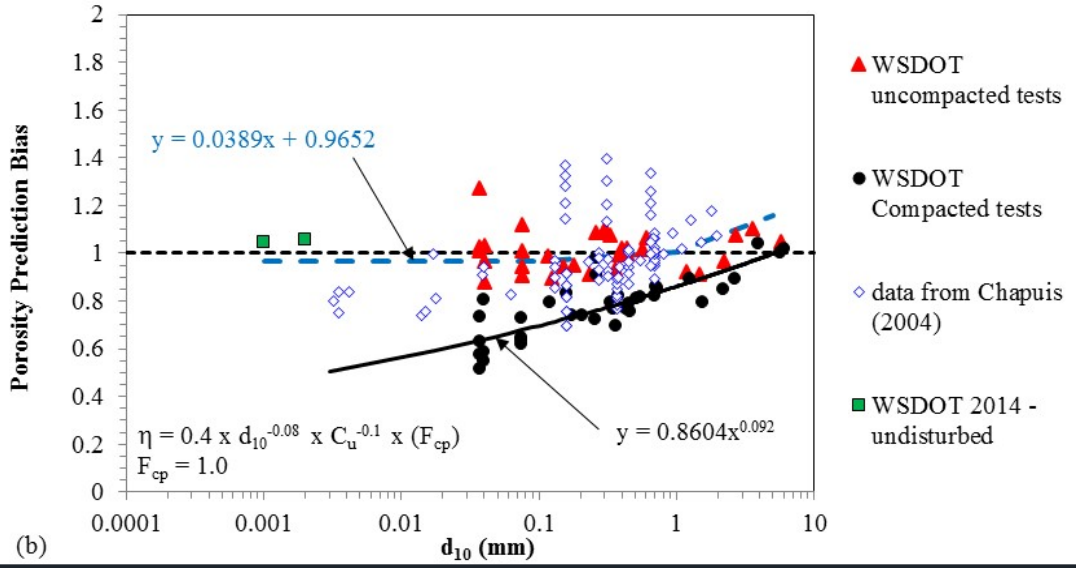
Note: Compaction effect on porosity is either “on” or “off”, but may be possible to interpolate to intermediate values. Compacted porosities approximately correspond to densest state possible, and uncompacted values approximately correspond to loosest state, at least for fill materials.

Compaction Effect on Porosity

- Plot to right assumes no d_{10} dependence
- No correction for compaction



- Plot to right corrects for d_{10} dependence for uncompacted and compacted data
- No correction for compaction



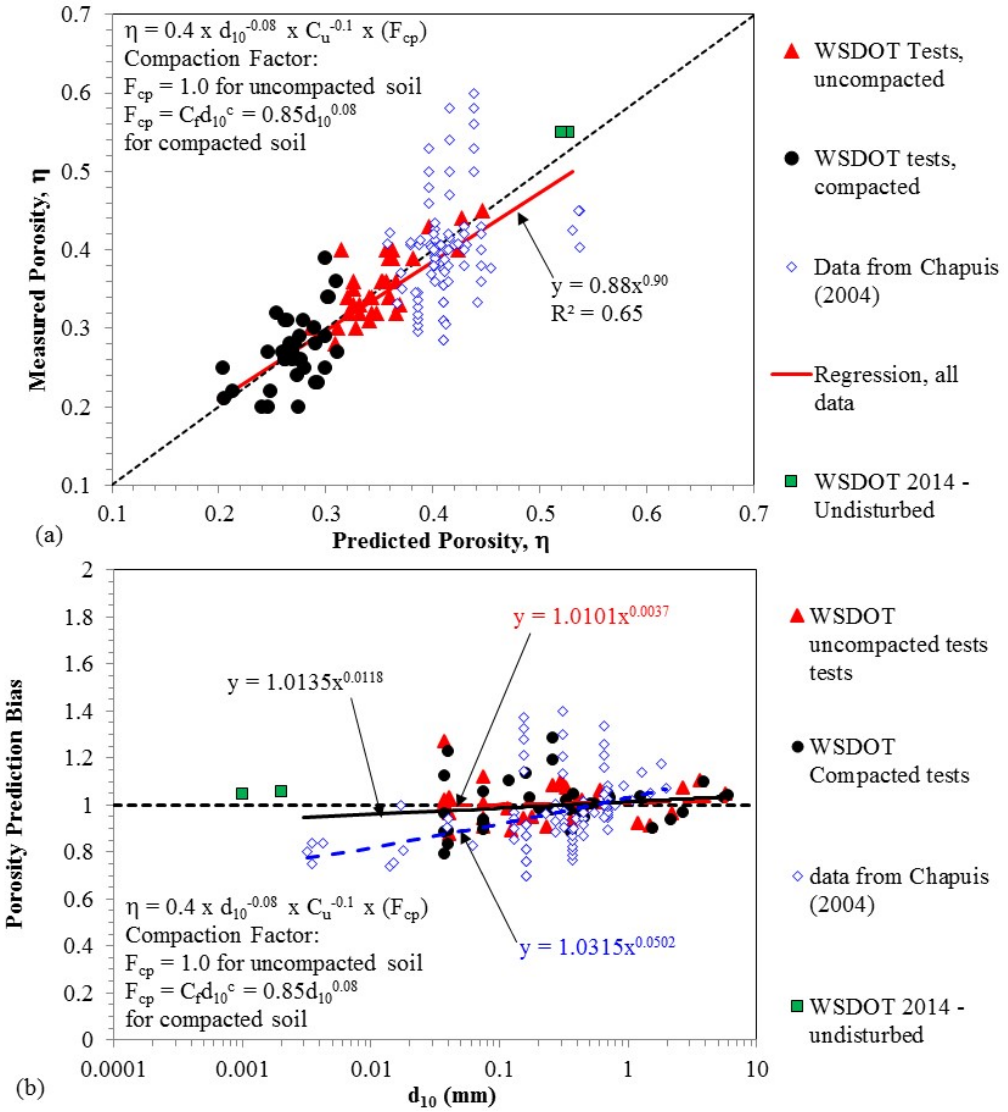
Estimating Porosity - Results

Since compacted soil porosity not affected by d_{10}, must cancel out d_{10} effect needed for uncompacted soils. Therefore,

$F_{cp} = 0.85d_{10}^{0.08}$

In effect, the porosity equation for compacted soils simplifies to:

$\eta = 0.34C_u^{-0.1}$



Effect of Compaction on Porosity and K_{sat}

- Using predicted η in optimized Slichter or Terzaghi K_{sat} equations:
- At d_{10} = 0.001 mm:
  - K_{sat} (compacted) = 0.083 x K_{sat} (uncompacted)
- At d_{10} = 1.0 mm:
  - K_{sat} (compacted) = 0.57 x K_{sat} (uncompacted)
- Current WSDOT HRM:
  - K_{sat} (compacted) = 0.067 x K_{sat} (uncompacted) for clayey soils
  - K_{sat} (compacted) = (0.1 to 0.2) x K_{sat} (uncompacted) for sands and gravels
  - Will be no need for these factors anyway if use the new K_{sat} equations

Method Statistics – Historical Methods

Data Set	No. of Meas., n	Hazen Method		Slichter Method		Terzaghi Method		Chapuis Method	
		Mean	COV	Mean	COV	Mean	COV	Mean	COV
WSDOT uncompacted tests	36	2.39	392%	3.59	180%	1.73	173%	1.96	148%
WSDOT compacted tests	37	--	--	2.20	83%	1.35	96%	1.76	157%
All WSDOT tests	74	--	--	2.89	164%	1.54	149%	1.86	151%
Chapuis (2004) tests	137	1.25	90%	2.50	86%	1.20	87%	1.05	70%
All Test data	210	1.49*	294%*	2.64	125%	1.32	121%	1.33	135%

*For the Hazen Equation, all test data does not include compacted WSDOT tests.

Method Statistics – Optimized Methods

Data Set	No. of Meas., n	Hazen Method		Slichter Method		Terzaghi Method		Chapuis Method	
		Mean	COV	Mean	COV	Mean	COV	Mean	COV
WSDOT uncompacted tests	36	1.05	129%	1.28	83%	1.20	88%	1.41	113%
WSDOT compacted tests	37	--	--	1.01	73%	0.90	73%	0.96	131%
All WSDOT tests	74	--	--	1.14	80%	1.05	84%	1.18	122%
Chapuis (2004) tests	137	1.19	59%	1.02	57%	1.01	54%	1.03	55%
All Test data	211	1.16*	76%*	1.06	67%	1.02	66%	1.08	89%

*For the Hazen Equation, all test data does not include compacted WSDOT tests.

Method Statistics – Porosity Prediction

Data Set	No. of Meas., n	Statistical Parameter	Proposed porosity Prediction Method
Chapuis (2004) and all WSDOT Tests	158	Mean	0.99
		COV	13%
All WSDOT tests	74	Mean	1.01
		COV	9.1%
Chapuis (2004) tests	85	Mean	0.97
		COV	16%
All uncompacted WSDOT tests	36	Mean	1.01
		COV	7.9%
All compacted WSDOT tests	38	Mean	1.00
		COV	10%

Method Statistics – Optimized Methods, but Using Est. Porosity

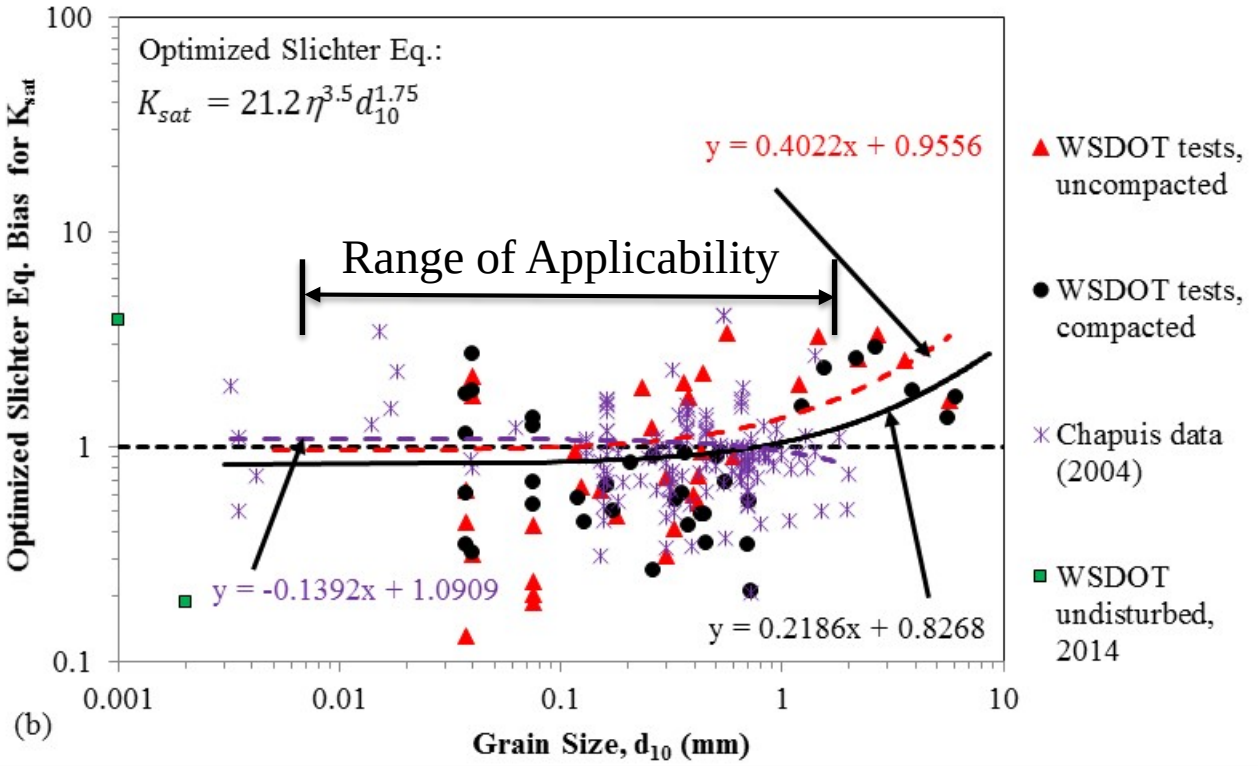
	Optimized Slichter Method				Optimized Terzaghi Method			
	Measured η		Estimated η		Measured η		Estimated η	
Data Set	Mean	COV	Mean	COV	Mean	COV	Mean	COV
WSDOT uncompacted tests	1.28	83%	1.31	88%	1.20	88%	1.23	94%
WSDOT compacted tests	1.01	73%	1.07	93%	0.90	73%	0.96	100%
All WSDOT tests	1.14	80%	1.19	91%	1.05	84%	1.09	97%
Chapuis (2004) tests	1.02	57%	0.95	57%	1.01	54%	0.97	56%
All Test data	1.06	67%	1.06	79%	1.02	66%	1.03	80%

Conclusions:

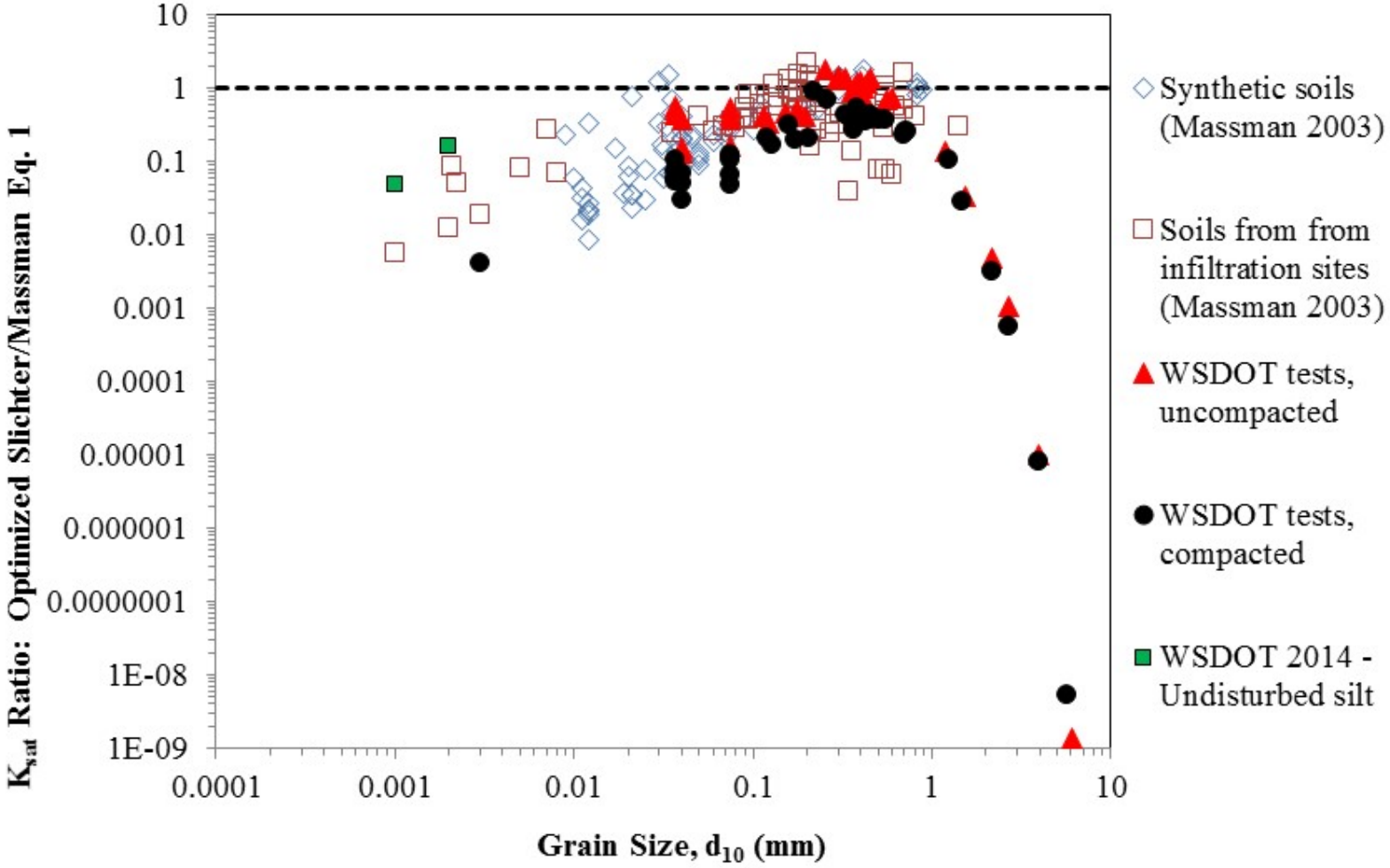
- Using measured porosity, both methods are about the same for accuracy
- Using estimated porosity, overall both methods are about the same for accuracy, but for the WSDOT test data, the optimized Slichter Method is slightly better than the optimized Terzaghi Method

Recommended K_{sat} Prediction Method

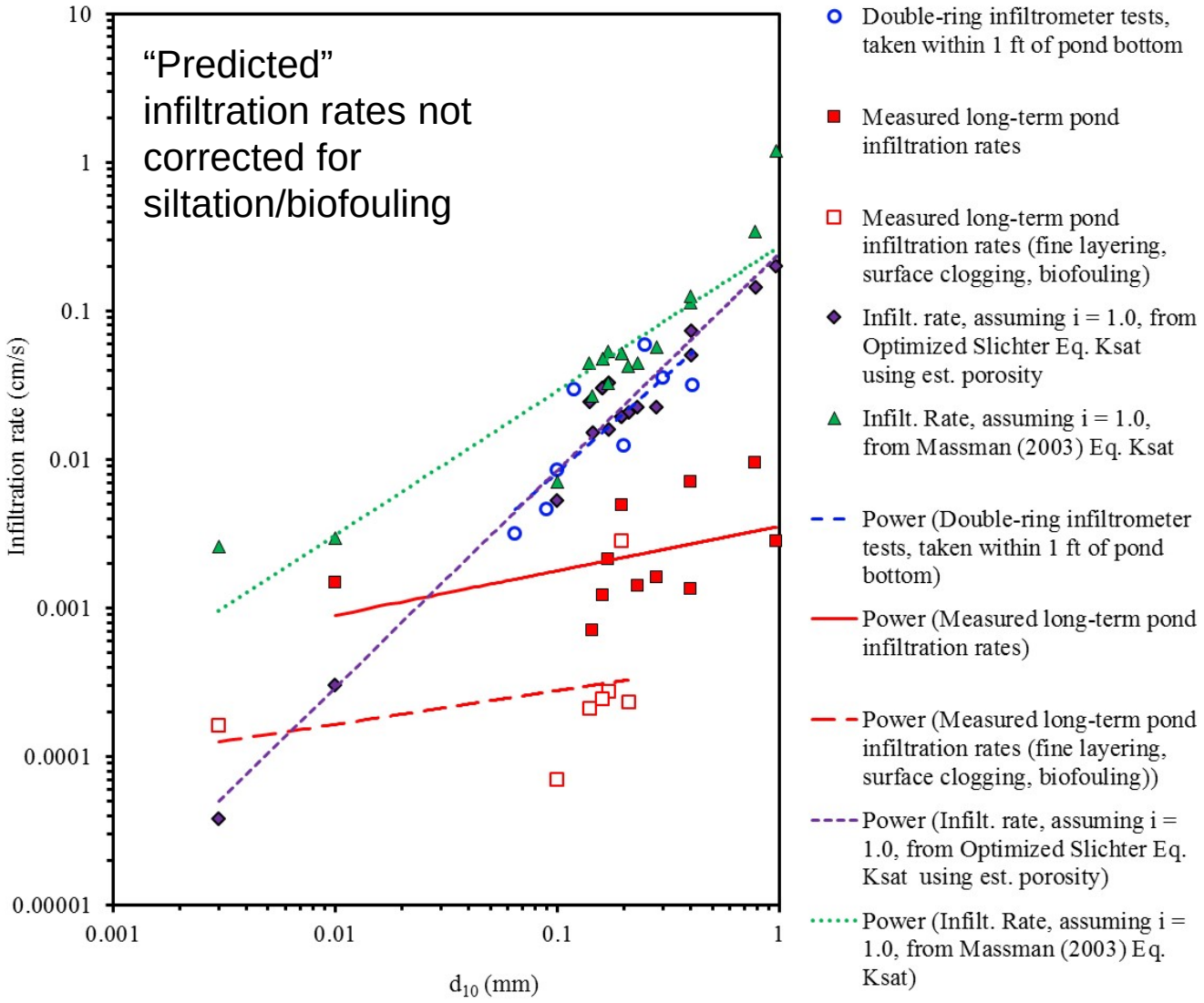
- Optimized Slichter and Terzaghi equations provide most accurate predictions with widest range of applicability, and work for rounded and angular soils, using measured or estimated porosity
- Range of applicability for the optimized Slichter Equation is shown below – optimized Terzaghi Method is similar



Application to Infiltration Design: Comparison to Current HRM

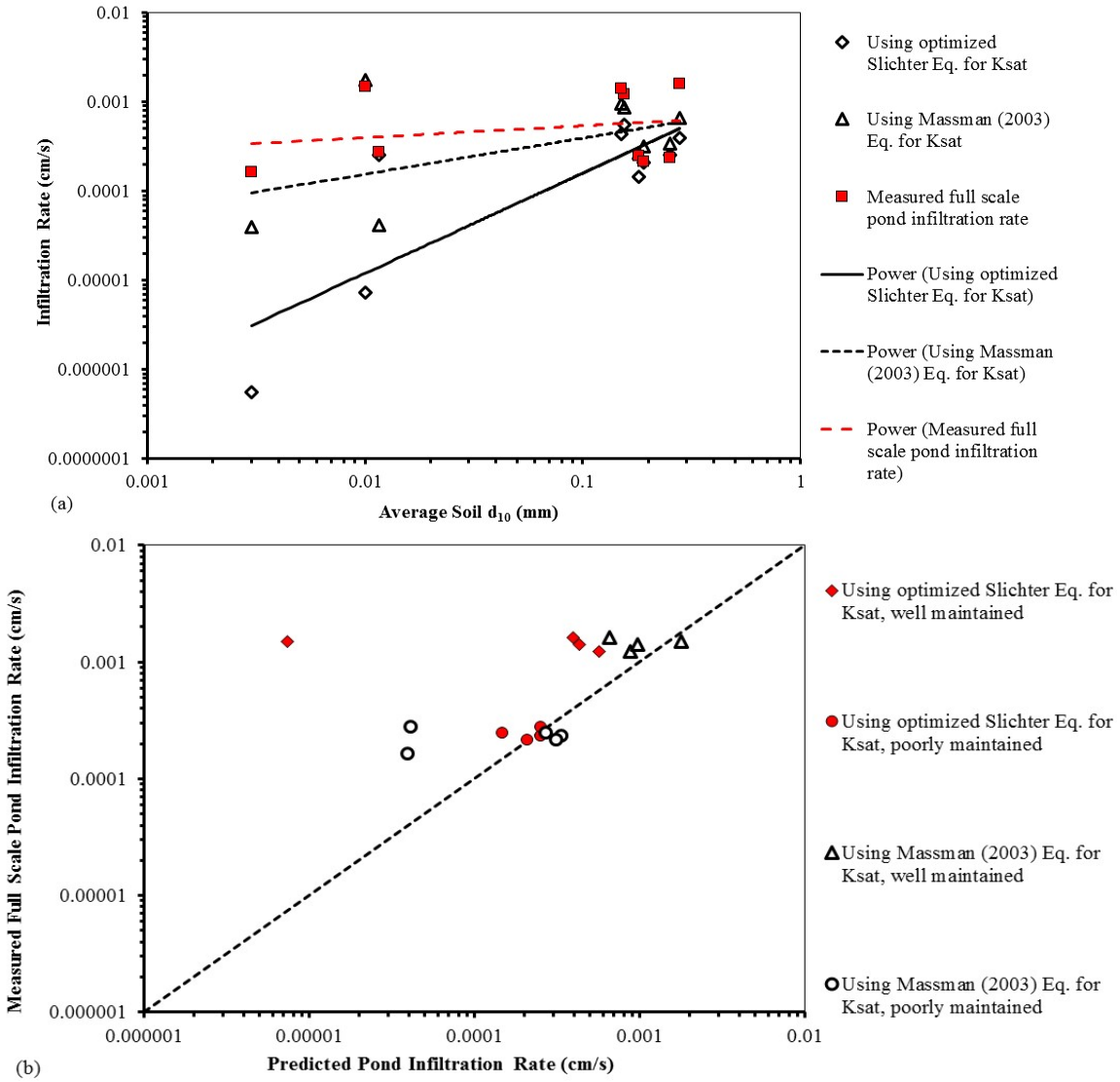


Comparison to Infiltration Rates from 1998 Thurston County Study



Comparison to Corrected Infiltration Rates from 1998 Thurston County Study

Predicted infiltration rates corrected for siltation/biofouling, and hydraulic gradient, i, calculated using WSDOT HRM equation for ponds



Concluding Remarks from Current Study

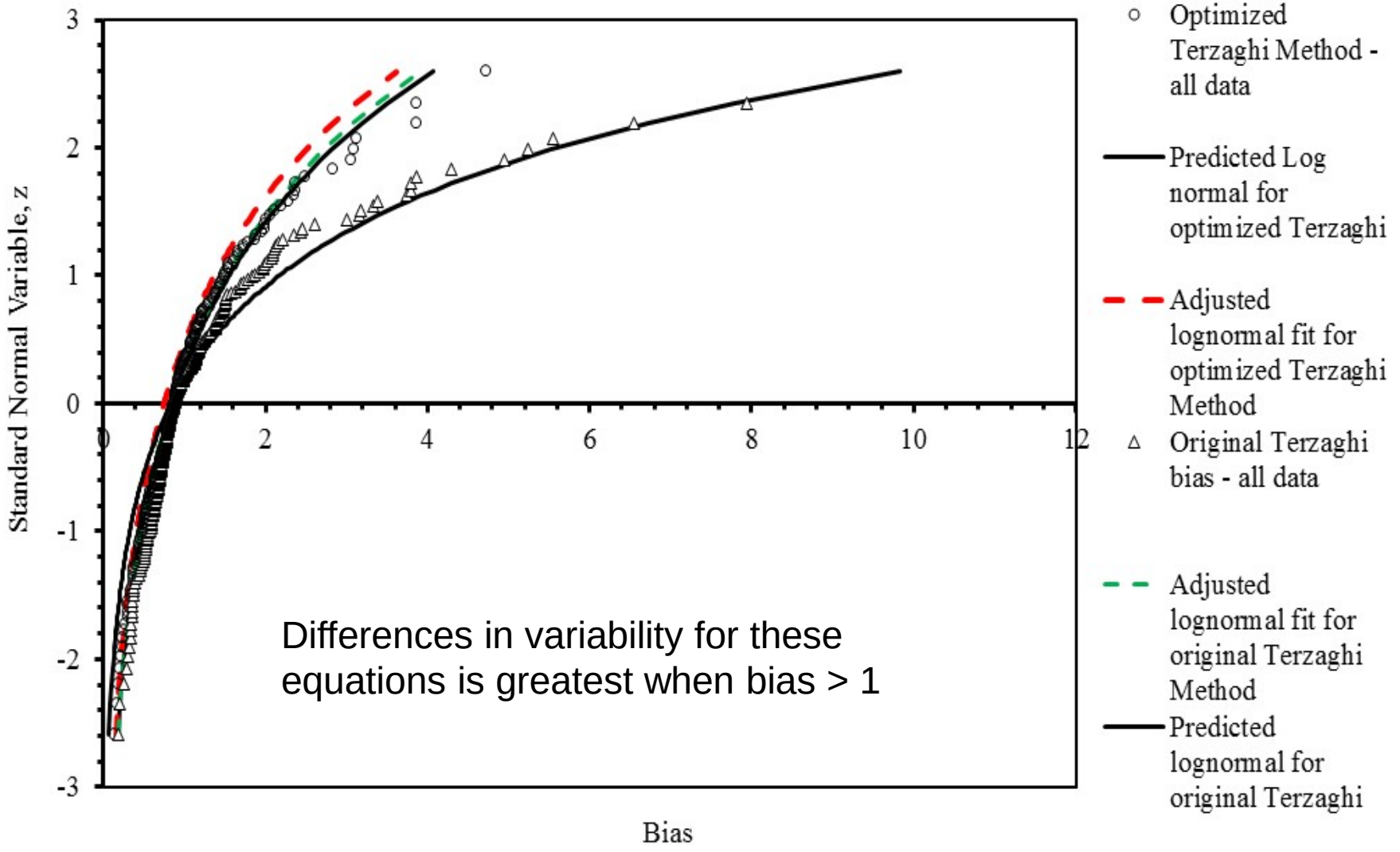
- Accuracy of K_{sat} prediction from grain size data significantly improved
  - Recommend optimized Slichter Equation
  - Best to use measured porosity, if available
  - Otherwise, can use grain size/compaction level based porosity equation
  - Optimized Slichter Equation is generally more conservative, but is also more accurate and consistent, especially for finer grained soils, than current specified equation
  - Reduction factors in WSDOT HRM for compaction no longer needed as this issue can be handled directly in proposed equation, and in general, those reduction factors are very conservative for sands and gravels
- Reduction factors for use of grain size based K_{sat} equation due to method uncertainty appear to be unnecessary
- Reduction factors only appear warranted if expect poor maintenance (e.g., siltation, biofouling)

Level of Safety for Infiltration Design

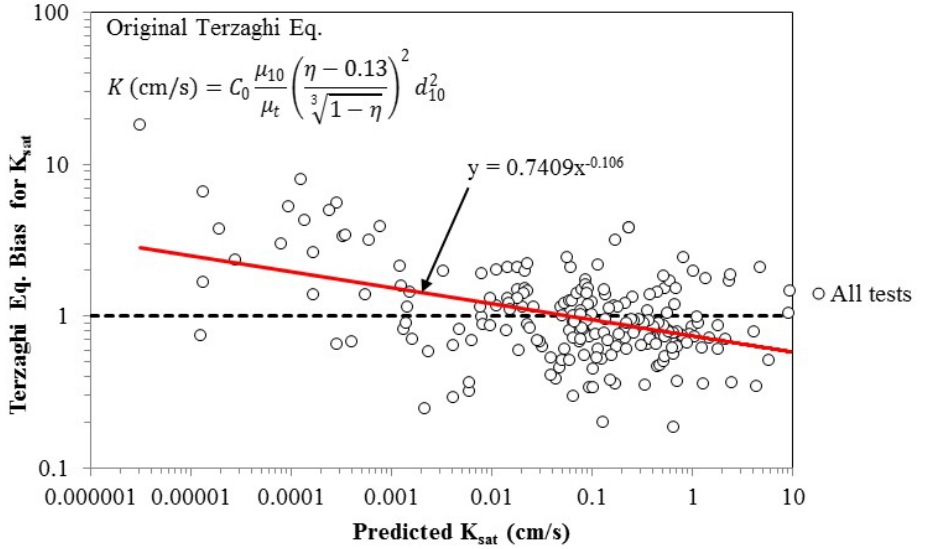
Overall Safety Factor Required

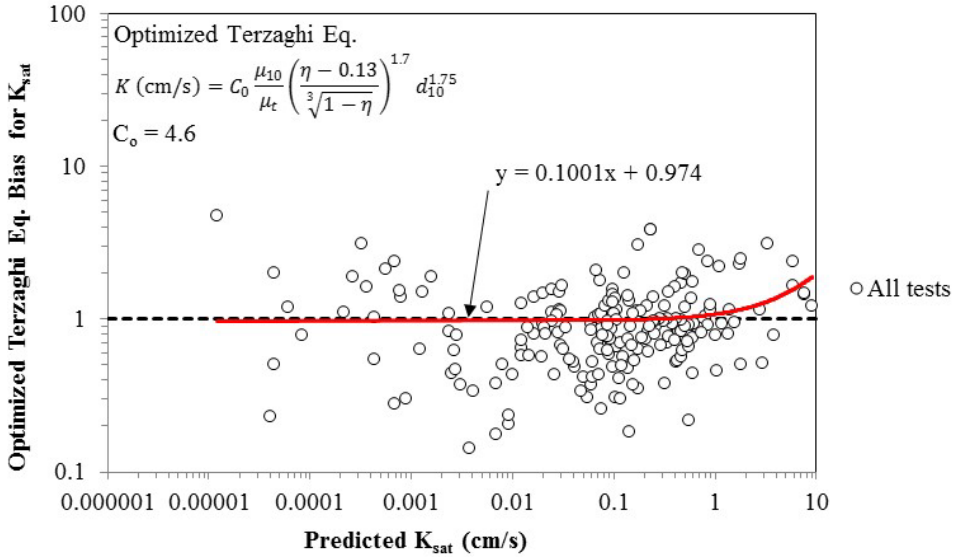
- Can be assessed through statistical reliability theory analysis (TRB Circular E-C079 - Allen et al. 2005)
- An adapted load and resistance factor approach
  - Resistance is infiltration rate
  - Load is volume of storm water generated
- Can estimate a safety factor needed to achieve maximum probability of exceedance
  - Need to establish what is the acceptable probability of exceedance, considering the impact of exceedance
  - Have statistics needed for method uncertainty in estimating infiltration rate – can combine with site variability statistics
  - Need statistics for estimation of storm water volume to be infiltrated
  - Can use Monte Carlo method to conduct analysis

Bias Statistical Distributions (CDF) for Original and Optimized Terzaghi Equations

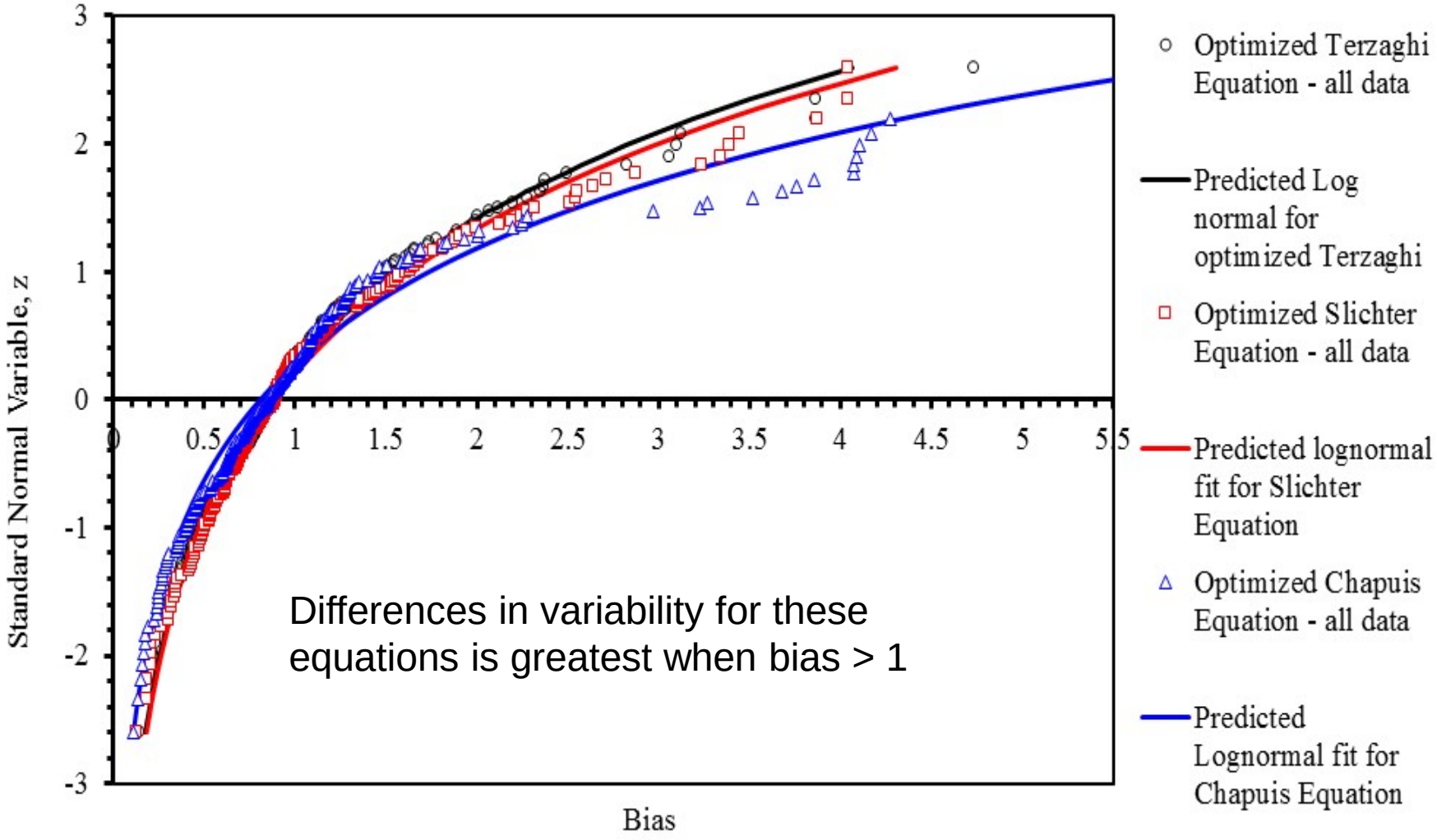


Bias Dependency Issues



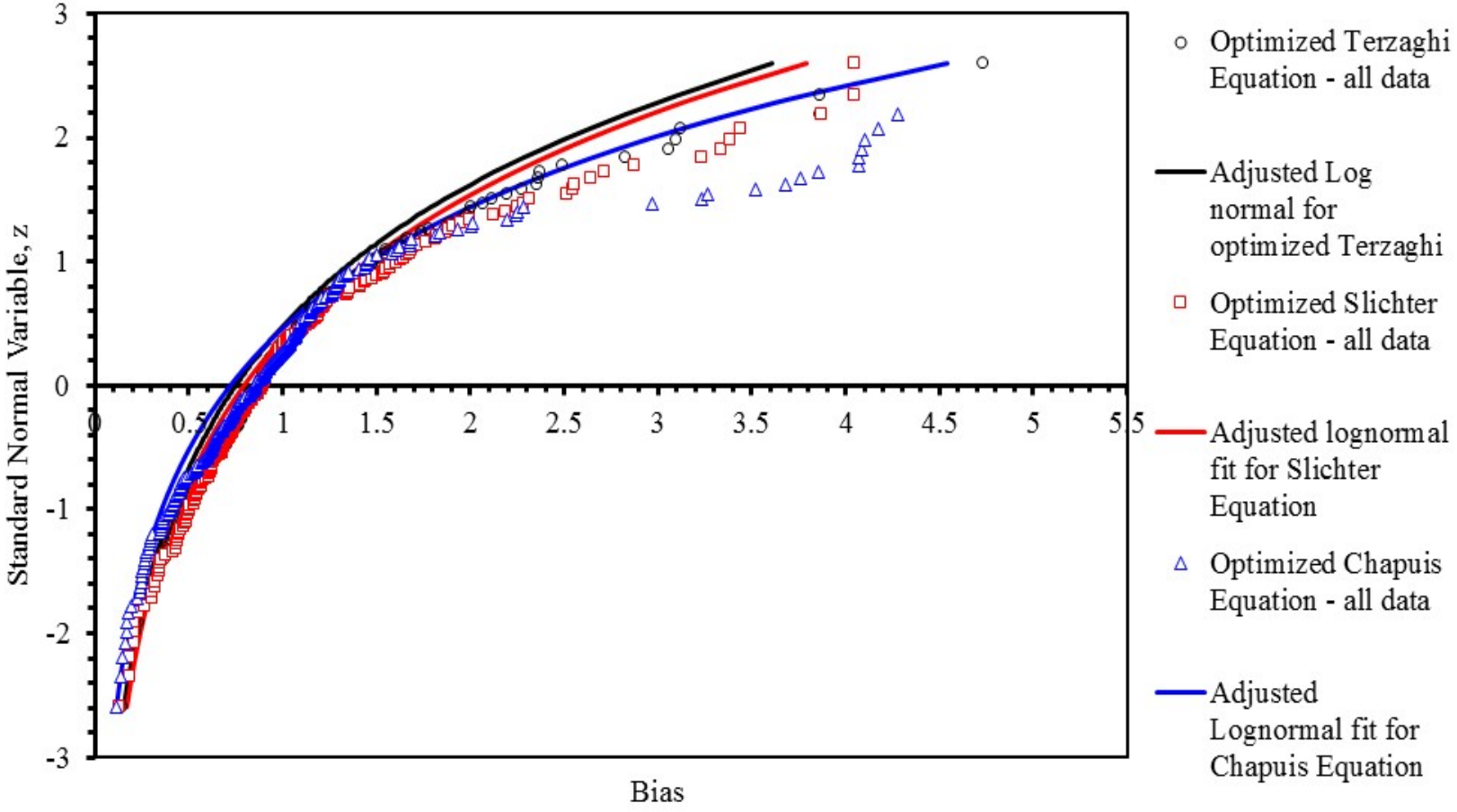


Bias Statistical Distributions (CDF) for Optimized K_{sat} Equations



Statistical Data Distributions for various Prediction Methods

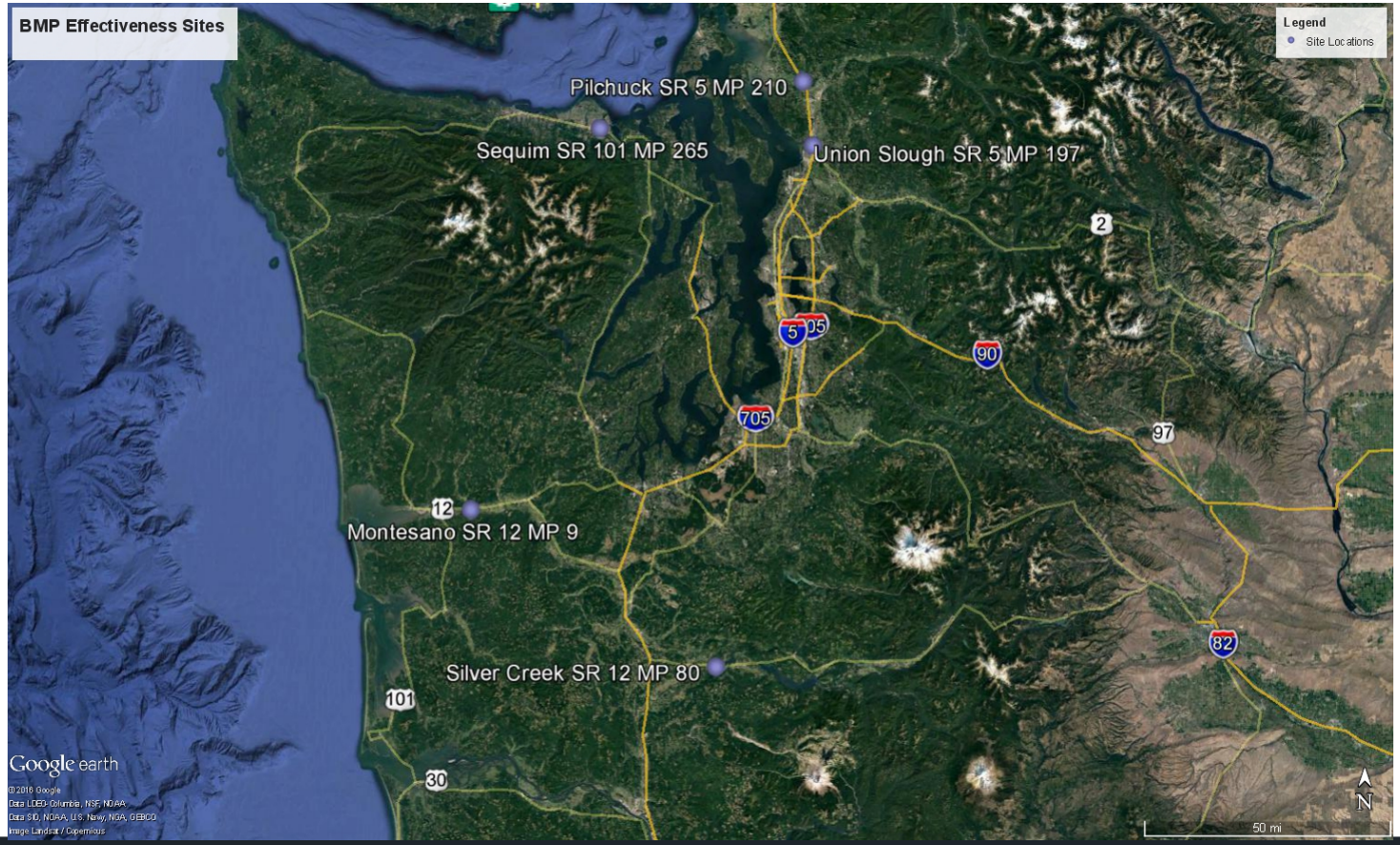
- Lower tail of K_{sat} prediction statistics most important for infiltration design
- Upper tail of storm water volume statistics will be most important for infiltration design



Current On-Going WSDOT Research on infiltration of Storm Water in Highway Embankments

Future Research Underway – Plan

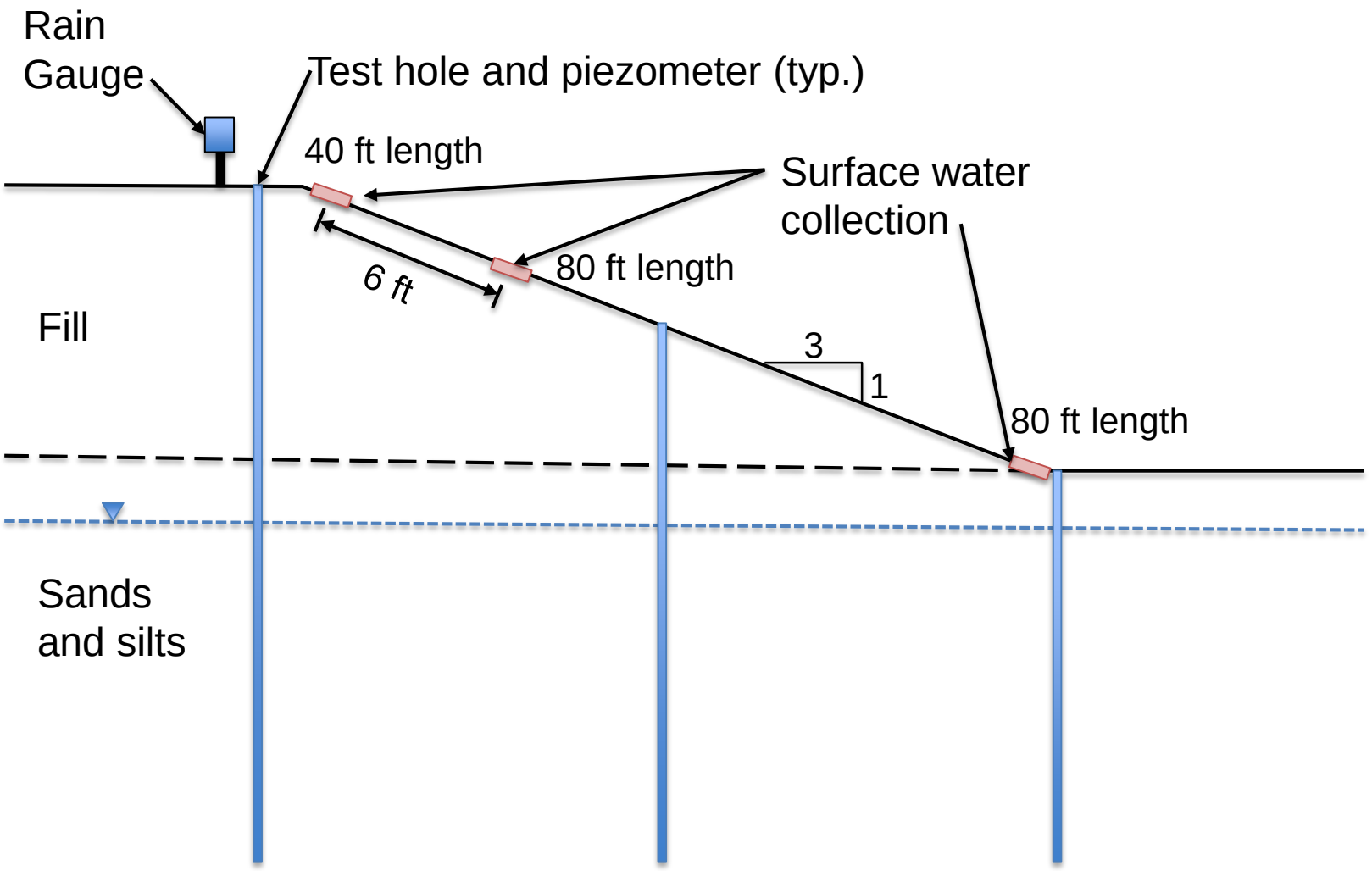
- Monitor storm water and infiltration at 4 to 5 existing embankment slopes
  - SR5, M.P. 197 and 210, near Marysville north of Everett (includes stormwater water quantity and quality meas.)
  - SR12 – M.P. 9, near Montesano (includes stormwater water quantity and quality measurements)
  - SR12 – M.P. 80, just west of Mayfield Lake (stormwater quantity only)
  - SR101 – M.P. 265, near Sequim (stormwater quantity only; optional site)



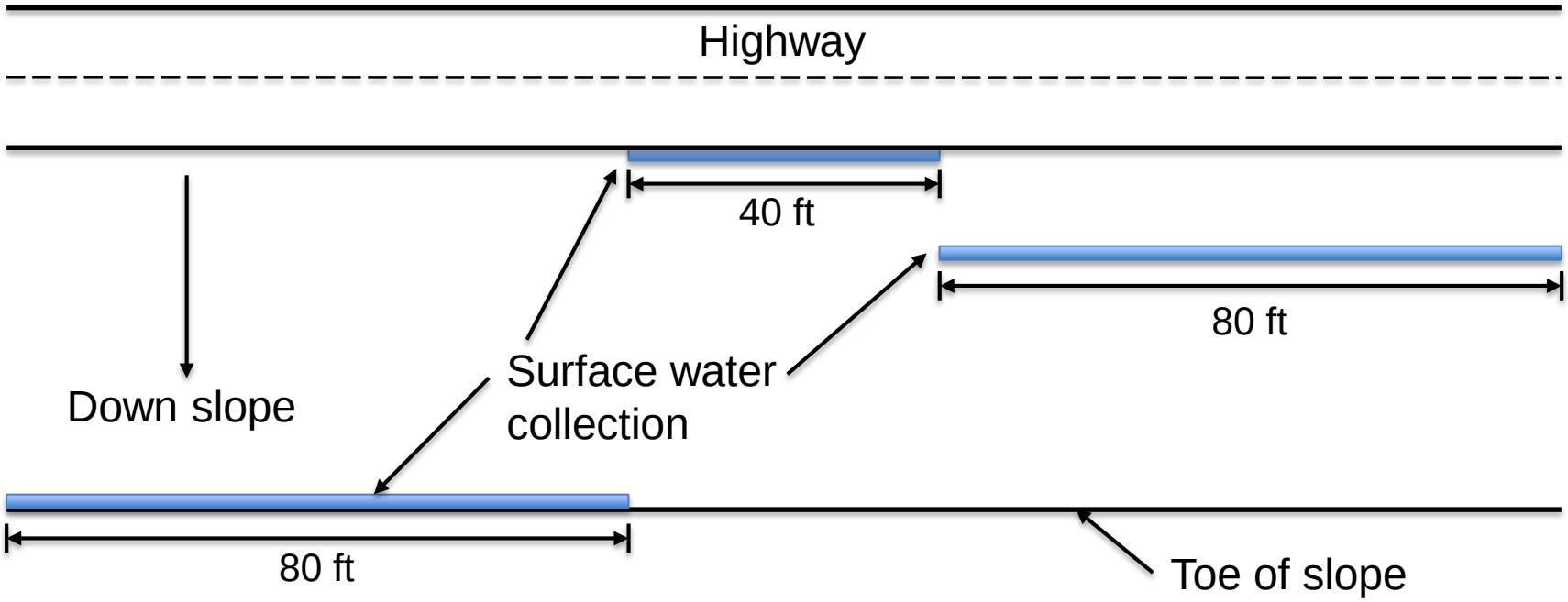
Future Research Underway – Plan

- Monitor storm water and infiltration at up to 5 existing embankment slopes (typically 3:1 side slopes, 10 to 15 ft in height)
- Subsurface characterization (in general, 3 test holes and piezometers per site)
- Measure K_{sat} from lab tests, both disturbed and undisturbed soil samples
- Measure K_{sat} from field permeability tests – mainly borehole tests (constant head hydraulic conductivity test in single borehole)
- Measure stormwater inflow at road edge, 6 ft below road shoulder edge, and any water outflow or runoff at slope toe
- Analytically model slopes using programs such as MODFLOW
- Develop design model for assessing infiltration in embankments (for MGSFlood)
- Update K_{sat} prediction equations using new K_{sat} and gradation test results from field study

Example Test Site Setup



Example Test Site Setup



Questions?