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Laboratory Investigation on the Influence of Cyclic Water Injection Pressure on Sands Hydraulic Conductivity

Houman Es-haghi Sharabiani[1], Mojtaba Gharavi[2*]

1. Ph.D. Candidate, School Of Civil Engineering, University of Science and Technology, P.O. Box 16765-163, Narmak, Tehran, Iran
2. Assistant Professor., School Of Civil Engineering, University of Science and Technology, P.O. Box 16765-163, Narmak, Tehran, Iran

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ABSTRACT

Hydraulic conductivity variations around the boreholes in uniformly graded sands for cyclic water injection pressure have been evaluated by laboratory tests. Prototype laboratory devices have been designed and constructed for this research. The cell has a capability to model the well, the boundary condition and to measure the hydraulic conductivity. While increasing water injection pressure, hydraulic conductivity suddenly increases in a special pressure value. Hydraulic conductivity is measured and compared with its initial value at the beginning of this cycle. Test procedures are conducted several times and results are compared and analyzed. In these sands with upper soil layers pressure up to 68.64 kPa, hydraulic conductivity at the end of the first cycle reaches to a 20% to 58% growth comparing to its initial amount at the beginning of the test. In the second cycle, this growth rate is up to 16% more than the first cycle. By decreasing the injection pressure at the end of each cycle, a part of the increased hydraulic conductivity due to the high injection pressure is dissipated.

Keywords

Well; Water injection pressure; Uniformly graded sand; Hydraulic conductivity

1. Introduction

High pressure injection is one of the methods used to increase the hydraulic conductivity around the boreholes. This is a well known method in oil industry (Massarsch 1978). Surguchev et al. (2002) studied the effect of cyclic water injection pressure on oil recovery in Heidrun field in the Norwegian Sea. They found that cyclic injection will improve water flooding efficiency and accelerate oil production. According to their research, the reserves are predicted to increase by 5 to 6% from the targeted reservoirs at Heidrun after ten years of cyclic water flooding. Surguchev et al. (2008) investigated the improvements of oil production in carbonate reservoirs by cyclic water injection. Although, they performed a lot of investigations in rock media and carbonate reservoirs, but water wells or wells which recharge the groundwater are placed in soil media. The Similar method of increasing the injection influence on oil wells by using cyclic injection pressure is used in this research. More than half of the surface sediments covering the continental shelves are sandy (Wilson et al. 2008).

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[*] Corresponding Author Email: (gharavi@iust.ac.ir)

Some studies which are performed on injection fields in sandy media are done by Golovin et al. (2011) and Sharabiani (2012). Golovin et al. (2011) studied the injection rate effects on water flooding mechanisms and injectivity in cohesionless sands. Sharabiani's studies show that by increasing the injection pressure in wells located in uniformly graded sands, hydraulic conductivity has a sudden increase in a special injection pressure (Sharabiani 2012). The amount of this special injection pressure and the hydraulic conductivity under this condition is measured for different uniformly graded sands. According to the oil industry experiences, evaluating the effect of cyclic water injection pressure on the hydraulic conductivity in sands seems to be important. This research has tried to evaluate the mentioned interest in uniformly graded sands media.

2. Materials and Methods

2.1. Laboratory Equipments

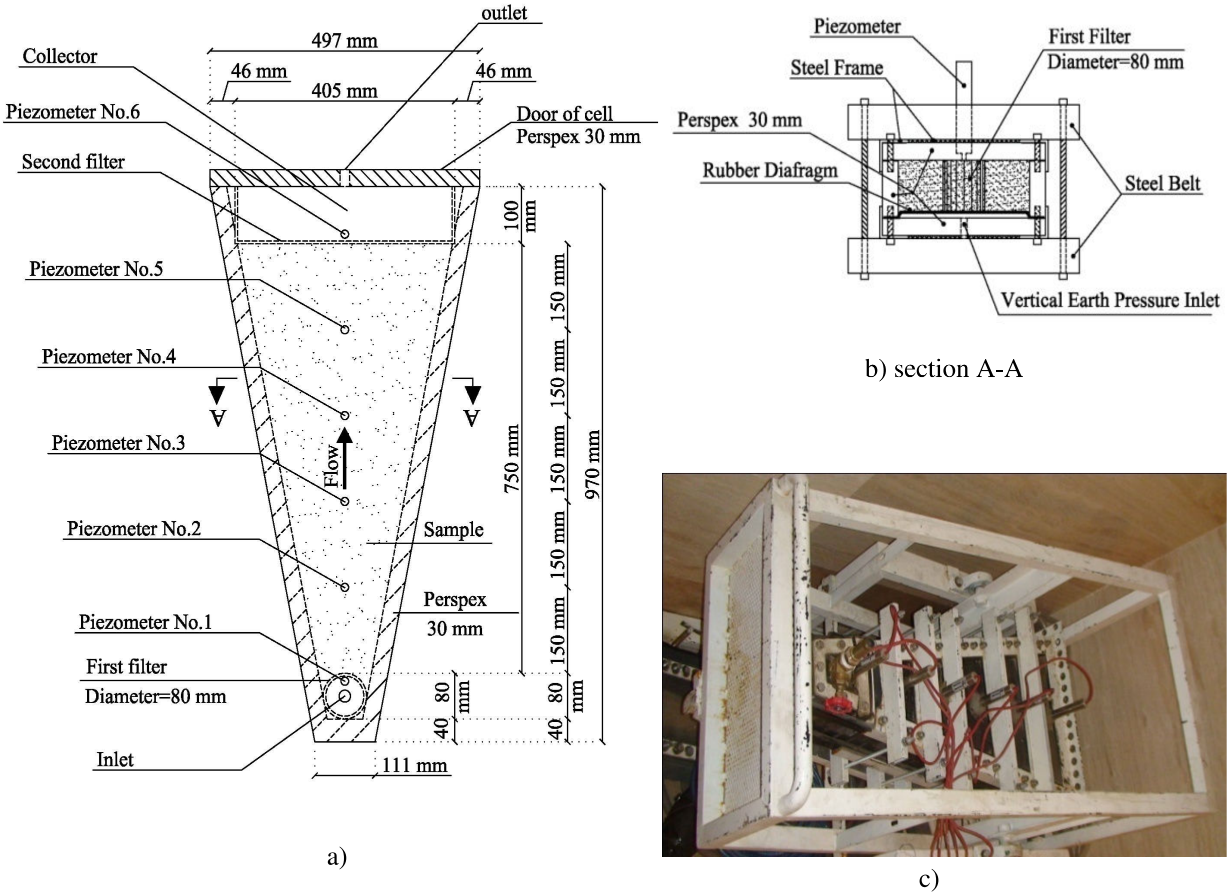
Experiments are conducted by using a hydraulic fracture apparatus which is made by Sharabiani and Gharavi (Sharabiani 2012). One of the main advantages of the cell in this apparatus is its big size comparing to similar cells (6 times bigger). This cell can model the well, the area around it and the hydraulic fracture in the wellbore wall. Another capability of this cell is the hydraulic conductivity measurement in various injection pressures for soils around the well. The sample used in this cell is a sector of a hollow cylinder. This sample has a 22.5° central angle, 750 mm radius and 100 mm thickness. By putting a cylindrical filter with an 80 mm diameter at the center of the sample, the central hole of the sample (well) is created. Water is injected from the inlet of the cell (located at the center of this cylindrical filter). Radial flow is injected to the cell from the center to the perimeter and the flow length is 750mm. Six vibrating wire piezometers are used in this cell to measure the pressure in the flow path.

The Upper Soil Layers Pressure (USLP) is hydra-ulically induced to the sample by a rubber diaphragm. The sample in the cell is surrounded by two filters with 50micron openings so that the grains would not run away. The first filter (cylindrical filter) is located at the center of the sample and the second one is located at the perimeter of the sample. Fig. 1 shows filters, piezometers, inlet, outlet and the rubber diaphragm which induces the USLP. Water injection pressure is produced by a portable tank. By changing the height level of this tank, the injection pressure could be changed. Injection pressure oscillation is prevented by fixing the water table in the tank.

The USLP is produced hydraulically and induced by a rubber diaphragm on the sample. Piezometers are connected to a data logger and the pressure data is transmitted via these piezometers to the data logger system.

2.2. Materials

The material used for the tests is uniformly graded sands. First, the sand derived from a deposit is dried in an oven and then it is graded according to the ASTM D422-63 standard. Remaining sand on five 20, 30, 40, 50 and 100 sieves is considered as the five uniformly graded sands in this research. In other words, five uniformly graded sands with grain diameters of 0.85, 0.6, 0.42, 0.3 and 0.15mm are used in this research.



a)

b) section A-A

c)

Fig.1 a) filters, piezometers, inlet and outlet location in the cell, b) A-A section and the rubber diaphragm location for inducing the USLP on the sample, and c) Cell and its stand (Sharabiani, 2012)

2.3. Upper Soil Layers Pressure (USLP)

Hydraulic conductivity changes near the wellbore wall in shallow depths are evaluated in these tests. Therefore, small amounts of USLP are considered here. The USLP for the samples are 24.52kPa and 68.64kPa. For each sample with a defined grain size, after conducting the test with a 24.52kPa USLP, the sample is changed and for the new USLP 68.64kPa, the new sample is tested.

2.4. Test Procedure

In the previous studies of these researchers, the primary hydraulic conductivity is defined for five uniformly graded sands under different USLPs (Sharabiani, 2012). In this research, first a 24.52kPa USLP is induced to the sample. Afterwards by moving the mobile tank (which produces the injection pressure) upwards, the injection pressure increases gradually. By asudden change in the hydraulic conductivity in a special injection pressure (threshold injection pressure), the tank is moved down and is fixed in its initial location to measure the hydraulic conductivity. So the first cycle of the injection pressure is finished.

Now it is possible to compare the final hydraulic conductivity to its primary value in the first cycle. As mentioned above, hydraulic conductivity of these sands at the beginning of the first cycle was measured by Sharabiani and Gharavi in their previous studies (Sharabiani 2012). After the first cycle has been finished, the injection pressure was gradually increased again. By reaching to the threshold injection pressure, the tank was moved down again to its initial location. Then the hydraulic conductivity was measured. Then by changing the sand and using a new sample, the hydraulic conductivity was measured again. This test was performed for five different uniformly graded sands with the grain sizes of 0.85, 0.6, 0.42, 0.3 and 0.15mm. Tests were repeated under a 68.64 kPa USLP.

2.5. Measuring the Hydraulic Conductivity for Small Injection Pressures

According to Fourcheimer equation for the radial flow around a well we have (Fourcheimer 1901):

$$\frac{dP}{dr} = (\frac{\mu}{k_i})V_r + \beta\rho V_r^2 \qquad (1)$$

Where P is pressure; μ is dynamic viscosity coefficient of fluid; k_i is intrinsic permeability; V_r is radial flow velocity; β is a coefficient and ρ is fluid density. By integrating equation 1, the average pressure gradient can be obtained as (Evans 1994):

$$i = \frac{P_o - P_i}{r_o - r_i} = (\frac{Q\mu}{2\pi k_i h(r_o - r_i)})Ln(\frac{r_o}{r_i}) + (\frac{\beta\rho Q^2}{4\pi^2 h^2(r_i r_o - r_i^2)})(1 - \frac{r_i}{r_o}) \qquad (2)$$

The hydraulic conductivity (k) can be expressed as (Kashef 1986):

$$k = k_i \frac{\rho g}{\mu} \qquad (3)$$

According to the results, by omitting the second part of equation 2, calculated gradient (i) has not changed remarkably and its error is low (about 5%). So this part is omitted for simplifying the equation. According to this simplified equation and equation 3, the hydraulic conductivity is calculated as follows:

$$k = \frac{Q\, ln \frac{r_o}{r_i}}{2\pi h(h_o - h_i)} \qquad (4)$$

Where h_o is the pressure head at the radius r_o from well axis, h_i is the pressure head at the radius r_i from well axis, h is the thickness of the media, k is hydraulic conductivity and Q is radial flow discharge towards the well.

To use equation 4 for hydraulic conductivity measurements in this research, some changes should be applied. The samples central angle is 22.5°. In other words, only 22.5° of the well perimeter is modeled in the cell. So the outlet discharge measured from the cell during the test (Q_t) is for a 22.5° sector. The Q parameter in equation 4 is the radial flow discharge that enters the well from 360° of the well perimeter. So for extending the discharge measured during the test, Q_t to 360°, the following equation is expressed as:

$$Q = \frac{360}{22.5} Q_t \qquad (5)$$

According to equation 5, and because the flow direction is from the wellbore wall towards the media around the well, equation 4 is changed into equation 6. So equation 6 is used to calculate the hydraulic conductivity in this research (Sharabiani 2012):

$$k = \frac{\frac{360}{22.5} Q_t \ln \frac{r_o}{r_i}}{2\pi h(h_i - h_o)} \qquad (6)$$

In the previous studies of these researchers, the primary hydraulic conductivity for five uniformly graded sands due to various USLPs is obtained (Sharabiani 2012).

Table 1. Primary hydraulic conductivity for different uniformly graded sands under different USLPs (σ_v) (Sharabiani 2012)

Grains Diameter (mm)	0.15	0.3	0.42	0.6	0.85
Primary Hydraulic Conductivity (m/s) with σ_v =24.52 kPa (Sharabiani's tests)	0.00031	0.00057	0.00095	0.00149	0.003
Primary Hydraulic Conductivity (m/s) with σ_v =68.64 kPa (Sharabiani's tests)	0.0003	0.00056	0.00082	0.00114	0.00283
Primary Hydraulic Conductivity (m/s) Hazen formula (Hazen 1892,1911)	0.0002	0.0009	0.0018	0.003	0.007

Table 2. Hydraulic conductivity under low injection pressures for different uniformly graded sands under different USLPs (σ_v) at the end of cycle 1

Grains Diameter (mm)	0.15	0.3	0.42	0.6	0.85
Hydraulic Conductivity (m/s) with σ_v =24.52 kPa	0.00044	0.0009	0.00139	0.00226	0.0037
Hydraulic Conductivity (m/s) with σ_v =68.64 kPa	0.00039	0.00079	0.0011	0.00162	0.0034

Table 3. Hydraulic conductivity under low injection pressures for different uniformly graded sands under different USLPs (σ_v) at the end of cycle 2

Grains Diameter (mm)	0.15	0.3	0.42	0.6	0.85
Hydraulic Conductivity (m/s) with σ_v =24.52 kPa	0.00049	0.00096	0.00151	0.00246	0.00393
Hydraulic Conductivity (m/s) with σ_v =68.64 kPa	0.00042	0.00082	0.00123	0.00174	0.00363

Hydraulic conductivity of different uniformly graded sands in low injection pressures is measured in these tests. Table 1 shows the primary hydraulic conductivity for different uniformly graded sands under different USLPs (σ_v). In other words, values in table 1 show the hydraulic conductivity at the beginning of cycle 1.

At the end of the first cycle, the tank which produces the injection pressure is located in a low level (low injection pressure) and the hydraulic conductivity is measured. Table 2 shows the new values of hydraulic conductivity at the end of cycle 1 for different uniformly graded sands under different USLPs (σ_v).

After the first cycle ends, this procedure is repeated again (cycle 2). At the end of cycle 2, the tank is again located at its primary condition at the beginning of the test and the hydraulic conductivity is measured.

Table 3 shows new values of hydraulic conductivity at the end of cycle 2 for different uniformly graded sands under different USLPs (σ_v). In fig. 2, hydraulic conductivity changes versus the grain size of uniformly graded sands under a 24.52kPa USLP are shown. This graph is drawn for three states namely the beginning of the test, end of cycle 1 and the end of cycle 2. Fig. 3 shows the hydraulic conductivity changes versus the grain size of uniformly graded sands under a 68.64 kPa USLP. This graph also shows the same three states. Fig. 4 shows the bar graph of the uniformly graded sands hydraulic conductivity for a grain size of 0.15mm under various USLPs at different cycles.

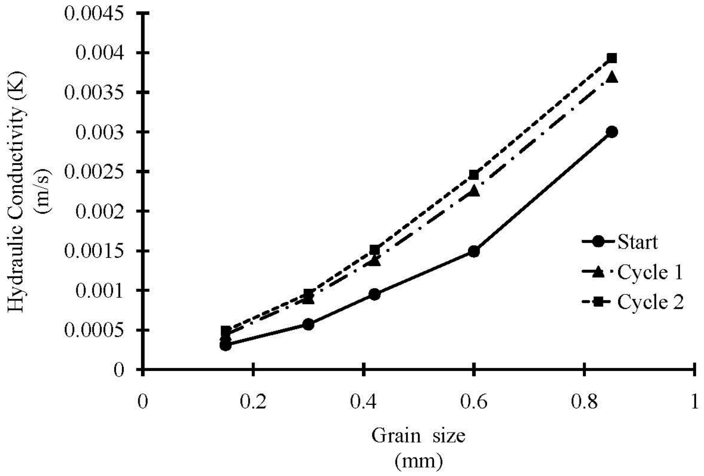


Fig.2 Hydraulic conductivity changes versus grain size of uniformly graded sands under a 24.52kPa USLP in three states: beginning of the test, end of cycle 1 and end of cycle 2

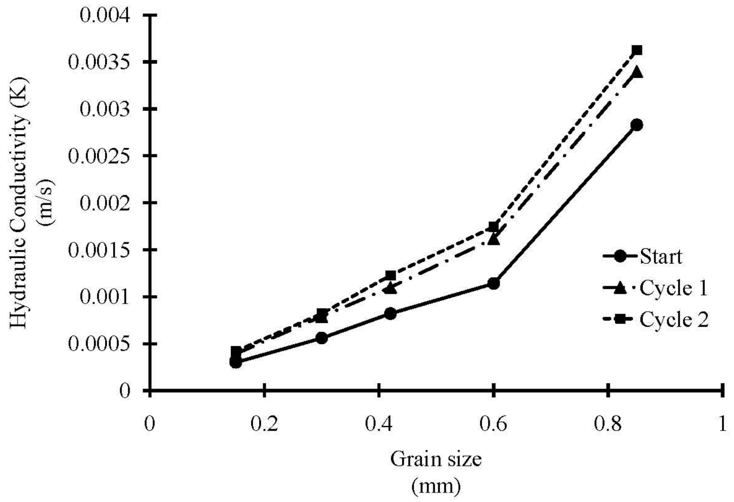


Fig.3 Hydraulic conductivity changes versus grain size of uniformly graded sands under a 68.64kPa USLP in three states: beginning of the test, end of cycle 1 and end of cycle 2

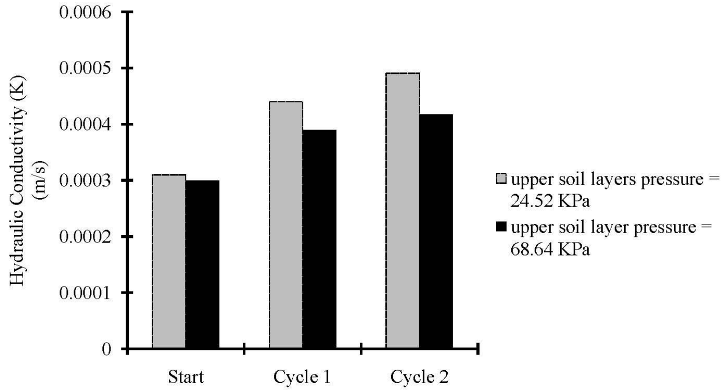


Fig.4 Bar graph of the uniformly graded sands hydraulic conductivity with a grain size of 0.15 mm under two 24.52kPa and 68.64kPa pressures of the USLP in three states: beginning of the test, end of cycle 1 and end of cycle 2

3. Discussion

According to fig. 2, hydraulic conductivity changes versus the grain size for uniformly graded sands at the beginning of the test is nonlinear. According to fig. 3 this process is not changed significantly due to USLP changes. According to figs. 2 and 3, the procedure of hydraulic conductivity change versus the grain size is not changed in cycle 1 and is still nonlinear. But the graph in cycle 1 is steeper than the beginning of the tests. This means that the influence of performing cycle 1 on the hydraulic conductivity is not the same. As it is clear in figs. 2 and 3, the amount of hydraulic conductivity change increases as the grain size grows after performing cycle 1. This means that after performing this cycle, the effective pore diameter in these sands grows as the grain size increases. But the hydraulic conductivity growth percentage does not show any special procedure after the first cycle. In USLP of 24.52 kPa, the hydraulic conductivity increase percentages after the first cycle for uniformly graded sands with 0.15, 0.3, 0.42, 0.6 and 0.85 mm grain sizes are 42%, 58%, 46%, 51% and 23%, respectively. For the USLP of 68.64 kPa, the hydraulic conductivity increase percentages after the first cycle for these sands with 0.15, 0.3, 0.42, 0.6 and 0.85 mm grain sizes are 30%, 41%, 34%, 42% and 20%, respectively. In other words, the influence of the first cycle decreases by increasing USLP.

According to figs. 2 and 3, after performing the cycle 2 of the tests, hydraulic conductivity changes versus the grain size in uniformly graded sands are still nonlinear. Due to these figs., the graph of the second cycle is steeper than the beginning of the test and even the first cycle. In other words, the influence of this cycle on the hydraulic conductivity of these sands with different grains diameters is not the same. According to figs. 2 and 3, after performing cycle 2, the hydraulic conductivity change in this type of sand increases as the grain size grows, similar to cycle 1. In the USLP of 24.52 kPa, the hydraulic conductivity increase percentages after the second cycle for sands with 0.15, 0.3, 0.42, 0.6 and 0.85 mm grain sizes are 58%, 68%, 59%, 65% and 31%, respectively. In the USLP of 68.64 kPa, the hydraulic conductivity increase percentages after the second cycle for sands with 0.15, 0.3, 0.42, 0.6 and 0.85 mm grain sizes are 39%, 46%, 50%, 53% and 28%, respectively.

In all the test levels, such as the beginning of the test, end of cycle 1 and end of cycle 2, by increasing USLP the growth rate of hydraulic conductivity decreases. The reason is that the growth rate of the effective pore diameter decreases as the USLP increases. According to what mentioned above, the hydraulic conductivity at the end of cycle1 towards its value at the beginning of the test has a 20% to 58% increase. By performing cycle 2, the hydraulic conductivity value will be more than cycle 1 and increases up to 16%. But according to fig. 4, the cycle's effectiveness decreases by repetition. In USLP of 24.52 kPa, the growth percentage of hydraulic conductivity in the threshold injection pressure beside the wellbore wall varies between 40 to 400% towards its initial amounts (Sharabiani 2012). But as mentioned before, the maximum growth percentage of the hydraulic conductivity at the end of cycle 1 towards its initial amount is 58%. For cycle2, this maximum value is 68%. In other words, we can conclude that a part of the increased hydraulic conductivity due to high injection pressure will dissipate because of the pressure decrease at the end of each cycle. Equation 7 can be obtained for hydraulic conductivity prediction in three states as the beginning of the test, end of cycle 1 and end of cycle 2. According to data, the logarithmic scale regression provided good results. Considering these results, equation 7 can be used to predict the hydraulic conductivity in the above mentioned three states:

$$K = 10^{-(0.0016\sigma_v - 0.087N + 2.466)} \times D^{1.221} \tag{7}$$

Where K is hydraulic conductivity in m/s for three different states (the beginning of the test, end of cycle 1 and end of cycle 2), σ_v is USLP in kPa, N is cycle number (N=0 for the beginning of the test, N=1 at end of cycle 1, N=2 at end of cycle 2) and D is grains size in mm. In equations 7, σ_v and D should be within two experiment conditions:

$9.81 \text{ kPa} \leq \sigma_v \leq 68.42 \text{ kPa}$

$0.15 \text{ mm} \leq D \leq 0.85 \text{ mm}$

For the data used to obtain equation 7, R^2 is 0.96. Table 4 shows the predicted values resulting from equation 7 and their errors in the three states. Furthermore, the observed and the predicted values are shown in fig. 5. As can be seen from the fig., agreement between the predicted and the observed values of hydraulic conductivity is 20%.

Table 4. predicted hydraulic conductivity from equation 7 and its error for different uniformly graded sands under different USLPs (σ_v) in three states: beginning of the test, end of cycle 1 and end of cycle 2.

σ_v (kPa)	State	Grains Diameter (mm)	Observed Hydraulic Conductivity (m/s)	Predicted Hydraulic Conductivity (m/s)	Error (%)
24.52	start	0.15	0.00031	0.0003	-3.23
24.52	start	0.3	0.00057	0.0007	22.81
24.52	start	0.42	0.00095	0.0011	15.79
24.52	start	0.6	0.00149	0.00168	12.75
24.52	start	0.85	0.003	0.00256	-14.67
24.52	Cycle 1	0.15	0.00044	0.00037	-15.91
24.52	Cycle 1	0.3	0.0009	0.00086	-4.44
24.52	Cycle 1	0.42	0.00139	0.00131	-5.76
24.52	Cycle 1	0.6	0.00226	0.002	-11.50
24.52	Cycle 1	0.85	0.0037	0.00306	-17.30
24.52	Cycle 2	0.15	0.00049	0.00045	-8.16
24.52	Cycle 2	0.3	0.00096	0.00105	9.37
24.52	Cycle 2	0.42	0.00151	0.0016	5.96
24.52	Cycle 2	0.6	0.00246	0.00244	-0.81
24.52	Cycle 2	0.85	0.00393	0.00374	-4.83
68.64	start	0.15	0.0003	0.00025	-16.67
68.64	start	0.3	0.00056	0.00057	1.79
68.64	start	0.42	0.00082	0.00088	7.32
68.64	start	0.6	0.00114	0.00142	24.56
68.64	start	0.85	0.00283	0.00218	-22.97
68.64	Cycle 1	0.15	0.00039	0.0003	-23.08
68.64	Cycle 1	0.3	0.00079	0.0007	-11.39
68.64	Cycle 1	0.42	0.0011	0.00107	-2.73
68.64	Cycle 1	0.6	0.00162	0.00163	0.62
68.64	Cycle 1	0.85	0.0034	0.0025	-26.47
68.64	Cycle 2	0.15	0.00042	0.00037	-11.9
68.64	Cycle 2	0.3	0.00082	0.00086	4.88
68.64	Cycle 2	0.42	0.00123	0.00131	6.50
68.64	Cycle 2	0.6	0.00174	0.002	14.94
68.64	Cycle 2	0.85	0.00363	0.00305	-15.98

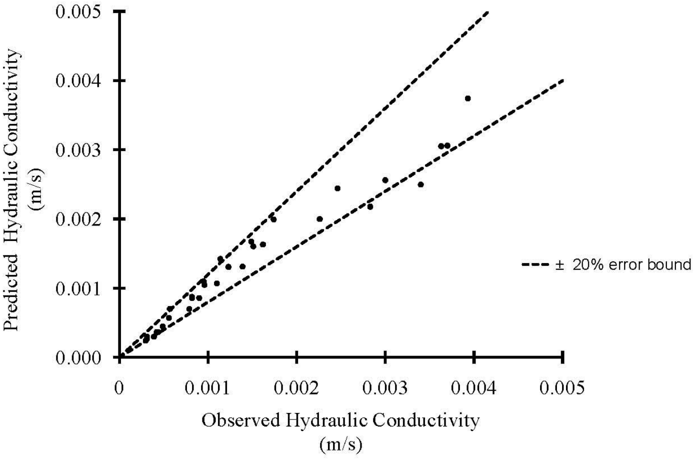


Fig. 5. predicted hydraulic conductivity using equation 7 versus observed values.

4. Conclusion

For uniformly graded sands, increasing the injection pressure up to the threshold injection pressure, and then decreasing it to the primary value causes some changes in the hydraulic conductivity. By repeating this cycle the hydraulic conductivity of these sands increases. According to test results, cycle repetition decreases the effectiveness rate. The hydraulic conductivity of these sands under a 68.64 kPa USLP at the end of cycle 1 comparing to its value at the beginning of the test shows a 20% to 58 % growth. By performing cycle 2, the hydraulic conductivity increases up to 16% more than cycle 1. The influence of cycle 1 and cycle 2 on the hydraulic conductivity due to grain size changes is not the same. After performing cycle 1 or cycle 2, the hydraulic conductivity change increases as the grain size grows. In uniformly graded sands, a part of the increased hydraulic conductivity due to high injection pressure dissipates as the injection pressure reduces at the end of each cycle. Hydraulic conductivity changes versus grain size in uniformly graded sands in all test levels, such as the beginning of the test, end of cycle 1 and end of cycle 2 are nonlinear.

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