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High-lift siphon flow velocity in a 4-mm siphon hose*

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Abstract: High-lift siphon drainage by 4-mm internal diameter siphon hoses is a real-time, free-power, and long-term approach for slope drainage. The conventional hydraulics formula for pressurized pipe flow is generally used to calculate the single-phase velocity of siphon flow. However, an intensive cavitation phenomenon occurs in the high-lift siphon hose and then a two-phase flow is formed. Research on the velocity of high-lift siphon flow is a prerequisite for the application of siphon drainage with a 4-mm siphon hose. Few investigations of this subject have been carried out. Hence, experiments on the high-lift (8 m$\leq H_0\leq$10.3 m) siphon drainage in a 4-mm siphon hose were performed. The characteristics of siphon flow under different conditions were observed and test data were obtained. Comparisons between test results and calculated results showed that significant errors were given by the hydraulics formula. It is demonstrated that the effect of gas in a siphon hose should be included in the calculation of flow velocity. The findings can be used to determine the number of siphon hoses and layout of siphon drainage holes, and provide valuable information for geotechnical companies.

Key words: Siphon flow velocity; High-lift siphon; Elevation difference; Water lift; Gas effect
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1 Introduction

Most landslides are triggered by the rise of the groundwater level caused by rainfall infiltration. In order to prevent landslides, it is important to control the rise of the groundwater level (Corominas *et al.*, 2005; Sun *et al.*, 2010; Igwe *et al.*, 2014). Since siphon drainage can drain the slope efficiently, and is economical and convenient to design, it has received the attention of many researchers and has been applied in many areas (Shang *et al.*, 2015). Moreover, it has also been used in many projects of landslide treatment in France and the UK (Clark *et al.*, 2007; Bomont, 2008; Gillarduzzi, 2008; Gress, 2008; Mrvik and Bomont, 2011).

The groundwater in a slope is generally replenished by rainwater. Hence, high-lift siphon drainage is necessary. Groundwater is plentiful during the rainy season, while it is probably deficient for a long term in the dry season. Therefore, the drainage is intermittent. For high-lift siphon drainage, when the water flow in a siphon hose rises slowly or stops, the air dissolved in water would be immediately released owing to the decrease of air pressure in the siphon hose, and the bubbles accumulate at the top of the siphon hose. It is demonstrated that excessive accumulation of bubbles might break the drainage process (Cai *et al.*, 2015). Numerical simulation, model test, and theoretical analysis have proved that only when the internal diameter of the siphon hose is smaller than or equal to 4 mm, can plug flow be formed (Cai *et al.*, 2014; Xiong *et al.*, 2014). Plug flow can prevent the accumulation of bubbles at the top of hose, and allows high-lift siphon drainage to operate

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ORCID: Cheng MEI, http://orcid.org/0000-0003-1593-3455; Hong-yue SUN, http://orcid.org/0000-0002-2267-305X continuously. Hence, 4-mm internal diameter is the best choice.

The efficiency of siphon drainage determines whether groundwater can be discharged in a timely manner from the slope in the case of the heavy rain and whether groundwater can be controlled to within a safety level. However, the small internal diameter of the 4-mm siphon hose might lead to strong resistance for hose flow, and thus the draining capacity could be insufficient. The bubbles accumulated in the high-lift siphon hose, moreover, also may reduce the flow velocity. Therefore, it is urgent to determine whether 4-mm siphon hoses can meet the requirements of slope drainage in the rainy season. That is to say, the drainage scheme and relevant parameters, such as the number of siphon hoses and layout of siphon holes, can only be determined when the computation method for a single 4-mm siphon draining capacity is developed.

Some researchers devote themselves to the investigation of siphon flow velocity for drainage of slopes, roofs, and reservoirs. There has been experimental study on indoor siphon drainage, examining such things as the maximum height of siphon drainage and the relationship between siphon velocity and elevation difference (Zhang, 1999; Zhang and Zhang, 1999). Related research indicates that siphonic roof drainage is an efficient alternative to conventional systems, and that the flow velocity plays a key role during priming (Wright *et al.*, 2006; Arthur and Wright, 2007). Tadayon and Ramamurthy (2012) investigated the discharge coefficient for siphon spillways using both experiments and numerical simulations. Rehbinder (1994) and Ullah *et al.* (2005) studied the removal of sediment and the equilibrium scour hole geometry by siphon flow. However, this study was restricted to water lifts lower than 8 m and diameters larger than 9.7 mm. To the best of the authors' knowledge, the practical drainage efficiency and capacity of the 4-mm internal diameter siphon hose have never been investigated in the literature.

2 Testing high-lift siphon drainage

2.1 Set-up

Fig. 1 shows a high-lift siphon drainage test model, the apparatus consisting of an upper hose, a lower hose, tank A, and tank B. The siphon hose is made of polyurethane (PU) with a 4-mm internal diameter and a curvature radius of 0.1 m at the vertex. A pipe was installed in order to keep the surface height of the water in tank A constant. The difference in height between the surface of the water in tank A and the siphon apex is defined as water lift H_0, and that between the surface of the water in tank A and the hose outlet as the elevation difference H_1. Both could be adjusted in accordance with various test requirements.

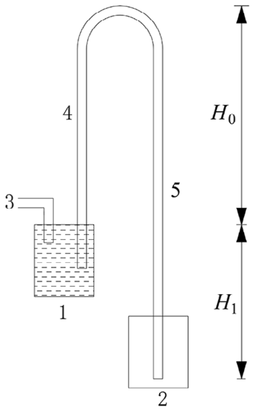

Fig. 1 Schematic diagram of siphon drainage system

1: tank A; 2: tank B; 3: replenished water pipe; 4: upper hose; 5: lower hose

2.2 Test scheme

The water lift H_0 was set at 9.5 m and the elevation difference H_1 at 1 m. The siphon drainage was initially run for 5 min and, when the water flow was stable, the outlet was placed in tank B. The siphon hose in tank B was removed one hour later and the amount of water was weighed and converted into the flow rate. H_1 was then set at 1.5 m and, when the siphon flow was stable, the amount of water in one hour was again weighed and converted into the flow rate. The adjustment of H_1 was continued until the siphon velocity had reached its maximum. Following the same procedure, the siphon flow velocity was measured at different H_1 while values for the H_0 were 9.3 m, 9 m, 8.55 m, 8.5 m, 8 m, and 10 m.

To analyze the effect of the length of the siphon hose, the procedure described above was used to test 40-m and 30-m siphon hoses.

2.3 Observations

A few bubbles were visible about 3.3 m above the surface of the water in tank A in the upper hose, with the amount and the size of the bubbles increasing with the vertical height from the datum plane. Clusters of small bubbles rose rapidly owing to buoyancy and the up thrust, subsequently becoming larger. The no-water section and plug flow of different sizes were found at the top of the siphon hose, so that the cavitation phenomenon was obvious. The direction of the water flow ran contrary to the buoyancy of bubbles in the lower hose, so that the bubbles showed a reverse movement relative to the water flow. The number of bubbles decreased and the size of bubbles appeared larger in the hose section at the top of the lower hose because the small bubbles merged. The diameter of many large bubbles could reach 4 mm when the siphon hose was at its maximum. The gas column became longer with the further merger of bubbles and moved along the water flow. The plug flow was stable and the gas column went down under the action of buoyancy and down thrust. The size of the bubbles in the hose varied with the different water lifts H_0. The higher the H_0, the bigger the bubbles. In Fig. 2, the length of the gas column varies with the water lift; the gas columns at 9.5-m H_0 are longer than those at 8-m H_0.

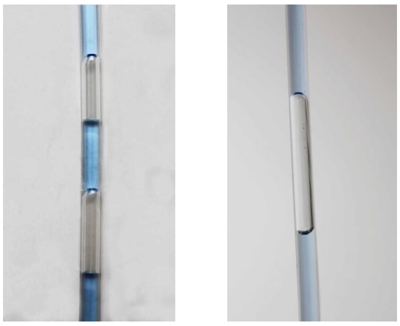

Fig. 2 Gas columns in an 8-m water lift (left) and a 9.5-m water lift (right)

2.4 Test data

All the statistical data were recorded only when the siphon flow velocity was stable and the apparatus had been correctly connected. Tables 1 and 2 show the statistical data recorded under different conditions.

Based on the test data, Fig. 3 indicates how siphon flow velocity varies with H_1 and H_0.

2.5 Analysis of test data

Tables 1 and 2 and Fig. 3 show some of the characteristics of siphon flow velocity.

The siphon flow rate has a negative correlation with the water lift H_0, which means the higher the water lift, the slower the flow rate. For instance, the siphon flow rate was 0.125 m/s with values for the H_1 at 2.5 m and the H_0 at 9 m, while the siphon flow rate was 0.159 m/s with values for the H_1 at 2.5 m and the H_0 at 8 m.

Within a certain range, the siphon flow velocity has a positive correlation with the elevation difference H_1. When the elevation difference is up to a certain value, the flow rate will remain fairly steady and the siphon flow rate is then defined as the critical

Table 2 Siphon flow velocities from different water lifts, elevation differences, and lengths of hose

H_1 (m)	H_0 (m)	Siphon flow velocity (m/s)		
		L=50 m	L=40 m	L=30 m
2.2	10.0	0.033	0.042	0.055
	9.0	0.121	0.157	0.234
	8.0	0.143	0.170	0.237
3.2	10.0	0.032	0.401	0.054
	9.0	0.128	0.169	0.278
	8.0	0.200	0.236	0.323
4.2	10.0	0.032	0.042	0.054
	9.0	0.129	0.169	0.278
	8.0	0.231	0.263	0.396

Table 1 Siphon flow velocities from different water lifts and elevation differences in a 50-m siphon hose

H_0 (m)	Siphon flow velocity (m/s)														
	H_1=0.0 m	1.0 m	1.5 m	2.0 m	2.5 m	3.0 m	3.5 m	4.0 m	5.0 m	6.0 m	7.0 m	8.0 m	9.0 m	10.0 m	11.0 m
8.0	0.000	0.075	0.104	0.130	0.159	0.190	0.205	0.200	0.223	0.224	0.225	0.226	0.234	0.230	0.231
8.5	0.000	0.070	0.095	0.122	0.146	0.150	0.177	0.188	0.187	0.188	0.188	0.188	0.190	0.189	0.190
8.55	0.000	0.069	0.094	0.120	0.142	0.150	0.153	0.166	0.168	0.170	0.171	0.170	0.172	0.172	0.173
9.0	0.000	0.058	0.090	0.116	0.125	0.128	0.129	0.128	0.129	0.129	0.128	0.129	0.128	0.129	0.129
9.3	0.000	0.052	0.072	0.090	0.098	0.097	0.102	0.103	0.102	0.104	0.102	0.104	0.103	0.102	0.104
9.5	0.000	0.040	0.068	0.075	0.077	0.079	0.078	0.077	0.078	0.079	0.078	0.074	0.074	0.074	0.074

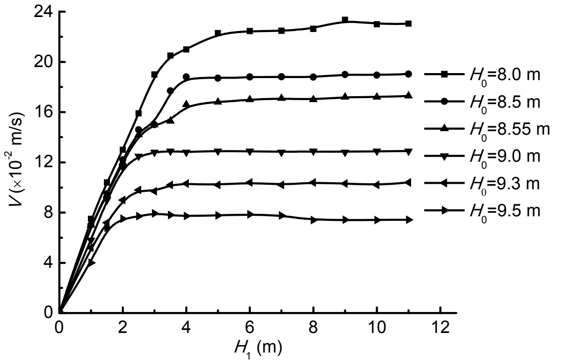

Fig. 3 Siphon flow velocities (*V*) in a 50-m hose when the water lifts are 8.0 m, 8.5 m, 8.55 m, 9.0 m, 9.3 m, and 9.5 m

flow rate, and $H_{1\mathrm{c}}$ is defined as the critical elevation difference. For example, when the siphon water lift was 8.5 m, the siphon flow velocity continued to ascend when H_1 increased from 0 m to 3.9 m.

There is a negative correlation between the siphon flow velocity and the length of the hose. The shorter the length of the hose, the faster the siphon flow velocity.

3 Comparative analysis of the flow rate between the test and calculated values

The hydraulics formula for pressurized pipe flow (Hu and Wu, 2011) is generally used in the calculation of the siphon flow velocity:

$$V=\sqrt{\frac{2gH}{1+\lambda\dfrac{L}{d}+\sum\zeta}}, \tag{1}$$

where V is the average siphon flow velocity, g is the gravitational acceleration, H is the water head difference, λ is the pipe friction coefficient, ζ is the local resistance coefficient for the pipe, d is the inside diameter of the pipe, and L is the length of the pipe.

The hose section with the smallest hydraulic gradient is the crucial factor controlling the siphon flow velocity. Therefore, before the siphon flow velocity is calculated, the difference ΔH between the highest limit of the siphon water lift $H_{\max}$ and H_0 should be compared with H_1. In the case where $\Delta H > H_1$, H_1 replaces H in Eq. (1). The equation for the siphon flow rate can be written as

$$V=\sqrt{\frac{2gH_1}{1+\lambda\dfrac{L}{d}+\sum\zeta}}. \tag{2}$$

When $\Delta H < H_1$, H is replaced by ΔH. The equation for the siphon flow rate can be written as

$$V=\sqrt{\frac{2g\Delta H}{1+\lambda\dfrac{L}{d}+\sum\zeta}}. \tag{3}$$

A swarm of bubbles will separate out owing to the fact that the gas pressure in the siphon hose drops dramatically when there is a high water lift. The gas-liquid two-phase flow can thus be clearly observed. However, whether Eqs. (2) and (3) can be applied to the calculation of the high-lift siphon flow rate is still a controversial matter. It can thus be analyzed by comparing the test values with the calculated ones.

With the water lift set at 8 m and 9 m for the 50-m siphon hose, Figs. 4 and 5 show the siphon flow velocity of the test values and the calculated ones. It is clear that the conformity of the two lines is poor and that the values being tested became steady later than the calculated ones. Tables 3 and 4 show the analysis that presents the obvious difference between the test and calculated flow rates, so that, when the water lift was 8 m, the calculated values were clearly larger, with the elevation difference increasing from 1 m to 2.5 m. The error was over 30% and went up as far as 50.77%, so the calculated values could not meet the requirements of the engineering application. Moreover, the difference between the test and calculated values remained large with regard to the analysis of the siphon flow velocity, with the values of the water lift at 8.5 m, 8.55 m, 9.3 m, and 9.5 m. The conventional hydraulics formula for the pressurized pipe flow might not therefore be directly applicable to the calculation of the high-lift siphon flow velocity. The gasification in the siphon hose is considerable with regard to a high-lift siphon, so the no-water sections occupy a certain hose length, particularly in the lower hose. The flow resistances in the hose consist of the frictions between the liquid, the gas, and the tube wall, all of which represent non-negligible factors. In conclusion, the conventional hydraulics formula for the pressurized pipe flow could not really meet the precise calculation required of the high-lift siphon flow velocity.

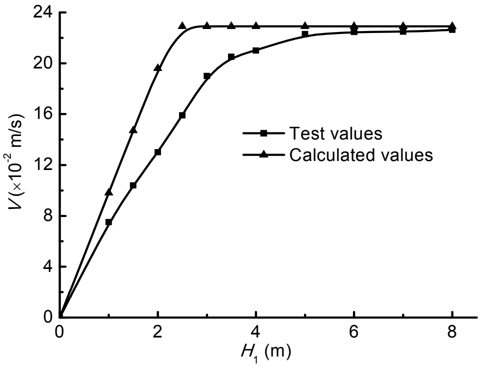

Fig. 4 Siphon flow velocity varies with H_1 in an 8-m water lift

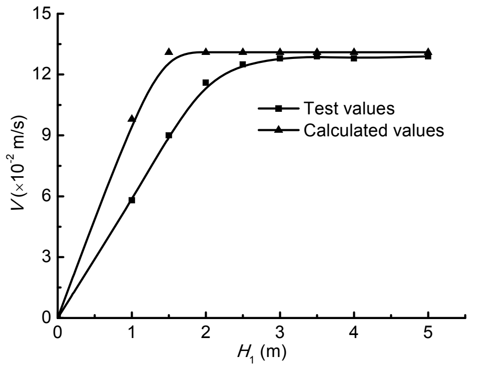

Fig. 5 Siphon flow velocity varies with H_1 in a 9-m water lift

Table 3 Error analysis between the test and calculated values with regard to the siphon flow rate in an 8-m water lift

H_1 (m)	Siphon flow velocity (m/s)		Error (%)
	Test	Calculated	
0.0	0.000	0.000	0.00
1.0	0.075	0.098	30.67
1.5	0.104	0.147	41.35
2.0	0.130	0.196	50.77
2.5	0.159	0.229	44.03
3.0	0.190	0.229	20.53
3.5	0.205	0.229	11.71
4.0	0.210	0.229	9.05
5.0	0.223	0.229	2.69
6.0	0.224	0.229	2.02
7.0	0.225	0.229	1.90
8.0	0.226	0.229	1.18
9.0	0.234	0.229	−1.95
10.0	0.230	0.229	−0.43
11.0	0.231	0.229	−0.66

Table 4 Error analysis between the test and calculated values with regard to the siphon flow rate in a 9-m water lift

H_1 (m)	Siphon flow velocity (m/s)		Error (%)
	Test	Calculated	
0.0	0.000	0.000	0.00
1.0	0.058	0.098	68.97
1.5	0.090	0.131	45.56
2.0	0.116	0.131	12.93
2.5	0.125	0.131	4.80
3.0	0.128	0.131	2.34
3.5	0.129	0.131	1.55
4.0	0.128	0.131	2.34
5.0	0.129	0.131	1.55
6.0	0.129	0.131	1.55
7.0	0.128	0.131	2.34
8.0	0.129	0.131	1.55
9.0	0.128	0.131	2.34
10.0	0.129	0.131	1.55
11.0	0.129	0.131	1.55

4 High-lift siphon flow velocity in a 4-mm siphon hose

The hydraulics formula for the siphon flow velocity is currently only suitable for a single flow in a large diameter pipe under a low water lift. First, a test appears to be a relatively direct method of calculating the high-lift siphon flow velocity in a 4-mm siphon hose and this is borne out by the related test data shown in Tables 1 and 2 and Fig. 3. Secondly, the empirical formula is also a frequently used method both in practical engineering and theoretical research.

4.1 Relationship between ΔH and H_0

Figs. 4 and 5, and Tables 3 and 4, in which comparative analysis was used, show that test values of the high-lift siphon flow rate became steady later than calculated ones. It can thus be inferred that the hose section with the smallest hydraulic gradient was incorrectly judged as far as calculating the siphon flow rate was concerned, i.e., the controlling factor of the siphon flow rate was inaccurate. In the case of a high-lift siphon, plug flow can be formed in a 4-mm siphon hose and the gas columns in the lower hose are longer. The influence of released air must thus be taken into consideration when judging the hose section with the smallest hydraulic gradient. Above all, the controlling factor for the siphon flow rate must be calculated, namely, the relationship between ΔH and H_0.

Tables 1 and 2 and Fig. 3 show that, when the water lifts H_0 were set as 8 m, 8.5 m, 8.55 m, 9 m, 9.3 m, and 9.5 m, the corresponding critical elevation differences were 4.6 m, 3.9 m, 3.8 m, 2.4 m, 2.1 m, and 1.5 m, respectively. In the test, the maximum water lift H_0 of 10.34 m corresponded to H_{1c} of 0 m. The relationship between ΔH and H_0 is shown in Table 5.

Eq. (4) was obtained by numerical fitting. In Fig. 6, the test data points were uniformly dispersed along the fitting line on both sides, giving a correlation coefficient R^2 of 0.996. The fitted relationship was

$$H_{1c}=2\Delta H. \tag{4}$$

Fig. 3 and Eq. (4) indicate that, when $H_1<2\Delta H$, the main controlling factor of the siphon flow rate is H_1, and when $H_1\geq 2\Delta H$, the controlling factor is the difference ΔH between the maximum limit of the water lift $H_{\max}$ and H_0.

Table 5 H_{1c} varies with ΔH

ΔH (m)	2.34	1.84	1.79	1.34	1.04	0.84	0
H_{1c} (m)	4.60	3.90	3.80	2.40	2.10	1.50	0

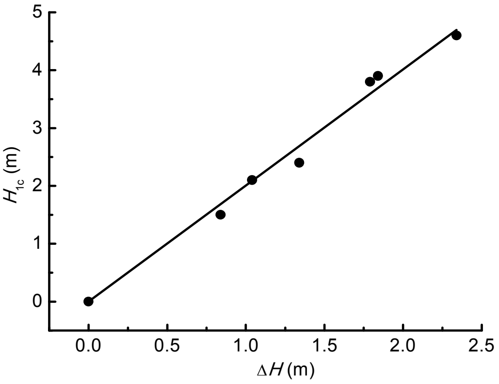

Fig. 6 Fitting relationship between the critical elevation difference H_{1c} and ΔH

4.2 $H_1\geq 2\Delta H$

When $H_1\geq 2\Delta H$, the siphon flow rate is controlled by the water lift rather than the elevation difference H_1. The difference ΔH between the maximum limit of the water lift $H_{\max}$ and H_0 is the hose section with the smallest hydraulic gradient, which is the controlling factor for the siphon flow rate. Therefore, under standard atmospheric pressure, the hydraulic formula for the high-lift siphon flow rate in a 4-mm siphon hose can be written as

$$V_1=\sqrt{\frac{2g\Delta H}{1+\lambda\dfrac{L}{d}+\sum\zeta}}, \tag{5}$$

where $\Delta H=H_{\max}-H_0$, 8 m$\leq H_0\leq$10.3 m.

4.3 $H_1<2\Delta H$

When $H_1<2\Delta H$, the elevation difference H_1 is the controlling factor for siphon flow velocity. However, the siphon flow rate, in Eq. (2), is obviously larger. The reduced coefficient α can thus be added in Eq. (2):

$$V=\sqrt{\frac{2\alpha gH_1}{1+\lambda\dfrac{L}{d}+\sum\zeta}}. \tag{6}$$

In Tables 1 and 2 and Eq. (6), α can be used to estimate the reduced coefficient before the siphon flow rate reaches a steady state. Table 6 shows a reduced coefficient for each high-lift siphon flow rate.

The reduced coefficient α was a variable before the siphon flow velocity became steady. The values of α in Table 6 fluctuated slightly with the elevation difference H_1, but had an obvious negative correlation with the water lift H_0. The reduced coefficient α was therefore defined as the coefficient related to the water lift H_0. The relationship between them could be identified by numerical fitting. Fig. 7 could be acquired through the numerical fitting of the reduced coefficient α in Table 6.

Table 6 Reduced coefficient α in every water lift

H_1 (m)	α						
	H_0=8.0 m	8.5 m	8.55 m	9.0 m	9.3 m	9.5 m	10.0 m
1.0	0.766	0.715	0.705	0.592	0.531	0.408	0.224
1.5	0.708	0.647	0.640	0.618	0.490	0.463	–
2.0	0.664	0.623	0.613	0.593	0.460	–	–
2.5	0.650	0.596	0.580	–	–	–	–
3.0	0.624	–	–	–	–	–	–
3.5	0.647	–	–	–	–	–	–

In Fig. 7, the data points were evenly dispersed along the curve on both sides with a correlation coefficient R^2 of 0.862. The fitting equation can be written as

$$\alpha = \frac{10.31 - H_0}{11.32 - H_0}. \tag{7}$$

In Eqs. (6) and (7), the empirical formula for the high-lift siphon flow velocity in a 4-mm siphon hose under standard atmospheric pressure can be written as

$$V_2 = \sqrt{\frac{2\alpha g H_1}{1 + \lambda \dfrac{L}{d} + \sum \zeta}}, \tag{8}$$

where $\alpha=(10.31-H_0)/(11.32-H_0)$, 8 m$\leq H_0 \leq$10.3 m, and $V_2 \leq V_1$.

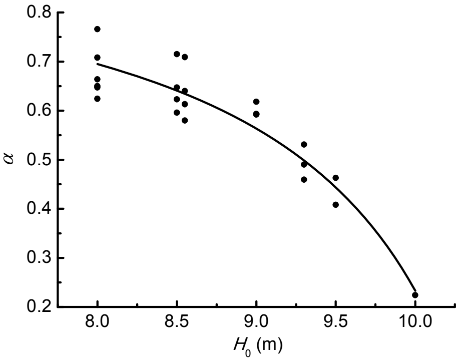

Fig. 7 Fitting relationship between the reduced coefficient *α* and the water lift *H_0*

4.4 Analysis between the test values and calculated values of the empirical formula

Figs. 8 and 9 show the comparative analysis between the test values and the empirical calculated ones of the siphon flow velocity when the water lift was set at 8.55 m and 9.3 m for the 50-m siphon hose. The graphs show that there is some agreement between the two curves. Tables 7 and 8 show the error analysis, in which the calculated errors of the cases were basically about ±5%. The errors were relatively small. Moreover, the differences between the test values and the empirical calculated ones were still about ±5% of the cases where the siphon water lift was 8.5 m, 8.55 m, 9.3 m, and 9.5 m, except that the errors at a few points were controlled in 10%–20% of cases owing to the accidental influence of limited test conditions. With respect to the gas-liquid two-phase flow, the empirical formula for the high-lift siphon flow rate in a 4-mm siphon hose can thus meet the requirements for engineering application.

Table 7 Error analysis between the test and calculated values of empirical formula with regard to the siphon flow rate in an 8.55-m water lift

H_1 (m)	Siphon flow velocity (m/s)		Error (%)
	Test	Calculated	
0.00	0.000	0.000	0.00
1.00	0.069	0.062	9.71
1.50	0.095	0.094	1.05
2.00	0.122	0.124	−1.64
2.50	0.146	0.155	−6.16
3.00	0.150	0.160	−6.67
3.50	0.153	0.175	−14.38
4.00	0.166	0.175	−5.42
5.00	0.168	0.175	−4.17
6.00	0.170	0.175	−2.94
7.00	0.171	0.175	−2.34
8.00	0.170	0.175	−2.94
9.00	0.172	0.175	−1.74
10.00	0.172	0.175	−1.74
11.00	0.173	0.175	−1.16

Table 8 Error analysis between the test and calculated values of empirical formula with regard to the siphon flow rate in a 9.3-m water lift

H_1 (m)	Siphon flow velocity (m/s)		Error (%)
	Test	Calculated	
0.00	0.000	0.000	0.00
1.00	0.052	0.049	5.77
1.50	0.072	0.073	−1.39
2.00	0.090	0.098	−8.78
2.50	0.098	0.102	−4.08
3.00	0.097	0.102	−5.15
3.50	0.102	0.102	0.00
4.00	0.103	0.102	0.97
5.00	0.102	0.102	0.00
6.00	0.104	0.102	1.92
7.00	0.102	0.102	0.00
8.00	0.104	0.102	1.92
9.00	0.103	0.102	0.97
10.00	0.102	0.102	0.00
11.00	0.104	0.102	1.92

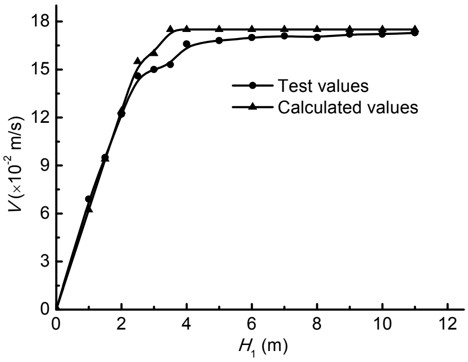

Fig. 8 Test and calculated values of empirical formula vary with H_1 in an 8.55-m water lift

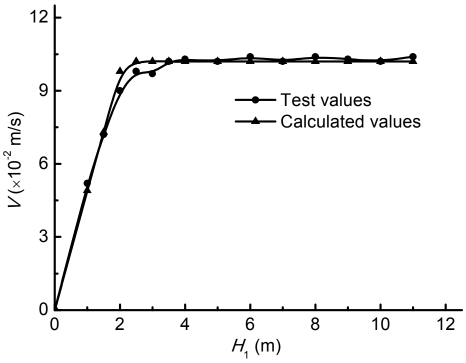

Fig. 9 Test and calculated values of empirical formula vary with H_1 in a 9.3-m water lift

5 Conclusions

The siphon flow velocity was the crucial indicator for weighing the capacity of siphon drainage. Solving the problem of the high-lift siphon flow velocity turned out to be necessary for the design of slope siphon drainage. The following conclusions were obtained from testing the siphon flow velocity and analyzing it comparatively:

1. When the elevation difference H_1 remained unchanged, the siphon flow velocity had a negative correlation with the water lift, but when the water lift H_0 was constant, the siphon flow rate accelerated with the increasing elevation difference H_1 until it reached the maximum flow rate and maintained a steady state. The stable flow rate was defined as the critical flow rate, at which the elevation difference H_1 was the critical elevation difference H_{1c}. The siphon flow velocity had a negative correlation with the length of the siphon hose.

2. In high-lift siphon drainage, the bubbles increased with the decreasing gas pressure and formed a gas-liquid two-phase flow, affecting the calculation of the siphon flow rate. As a result, the current hydraulics formula for pressurized pipe flow proved to be an inappropriate way of measuring the siphon flow velocity in a 4-mm siphon hose.

3. The high-lift siphon flow velocity in a 4-mm siphon hose under standard atmospheric pressure was controlled by the hose section with the smallest hydraulic gradient. When $H_1<2\Delta H$, the elevation difference H_1 was the controlling factor for the siphon flow rate. When $H_1\geq 2\Delta H$, the difference ΔH between the maximum limit of the local siphon water lift $H_{\max}$ and H_0 was the most important factor. In an engineering setting, it is thus unnecessary to increase the siphon elevation difference blindly; this should approach the critical elevation difference and act as a convenient way of designing a practical siphon.

4. A direct test is available for related data with respect to high-lift siphon flow velocity in a 4-mm siphon hose. The empirical formula is also a fairly precise way of accessing the siphon flow rate. The calculated values for the siphon flow rate can provide a basis for operational parameters, e.g., the number of siphon hoses and the layout of siphon drainage holes in practical engineering.

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中文概要

题　目：4 mm 虹吸管高扬程虹吸流速研究

目　的：探索高扬程条件下 4 mm 虹吸管内气体集聚现象对虹吸流速的影响，并对传统虹吸流速水力学计算公式进行修正。

创新点：1. 通过对比物理模型实验值和计算值，得出了高扬程虹吸流速的控制因素及传统虹吸流速计算公式在高扬程条件下的不适用性；2. 通过分析实验数据，对有压管流水力学公式进行修正，使之适应高扬程条件下的虹吸流速计算。

方　法：通过物理模型试验，揭示高扬程虹吸流速的特征（图 3）；将高扬程虹吸流速实验值和传统虹吸流速水力学公式计算值进行对比（表 3 和 4）；通过分析实验数据，结合有压管流水力学公式，得出高扬程虹吸流速经验公式（公式(5)和(8)）。

结　论：1. 在高程差 H_1 一定时，虹吸流速与扬程呈负相关；在扬程 H_0 一定时，虹吸流速随高程差 H_1 的增大而流速加快，直至达到最大流速，并保持稳定状态；虹吸流速与管长呈负相关。2. 高扬程虹吸排水由于管内气压降低析出大量气泡，形成气液二相流，影响虹吸流速的计算；目前采用的有压管流水力学计算公式不适用高扬程 4 mm 虹吸管的虹吸水流。3. 当 $H_1<2\Delta H$, 虹吸流速的控制因素为高程差 H_1；当 $H_1\geq 2\Delta H$, 虹吸流速的控制因素为当地虹吸极限扬程 $H_{\max}$ 和 H_0 的差值 ΔH；4. 对于高扬程 4 mm 虹吸管虹吸流速的确定，一是可以直接实验测定，查找相关数据，二是可以采用经验公式来确定相关的虹吸流速。

关键词：虹吸流速；高扬程虹吸；高程差；扬程；气体影响