Sunjoto Shape Factor under Full Penetration Slug Test

Thinzar Aye, S. Sunjoto, and Djoko Luknanto

***Abstract*—Sunjoto developed shape factor equations in order to determine the drawdown and hydraulic conductivity value. Many researchers had conducted research using these equations under the pump test. Moreover, most of the research used Sunjoto equations as the comparison with the other pump test equations. Since 1951, shape factor equations have been developed to determine hydraulic conductivity value under slug test which mainly focus on the dimension of well. Afterwards, many scientists and researchers developed shape factor equations including Sunjoto, Bouwer and Rice. Therefore, this research intends to use Sunjoto equation under the slug test. The comparison of hydraulic conductivity by constant head test and slug test has been conducted in this research. The comparison value is acceptable although there are difference values that were caused by disturb and Un-disturb sample.**

***Index Terms*—Constant head test, hydraulic conductivity value, and Sunjoto shape factor.**

I. Introduction

The aquifer parameters *K*, which is known as hydraulic conductivity value, can be determined by many kinds of methods in the field of groundwater engineering [1], [2]. Hydraulic conductivity test can be conducted not only in the filed area, but also in the laboratory. The field methods can be divided into two types, pump test and slug test. Pump test is a well-known method to determine aquifer parameters in the hydrogeology. A slug test is different from standard aquifer tests, which typically involves well pumping at a constant flow rate, and monitoring the response of aquifer in monitoring wells nearby. The slug tests are preferably to be performed instead of constant rate test, because the slug tests do not require pumping and there is no need to take too much time for test [3], [4]. The equations for slug test are mainly focused on the well dimension than geomorphology of aquifer. Many equations were developed and mainly focused on well dimension, i.e. shape factor. Sunjoto also developed shape factor with various well dimension in the groundwater engineering field based on Hvorslev (1951) equations [5], [6]. These equations have been used in many previous researches. Most of the researcher used Sunjoto equations under groundwater pumping test [7]. Researcher used Sunjoto shape factor under pump test at the laboratory with different kinds of well. The result could be acceptable as it is compared with Theis equation which was combined with image well method and constant head test. However, there were some errors that can be found as conditional error, computational error and assumptions of equation error. Therefore, this research aims to use Sunjoto equations under slug test.

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II. Materials and Methods

The main objective of this research is to prove the Sunjoto shape factor for determination of hydraulic conductivity value under slug test. The methods can be divided into two types, i.e. constant head test and slug test. These two tests have been conducted in the laboratory. The hydraulic conductivity value from constant head test has been taken as reference for comparison to prove Sunjoto equation.

A. Constant Head Test

Constant head permeameter can be used to measure hydraulic conductivities of consolidated or unconsolidated formations under low heads. Water enters the cylinder medium from the bottom and it is collected as overflow once it pass upward through the material. According to Darcy's law, hydraulic conductivity can be obtained using the constant head test equation [8].

B. Slug Test

Researcher has conducted the test in the laboratory in order to have slug test with various well dimensions even though slug test can be easily conducted at any field area. The experiment design was built in Laboratory of Hydraulic, Department of Civil and Environmental Engineering, Universitas Gadjah Mada. The 50 cm dimension of glass tank has been used to demonstrate aquifer and the 2.6 cm diameter and 70 cm length of PVC pipe has been used for groundwater well demonstration. The 114.20 g container was used to slug into the well as transducer (Fig. 1). The Progo river sand has been used as the groundwater aquifer.

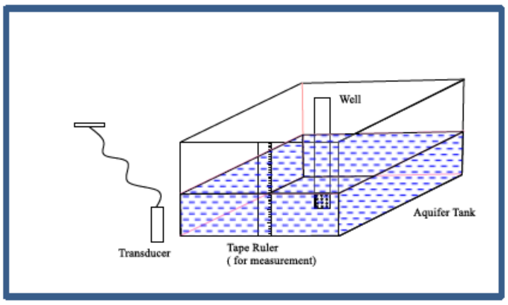

Fig. 1. Experiment tank for slug test at laboratory.

III. Constant Head Test

The soil test, including grain size analysis and constant head test of this soil sample, was conducted in Laboratory of Soil Mechanics, Department of Civil and Environmental Engineering, Universitas Gadjah Mada, to find out the soil characteristics. According to grain size result analysis, the

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soil sample can be determined as fine sand. The disturbed soil sample must undergo constant head test in the laboratory to determine its soil characteristics. This test method covers the determination of permeability coefficient with a constant-head method for the water laminar flow through soils.

The diameter of specimen is 7.5 cm, area is 44.18 cm^2 and volume is 618.5 cm^3. The data measurement was taken as the constant head test (Table 1) was performed. The average discharge q is 2.176 cm^3/sec, hydraulic gradient I value is 2 and the Correction factor, R_t is 0.838. The hydraulic conductivity K value gets **2.1E-0.4 m/sec**, based on the determination of constant head test at the laboratory.

TABLE I: DATA OF CONSTANT HEAD TEST

t (time in sec)	Manometers		Volume cm_3	Temperature °C	Q (Constant Head)cm^3/sec
	h_1 cm	h_2 cm			
235	100	80	500	27.5	2.128
232	100	80	500	27.5	2.155
235	100	80	500	27.5	2.128
230	100	80	500	27.5	2.174
229	100	80	500	27.5	2.183
228	100	80	500	27.5	2.193
228	100	80	500	27.5	2.193
229	100	80	500	27.5	2.183

IV. SLUG TEST TO DETERMINE K VALUE

In a slug test, a small volume of water is suddenly removed from a well once the rise rate of water level in the well is measured. Alternatively, a small slug of water is poured into the well and the rise and subsequent fall of water level are measured. The aquifers transmissivity or hydraulic conductivity can be determined based on the measurements. The slug test has advantages, i.e. there is no pumping required, no piezometers are needed, and the test can be completed within a few minutes, or in a few hours at the most [3], [4]. The slug test method has been used in this research by using the transducer (Fig. 2).

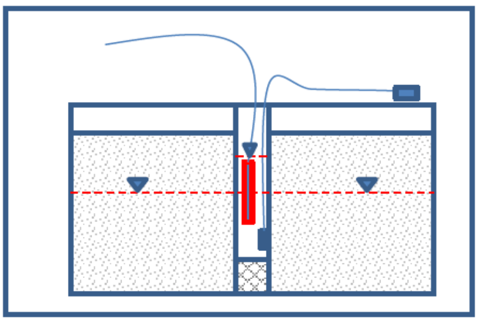


Fig. 2. Slug test with transducer and data logger.

V. SUNJOTO EQUATION

The coefficient of permeability can be computed with different kind of methods, e.g. Thesis and Cooper-Jacob method, but the methods requires table and graphic. In 1988, Sunjoto developed his unsteady flow condition equation:

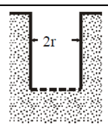
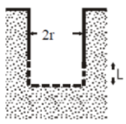
$$K = \frac{Q}{FS} \tag{2}$$

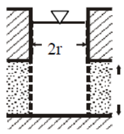
where K is the Coefficient Permeability value (m/sec), Q is the constant recharged rate (m^3/sec), S is the drawdown value (m), and F is the shape factor (Geometry of Well) in (m) [5]-[7]. He modified this equation in 2014 to compute the drawdown and coefficient of permeability on pumping test, and furthermore it is called Sunjoto method [9]-[11]. This method does not require table or graphics; it only needs equation which is computed by trial and error or iteration solution. Sunjoto's method does not require table or graphic, but only needs the well test data (F) which are computed by equation. For steady state condition where there is no more change on water elevation on the well, then the solution is using the equation. For unsteady state condition, the equation is modified by Sunjoto in 2014 [9].

VI. DIMENSION OF WELL (SHAPE FACTOR)

First, the dimension of well, i.e. shape factor, was proposed by Hvorslev (1951) [12]. Later, many researchers have studied and developed many well shape factor equations including Sunjoto. Shape factor is a representation of circumference and cross section of the area, hydraulic gradient, soil layers condition, and position of the well. Shape Factor is a value that function as diameter of casing, length of perforated casing, base condition of casing (pervious or impervious), the tip of casing position to the aquifer layer position, and confined or unconfined aquifer [13], [14]. Research on shape factor of the Well has been conducted by many researchers, e.g. Shape factor (F) for various condition in graphic form by Luthian J.N., Kirkham D. (1949) etc. [15]-[17]. Sunjoto also developed the shape factors under confined and an unconfined aquifer with full and partial penetration [6]. Sunjoto shape factor under full and partial test, and other shape factor equations that were not practically proved yet, as it is described in Table II.

TABLE II: SHAPE FACTOR WITH VARIOUS WELL CONDITIONS

Well Condition	Shape Factors	Result	Researchers
 Unconfined Aquifer	F (4b) = 5.50 r	Practical Test has not been conducted yet	Harza (1935), Taylor (1948), Hvorslev (1951).
 Unconfined Aquifer	F (6b)= $\frac{2\pi L+2\pi r\ Ln2}{Ln\left\{\frac{L+2r}{2r}+\sqrt{\left(\frac{L}{2r}\right)^2+1}\right\}}$	Practical Test has not been conducted yet	Sunjoto (2002) (Partial Penetration)
	F (6c) = $\frac{2\pi L}{Ln\left\{\frac{L+2r}{2r}+\sqrt{\left(\frac{L}{2r}\right)^2+1}\right\}}$	Practical Test has not been conducted yet	Sunjoto (2016) (Full Penetration)

 Confined Aquifer	$F(1)=\frac{2\pi D+2\pi r\, Ln2}{Ln\left\{\frac{D+2r}{2r}+\sqrt{\left(\frac{D}{2r}\right)^2+1}\right\}}$	Practical Test has not been conducted yet	Sunjoto (2016) (Partial Penetration)
	$F=\frac{2\pi D}{Ln\left\{\frac{D+2r_w}{r_w}+\sqrt{\left(\frac{D}{r_w}\right)^2+1}\right\}}$	Practical Test has not been conducted yet	Sunjoto (2017) (Full Penetration)

VII. Data Measurement

Different from pump test, the slug test only requires the measurements for around the well dimension. The slug test has been conducted using experiment tank in the laboratory of hydraulic, Department of Civil and Environmental Engineering, Universitas Gadjah Mada. This research only uses full penetration of well under unconfined aquifer. The static water level is 12.05 cm and aquifer thickness is 20 cm during the slug test, and the data measurement has been taken for (7) hours from 1:50 to 9:00 pm. The 114.0 g transducer was put in the well according to the procedure of slug test. The researcher conducted water level measurement in the well with tape ruler that was put around the tank boundary.

TABLE III: Data Measurement under Slug Test

	Elapsed Time	Depth of Water Leve	Change in Level	h/h0
	Static Water Level	12.5		
1:50		14.8 ho	14.8	
1:51	1		14.8	1
1:52	2		14.8	1
1:53	3		14.7	0.99324324
1:54	4		14.6	0.986486486
1:55	5		14.5	0.97972973
2:00	10		14.4	0.972972973
2:05	15		14.4	0.97297297
2:10	20		14.4	0.972972973
2:15	25		14.4	0.97297297
2:20	30		14.4	0.972972973
2:30	40		14.4	0.97297297
2:40	50		14.4	0.972972973
2:50	60		14.3	0.96621622
3:00	70		14.3	0.966216216
3:10	80		14.3	0.96621622
3:20	90		14.2	0.959459459
3:30	100		14.2	0.95945946
3:45	115		14.2	0.959459459
4:00	130		14.1	0.9527027
4:15	145		14	0.945945946
4:30	160		13.9	0.93918919
4:45	175		13.9	0.939189189
5:00	190		13.8	0.93243243
5:15	205		13.7	0.925675676
5:30	220		13.7	0.92567568
5:45	235		13.6	0.918918919
6:00	250		13.6	0.91891892
6:15	265		13.5	0.912162162
6:30	280		13.4	0.90540541
6:45	295		13.2	0.891891892
7:00	310		13.1	0.88513514
7:15	325		13	0.878378378
7:30	340		12.9	0.87162162
7:45	355		12.9	0.871621622
8:00	370		12.8	0.86486486
8:15	385		12.7	0.858108108
8:30	400		12.6	0.85135135
8:45	415		12.6	0.851351351
9:00	430		12.5	0.84459459

VIII. Analysis by Sunjoto Equation

Sunjoto developed his equation under unsteady flow conditions in 1988. In 2014, he modified his equation in order to compute drawdown and hydraulic conductivity value. Many researchers have used this equation under pump test and there also many researches have used this equation by doing the comparison with other pump test equations for example with the Cooper-Jacob method. In 1951, Hvorslev firstly introduced the equations for well shape factor and these equations developed for slug test [12]. Therefore, the researcher has tried to use this equation under slug test yet some of the previous research used this equation under pump test. Data analysis was conducted using Sunjoto equations (Equation. 2) and shape factor equations for full penetration test, and shape factor for unconfined aquifer by Hvorslev (1951), Taylor (1948) and Harza (1935) (from Table II). In this research, the trial and error method were used to determine hydraulic conductivity value without graphic method.

TABLE IV: Data Analysis by Sunjoto Equation

Elapsed Time	Chang in Level	H/H0			Iteration
Static Water Level	12.5		K value by F (Full Penetration)	K value by F (F=5.50r)	
1	14.8	1	0.229841312	0.062609457	1.0000351
2	14.8	1	0.229841312	0.062609457	1.7702428
3	14.7	0.99324324	0.139024556	0.062186418	0.9933308
4	14.6	0.98648649	0.122248358	0.061763378	0.9865245
5	14.5	0.97972973	0.110794394	0.061340301	0.979739
10	14.4	0.97297297	0.110794394	0.060917305	1.5018607
15	14.4	0.97297297	0.110794394	0.060917305	1.7801094
20	14.4	0.97297297	0.110794394	0.060917305	1.9283934
25	14.4	0.97297297	0.110794394	0.060917305	2.0074168
30	14.4	0.97297297	0.110794394	0.060917305	2.0495299
40	14.4	0.97297297	0.110794394	0.060917305	2.083933
50	14.4	0.97297297	0.110794394	0.060917305	2.0937036
60	14.3	0.96621622	0.052501013	0.060494272	0.9662203
70	14.3	0.96621622	0.051913759	0.060494272	0.9670125
80	14.3	0.96621622	0.05152818	0.060494272	0.9665196
90	14.2	0.95945946	0.050963078	0.060071207	0.959578
100	14.2	0.95945946	0.050963078	0.060071207	0.9618918
115	14.2	0.95945946	0.050963078	0.060071207	0.9636042
130	14.1	0.9527027	0.050321876	0.059648199	0.9521389
145	14	0.94594595	0.049964669	0.059225159	0.9456882
160	13.9	0.93918919	0.049608081	0.05880212	0.9390751
175	13.9	0.93918919	0.049608081	0.05880212	0.9391401
190	13.8	0.93243243	0.049251175	0.058379061	0.9324095
205	13.7	0.92567568	0.048894269	0.057955696	0.9256645
220	13.7	0.92567568	0.048894005	0.057955696	0.9256654
235	13.6	0.91891892	0.048536941	0.057533014	0.9189078

250	13.6	0.91891892	0.048536413	0.057533014	0.9188991
265	13.5	0.91216216	0.048177236	0.057109968	0.9120995
280	13.4	0.90540541	0.047823341	0.056686602	0.9053998
295	13.2	0.89189189	0.047109741	0.055840811	0.8918899
310	13.1	0.88513514	0.046751093	0.055417822	0.8850999
325	13	0.87837838	0.046391916	0.054994788	0.8783
340	12.9	0.87162162	0.04603913	0.054571718	0.871621
355	12.9	0.87162162	0.046039077	0.054571718	0.87162
370	12.8	0.86486486	0.045678844	0.054148415	0.8648
385	12.7	0.85810811	0.045324949	0.053725683	0.8581
400	12.6	0.85135135	0.044949927	0.053302646	0.851
415	12.6	0.85135135	0.044949927	0.053302646	0.851
430	12.5	0.84459459	0.044580186	0.052879609	0.844

IX. Research Comparison

The researcher has conducted this research to prove that Sunjoto equation can determine the hydraulic conductivity under slug test. The comparison has been done using *k* value from constant head test, *K* value by Sunjoto equation, shape factor value *F* by Sunjoto, and by Harza, Taylor and Hvorslev. The hydraulic conductivity value is 0.00021 m/sec from constant head test, 0.00071 from Sunjoto equations with *F* by Sunjoto, and 0.00058 m/sec from *F* by Harza, Taylor and Hvorslev. According to the comparison result, Sunjoto equation is acceptable to determine the hydraulic conductivity value (Fig. 3). It is important to use shape factor with appropriate well conditions.

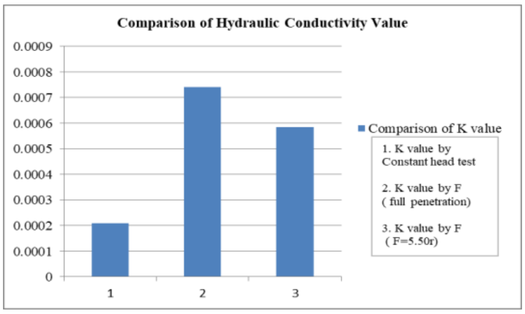


Fig. 3. Hydraulic conductivity value by Sunjoto equation (in m/sec).

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Thinzar Aye has conducted the data analysis and wrote the research. S. Sunjoto and Djoko Luknanto supervised this research. All authors had approved the final version.

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