

# **A SPREADSHEET TEACHING TOOL FOR ANALYSIS OF PIPE NETWORKS**

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## **ABSTRACT**

Spreadsheets are used widely in engineering to perform several analysis and design calculations. They are also very attractive as educational tools due to their flexibility and efficiency. This paper demonstrates the use of spreadsheets in teaching the analysis of water pipe networks, which involves the calculation of pipe flows or nodal heads given the network layout, pipe characteristics (diameter, length, and roughness), in addition to external flows. The network performance is better understood if students can change pipe characteristics and/or external flows and be able to monitor the corresponding changes in pipe flows and head losses. The solution of the analysis problem is characterized by the possibility of solving it using different system variables (i.e. flows, head, incremental flows, and incremental heads), resulting in different system of equations, in addition to different methods of solution (i.e. Newton Raphson, linearization, or single adjustment). The developed spreadsheets can be used to introduce the network design concept as a series of analysis problems, performed by trial and error, to satisfy operational constraints.

**Keywords:** Pipe network analysis, Spreadsheets, Teaching tool

## **INTRODUCTION**

Spreadsheets are powerful computational tools that are used for many engineering applications. Several examples were given for the use of spreadsheets in civil engineering and particularly in water resources (1,2,3). Also, spreadsheets provide an interesting tool for engineering education, which is appealing for both students and instructors (4). The presented paper is an application of the use of spreadsheets in the area of hydraulics, used by the instructor to explain the different analysis techniques for water pipe networks.

The paper starts by defining the network topology components required to set up the governing system of equations. Then, the equations commonly used to calculate the frictional head loss through pipes are given, followed by a review of possible analysis techniques based on the variable used to formulate the problem, and the available solution methods. Finally, an illustrative example network is solved in detail demonstrating the different analysis techniques with their spreadsheet solution.

## PIPE DISTRIBUTION NETWORKS

A typical network consists of nodes and pipes, where the nodes can be sources (supply nodes), sinks (demand nodes) or junctions. A network can be a tree network or a looped one. Tree distribution networks are used only in rural areas or for pipe irrigation. Loops are needed for reliability purposes. The tree pipes are the minimum number required to convey flow from sources to sinks or junctions. If the number of nodes is  $NN$  and the number of pipes is  $NP$ , then the number of pipes in the tree network is  $(NN-1)$ , and the number of basic closed loops  $NLP$  is  $[NP - (NN-1)]$ . In other words the number of loops is equal to the number of pipes in excess of the tree. As an example, Figure 1 shows a network where the number of nodes is 7, the number of pipes is 11. The number of pipes for the tree network is then 6, and the number of basic loops is  $(11-6=5)$ . A distribution network comprises components other than pipes like pumps, reservoirs, minor loss devices, pressure reducing valves, etc.

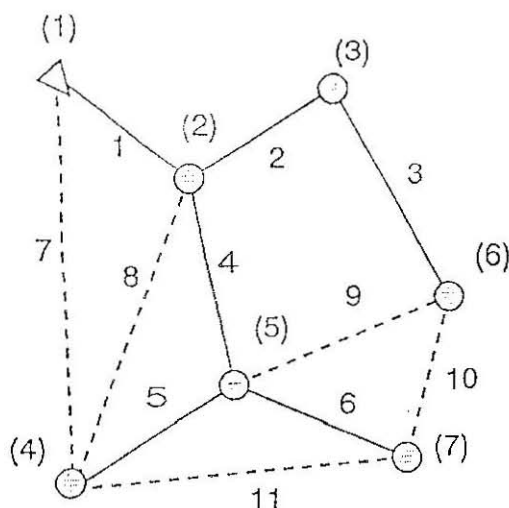


Fig. 1. Water distribution network

## ANALYSIS, DESIGN AND OPTIMIZATION

Three types of problem can be identified when dealing with pipe distribution networks, namely: the analysis, design and optimization problems. The analysis problem - where the layout of the network, external flows and pipe characteristics are given - is to calculate the flow through pipes. The solution of the analysis problem is unique irrespective of the technique used to obtain the solution. The design problem is the one where some of the network components, e.g. pipe diameters, pump lift or reservoir levels are required to obtain certain operation conditions. The design problem is commonly solved by trial and error using a series of analysis problems. The optimization problem is the one which satisfies the design constraints with the minimum cost of network. The cost includes both capital and running costs. Analysis is needed also to evaluate the different design alternatives and choose the optimal one.

## FRICTIONAL HEAD LOSS EQUATIONS

There are many equations available to express the friction head loss  $h_f$  as a function of pipe length  $L$ , pipe diameter  $D$  and a coefficient of friction.

The rational equation of Darcy- Weisbach reads:

$$h_f = \frac{fL}{D} \frac{V^2}{2g} = \frac{8fLQ^2}{\pi^2 g D^5} \quad (1)$$

where  $f$  is the friction coefficient, which can be calculated using the implicit Colebrook-White equation as follows:

$$\frac{1}{\sqrt{f}} = -2 \log \left[ \frac{e}{3.7 D} + \frac{2.51}{R_e \sqrt{f}} \right] \quad (2)$$

where  $e$  is the average roughness height, and  $R_e$  is the Reynolds number. This implicit expression for  $f$  can be solved efficiently by spreadsheets using circular calculation (3).

Another equation, which is widely used for pipe networks is the Hazen-Williams equation,

$$h_f = \frac{K_u L Q^{1.852}}{C_{HW}^{1.852} D^{4.87}} \quad (3)$$

where  $K_u$  is a unit conversion constant equals 4.73 for English units and 10.7 for S.I. units.

A general expression of head loss equations can be written in the form

$$h_f = KQ^n \quad (4)$$

where the constant  $K$  and the exponent  $n$  depend on the equation used.

## CLASSIFICATION OF ANALYSIS TECHNIQUES

Analysis techniques can be classified according to the variables used to solve the network.

### Pipe Flows as Unknowns (Q-system)

The number of unknowns is  $NP$ , which is equal to the number of equations comprising  $(NN-1)$  independent continuity equations, assuming a balanced network, and  $NLP$  loop equations. For a balanced network, the external inflows from sources is equal to the external outflows from sinks. The system is a mixture of linear (continuity) and nonlinear (loop) equations.

### Heads at Junctions as Unknowns (H-system)

This technique uses heads at nodes as unknowns. The number of unknowns is  $NN$  which is less than  $NP$ . Only  $(NN-1)$  continuity equations are written at each node by expressing the discharge through each pipe as,

$$Q_{12} = \left[ \frac{H_1 - H_2}{K_{12}} \right]^{1/n} \quad (5)$$

where 1 and 2 are the upstream and downstream nodes,  $1/n$  is the reciprocal of the exponent in equation (4). The resulting system of equations is nonlinear.

### Corrective Flow Rates as Unknowns ( $\Delta Q$ -system)

The variables in this technique are the corrective flows  $\Delta Q$  required to satisfy the energy equation around loops. The solution can be obtained by considering one loop at a time, i.e. the known Hardy Cross method, or by considering all loops together where the number of nonlinear equations solved simultaneously equals the number of loops. The loop equation is written in the following form,

$$\sum_{i=1}^{l} K_i (Q_{oi} - \Delta Q_i)^n = 0 \quad (6)$$

where  $Q_{oi}$  is the initial guess of flow for the  $i^{\text{th}}$  pipe, and  $l$  is the number of pipes in the loop.

### Corrective Nodal Heads as Unknowns ( $\Delta H$ -system)

The corrective nodal head  $\Delta H$  is the correction required to satisfy the continuity equation at a node. Similar to the previous technique, two methods are available using the corrective head  $\Delta H$ , i.e. the single adjustment method of Hardy Cross, and the global adjustment using (NN-1) nonlinear simultaneous equations. The continuity equation at any node is written as:

$$\sum_{i=1}^{p} \left( \frac{1}{K} \right)^{1/n} (H_{oi} - \Delta H)^{1/n} - Q_{\text{ext}} = 0 \quad (7)$$

where  $p$  is the number of pipes connected to the node.

The choice of analysis technique depends on available data, required output, and the computational tool used.

## METHOD OF SOLUTION

The method of solution for the network unknowns depends on the analysis technique used. The single adjustment techniques for  $\Delta Q$  and  $\Delta H$  use the Hardy Cross method which will be explained in the illustrative example below. The system of nonlinear equations resulting from global adjustment using  $Q$ ,  $H$ ,  $\Delta H$ ,

or  $\Delta Q$  can be solved using the Newton-Raphson method. A special method, the linear approximation, is used to solve the Q-system.

### The Newton - Raphson Method

The nonlinear system of equations resulting from using any of the unknowns mentioned above can be solved by the Newton-Raphson method. The value of the unknowns or variables at iteration  $i+1$  is calculated as

$$\underline{X}_{i+1} = \underline{X}_i - D^{-1} \underline{F}(\underline{X}_i) \quad (8)$$

where  $D^{-1}$  is the Jacobean matrix, which is the first derivative of the function  $F$  with respect to the variables  $X$ .

### The Linear Approximation

The linear approximation is a widely used method to solve the analysis problem with pipe flows as unknowns. It depends on approximating the nonlinear head loss equation in the following linear form,

$$hf = K' Q \quad (9)$$

where  $K' = K Q^{n-1}$

The resulting system is linear, and the values of  $K'$  are updated after each solution of the linear equations until convergence is reached.

To solve the analysis problem efficiently, the user has to choose a match between the analysis technique and the method of solution.

## ILLUSTRATIVE EXAMPLE

Figure 2 shows a very simple water distribution network in which a single source 1 supplies two sinks 2 and 4. Node 3 serves merely as a junction. The network has four nodes, four pipes and one loop. It is assumed that the system is balanced. The friction equation used is the Hazen-Williams equation. The constant  $K$  of the equation is given for each pipe. The sign convention for node continuity equations is positive for flows entering and negative for flows leaving.

For energy (loop) equations, head loss is positive when flow is clockwise and vice versa.

The following section illustrates how the system of equations is written for the different analysis techniques, and how the solution is obtained using spreadsheets. The section is arranged under the same headings given above under 'Classification of Analysis Techniques'.

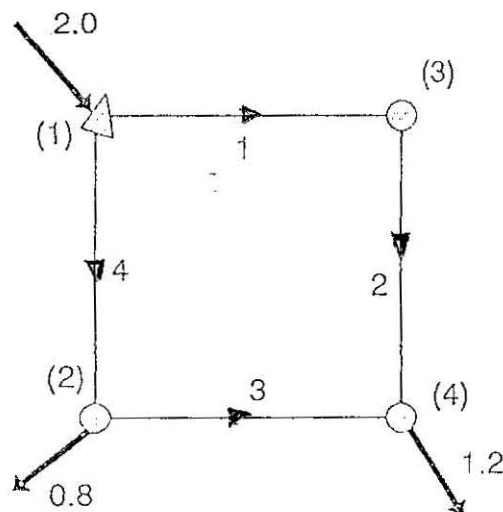


Fig. 2. Example network 1

The details of the spreadsheet design are given in Tables 1 through 4. Both starting point and final solution are given for each example, except for the automatic solution provided by the use of circular calculation. Also, contents of important cells are shown to explain calculation details.

### Pipe Flows as Unknowns (Q-system)

The system of equations comprise three independent continuity equations and one loop equation,

$$\begin{array}{rcl}
 Q_1 & +Q_4 & = 2.0 \\
 -Q_3 & +Q_4 & = 0.8 \\
 Q_1 & -Q_2 & = 0.0 \\
 2.0 Q_1^{1.85} + 1.5 Q_2^{1.85} - 3.0 Q_3^{1.85} - 1.0 Q_4^{1.85} & = & 0.0
 \end{array} \quad (10)$$

Table 1-a shows the solution using the linear method. The starting point used to calculate the coefficients for the energy equation assume a value of 1 for all flows. Therefore, the loop equation at the starting point takes the form:

$$2.0 Q_1 + 1.5 Q_2 - 3.0 Q_3 - 1.0 Q_4 = 0.0 \quad (11)$$

Table 1-a. Linear Approximation (Q-equations)

	A	B	C	D	E	F	G	H	I
1	Coefficient Matrix					RHS	sumhf		
2									
3	1	0	0	1		2			
4	0	0	-1	1		0.8			
5	1	-1	0	0		0			
6	2.000	1.500	-3.000	-1.000		0	-0.5		
7									
8	Inverted Coefficient Matrix				Q	Qupd	Qavg		
9									
10	0.533	-0.400	0.200	0.133		1.000	0.747	0.873	
11	0.533	-0.400	-0.800	0.133		1.000	0.747	0.873	
12	0.467	-0.600	-0.200	-0.133		1.000	0.453	0.727	
13	0.467	0.400	-0.200	-0.133		1.000	1.253	1.127	
14									
15	Starting Point								
16									
17	Coefficient Matrix					RHS	sumhf		
18									
19	1	0	0	1		2			
20	0	0	-1	1		0.8			
21	1	-1	0	0		0			
22	1.591	1.194	-1.485	-1.197		0	-2.6E-06		
23									
24	Inverted Coefficient Matrix				Q	Qupd	Qavg		
25									
26	0.491	-0.272	0.218	0.183		0.764	0.764	0.764	
27	0.491	-0.272	-0.782	0.183		0.764	0.764	0.764	
28	0.509	-0.728	-0.218	-0.183		0.437	0.436	0.437	
29	0.509	0.272	-0.218	-0.183		1.236	1.236	1.236	
30									
31	Final Solution								
32									
33	Cell G22 +A22*F26+B22*F27+C22*F28+D22*F29								
34									
35									



The solution steps involve the inversion of the coefficient matrix, and the multiplication of the inverted matrix by the vector of right hand sides of the equations to obtain the updated values of flow. The coefficients of the energy equation are updated each time the system of equations is solved, until convergence is obtained. To accelerate the solution and avoid oscillation, the updated value of flow is calculated using the average values from the previous two iterations. The solution vector is given by the range F26..F29. Cell G23 shows how the sum of head losses around the loop is calculated. A simple macro may be written to automate the solution steps and count the number of iterations needed to arrive at the solution. The macro is a small program that repeats a sequence of key strokes. Table 1-b shows a typical macro applied to the starting point in Table 1-a. Each time the macro is run, it carries out the solution steps, updates the number of iterations, and stores it in cell C16.

Table 1-b. Simple Macro to Automate the Solution

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```
{Notebook.Recalc_Settings "Manual,Natural,1,No,No"}
{Invert.Source LINEAR:A3..D6}
{Invert.Destination LINEAR:A10}
{Invert.Go}
{Multiply.Matrix_1 LINEAR:A10..D13}
{Multiply.Matrix_2 LINEAR:F3..F6}
{Multiply.Destination LINEAR:G10}
{Multiply.Go}
{Calc}
{BlockValues LINEAR:H10..H13,LINEAR:F10}
{Calc}
{let c16, c16+1}
```

### Heads at Junctions as Unknowns (H-system)

The system of equations comprise three independent continuity equations. Assuming the head at node 1 equals 100 units, the equations read:

$$\begin{aligned}
\left[ \frac{100 - H_3}{2.0} \right]^{1.85} + \left[ \frac{100 - H_2}{1.0} \right]^{1.85} &= 2.0 \\
\left[ \frac{100 - H_2}{1.0} \right]^{1.85} - \left[ \frac{H_2 - H_4}{3.0} \right]^{1.85} &= 0.8 \\
\left[ \frac{100 - H_3}{2.0} \right]^{1.85} - \left[ \frac{H_3 - H_4}{1.5} \right]^{1.85} &= 0.0
\end{aligned} \tag{12}$$

Table 2 shows the solution using the Newton-Raphson method. The solution steps start by assuming values of the unknown heads and calculating the functions  $F$ . The Jacobean matrix  $D$  is then calculated, inverted and the values of heads are updated according to the Newton-Raphson formula. The nodal heads are then converted to pipe flows to compare the solutions. The latter steps are repeated until convergence is obtained. Cell F21 shows how the first element of the Jacobean matrix is calculated. The solution is given by the range B31..B34.

### Corrective Flow Rates as Unknowns ( $\Delta Q$ -system)

There is only one loop, and therefore only one equation is written in terms of  $\Delta Q$ . Assuming a positive correction, the equation reads,

$$\begin{aligned}
2.0(Q_{10} + \Delta Q)^{1.85} + 1.5(Q_{20} + \Delta Q)^{1.85} \\
- 3.0(Q_{30} + \Delta Q)^{1.85} - 1.0(Q_{40} + \Delta Q)^{1.85} &= 0.0
\end{aligned} \tag{13}$$

Using equation (6) the correction  $\Delta Q$  used in the Hardy-Cross single adjustment method can be expressed as:

$$\Delta Q = - \frac{\sum KQ^n}{n \left| \sum KQ^{n-1} \right|} \tag{14}$$

The solution proceeds by assuming values of flow that satisfies the continuity equations, then calculating the correction and updating the values of flow. The steps are repeated until the correction becomes acceptably small. The starting point assumed has to fulfill the continuity conditions and its value affects

Table 2. Newton Raphson (H-system)

	A	B	C	D	E	F	G	H	I
1		H		F		Jacobian Matrix (D)			
2									
3	H2	97.000	F1	0.812	DF1	-0.327	-0.271	0.000	
4	H3	98.000	F2	0.209	DF2	-0.544	0.000	0.217	
5	H4	95.000	F3	-0.455	DF3	0.000	-0.533	0.262	
6									
7		Hupd		D-1*F		Inverse of Jacobian (D-1)			
8									
9		98.773		-1.773		-1.514	-0.929	0.769	
10		98.859		-0.859		-1.868	1.122	-0.929	
11		98.479		-3.479		-3.793	2.278	1.925	
12									
13	Q1	1.000							
14	Q2	1.455							
15	Q3	0.803							
16	Q4	1.811							
17						Starting Point			
18									
19		H		F		Jacobian Matrix (D)			
20									
21	H2	98.520	F1	0.000	DF1	-0.452	-0.340	0.000	
22	H3	98.785	F2	0.000	DF2	-0.816	0.000	0.365	
23	H4	97.873	F3	0.000	DF3	0.000	-0.793	0.453	
24									
25		Hupd		D-1*F		Inverse of Jacobian (D-1)			
26									
27		98.520		0.000		-1.127	-0.601	0.483	
28		98.785		0.000		-1.443	0.799	-0.642	
29		97.873		0.000		-2.525	1.398	1.082	
30									
31	Q1	0.764							
32	Q2	0.764							
33	Q3	0.436							
34	Q4	1.236							
35						Final Solution			
36									
37		Cell F21	0.541*((100-B21)/1)^(-0.459)*-1^						
38									
39									

the number of iterations required to arrive at the solution. Table 3-a shows the solution using the Hardy-Cross method. Cells D13 through F13 show how the terms in equation (13) are calculated. The solution is given by the range F13..F16. The solution procedure can be improved by using the circular calculation facility of the spreadsheet which carries out the iterations needed internally. Table 3-b shows how the sheet is set up to activate the circular calculation by connecting the cells C3 and F3 as shown in the table. The solution is given by the range F3..F6.

### Corrective Nodal Heads as Unknowns ( $\Delta H$ -system)

The number of independent continuity equations written in terms of  $\Delta H$  is three. If the Hardy-Cross single adjustment method is used, the corrective head can be expressed as:

$$\Delta H = \frac{\sum kh - Q_{ex}}{m \left| \sum \frac{k}{h^m} \right|} \quad (15)$$

where  $h$  is head loss, while  $k$  and  $m$  are the constant and exponent respectively in the equation:

$$Q = kh^m \quad (16)$$

Tables 4-a and 4-b show the starting point and the final solution considering each node at a time. The head loss,  $h$ , is calculated by looking up the table of origin destination pairs F2..H5, and the table of nodal heads A2..B5, as described by the content of cell C8. The solution in terms of flow in pipes is given by the values of  $kh^m$  in column D. Another solution is given in Table 4-c where all nodes are considered together through the use of circular calculation. As shown from the latter table, the spreadsheet is arranged in a different way by dividing it into two sections for node and pipe description, and the circular calculation is activated by connecting the cells D5, E11, I15, and I16. The solution is given by the range F11..F14.

The equations needed for global adjustment can be written in the form:

$$\begin{aligned} k_1(h_1 - \Delta H_3)^m & - k_2(h_2 + \Delta H_3 - \Delta H_4)^m & = 0.0 \\ k_4(h_4 - \Delta H_2)^m & - k_3(h_3 + \Delta H_2 + \Delta H_4)^m & = 0.8 \\ -k_3(h_3 - \Delta H_4 - \Delta H_2)^m & - k_2(h_2 + \Delta H_3 - \Delta H_4)^m & = 1.2 \end{aligned} \quad (17)$$

Table 3-a. Hardy Cross ( $\Delta Q$ -equations)

	A	B	C	D	E	F	G
1	n	1.85		del Q	-0.241		
2	pipe	K	Q	$KQ^n$	$nKQ^{(n-1)}$	Qupd	
3	1	2	1.000	2.000	3.700	0.759	
4	2	1.5	1.000	1.500	2.775	0.759	
5	3	3	-0.200	-0.153	1.413	-0.441	
6	4	1	-1.000	-1.000	1.850	-1.241	
7		sum		2.347	9.738		
8							
9			Starting Point				
10							
11	n	1.85		del Q	-0.241		
12	pipe	K	Q	$KQ^n$	$nKQ^{(n-1)}$	Qupd	
13	1	2	0.764	1.215	2.943	0.523	
14	2	1.5	0.764	0.911	2.207	0.523	
15	3	3	-0.436	-0.646	2.741	-0.677	
16	4	1	-1.236	-1.480	2.215	-1.477	
17		sum		-1E-12	10.107		
18							
19			Final Solution				
20							
21	Cell D13	+E13/\$B\$1*C13					
22	Cell E13	+\$B\$1*B13*@ABS(C13)^(\$B\$1-1)					
23	Cell F13	+C13+\$E\$1					
24							

Table 3-b. Hardy Cross ( $\Delta Q$ -equations) - Automatic

	A	B	C	D	E	F	G
1	n	1.85			delQ	1.1E-17	
2	pipe no	K	Q	$KQ^n$	$nKQ^{(n-1)}$	Qupd	
3	1	2	0.753	1.182	2.906	0.753	
4	2	1.5	0.753	0.887	2.180	0.753	
5	3	3	-0.447	-0.677	2.801	-0.447	
6	4	1	-1.196	-1.392	2.153	-1.196	
7		sum		0.000	10.040		
8							
9	Cell C3	+F3					
10	Cell F3	+C3-\$D\$7/\$E\$7					
11							

Table 4-a. Hardy Cross ( $\Delta H$ -system)

	A	B	C	D	E	F	G	H	I
1	Node	H	Hupd	m	0.541	Pipe	USnode	DSnode	
2	1	100.000	100.000				1	1	3
3	2	97.000	97.414				2	3	4
4	3	98.000	97.084				3	4	2
5	4	95.000	97.378				4	1	2
6	Node 2	Qex	0.8						
7	pipe	k	h	kh <sup>m</sup>	k/h <sup>m</sup>	DelH2			
8	3	0.552	-2.000	-0.803	0.379	0.414			
9	4	1.000	3.000	1.812	0.552				
10			sum	1.009	0.000				
11	Node 3	Qex	0						
12	pipe	k	h	kh <sup>m</sup>	k/h <sup>m</sup>	DelH3			
13	1	0.688	2.000	1.001	0.473	-0.916			
14	2	-0.803	3.000	-1.455	0.443				
15			sum	-0.454	0.916				
16	Node 4	Qex	1.2						
17	pipe	k	h	kh <sup>m</sup>	k/h <sup>m</sup>	DelH4			
18	2	0.803	3.000	1.455	0.443	2.378			
19	3	-0.552	-2.000	0.803	0.379				
20			sum	2.258	0.823				
21									
22			Starting Point						
23									
24									

Table 4-b. Hardy Cross ( $\Delta H$ -system)

	A	B	C	D	E	F	G	H	I
1	Node	H	Hupd	m	0.541	Pipe	USnode	DSnode	
2		1	100.000	100.000			1	1	3
3		2	98.521	98.520			2	3	4
4		3	98.786	98.786			3	4	2
5		4	97.874	97.874			4	1	2
6	Node 2	Qex	0.8						
7	pipe	k	h	kh <sup>m</sup>	k/h <sup>m</sup>	DelH2			
8		3	0.552	-0.647	-0.436	0.699	0.000		
9		4	1.000	1.479	1.236	0.809			
10			sum	0.800	0.000				
11	Node 3	Qex	0						
12	pipe	k	h	kh <sup>m</sup>	k/h <sup>m</sup>	DelH3			
13		1	0.688	1.214	0.764	0.620	0.000		
14		2	-0.803	0.913	-0.764	0.844			
15			sum	0.000	1.463				
16	Node 4	Qex	1.2						
17	pipe	k	h	kh <sup>m</sup>	k/h <sup>m</sup>	DelH4			
18		2	0.803	0.913	0.764	0.844	0.000		
19		3	-0.552	-0.647	0.436	0.699			
20			sum	1.200	1.542				
21									
22									
23									
24	Cell C8	@VLOOKUP(@VLOOKUP(A8,\$F\$2:\$H\$5,1),\$A\$2:\$B\$5,1)							
25		-@VLOOKUP(@VLOOKUP(A8,\$F\$2:\$H\$5,2)),\$A\$2:\$B\$5,1)							
26	Cell F8	(D10-C6)/(\$E\$1*E10)							
27									

Table 4-c. Hardy Cross ( $\Delta H$ -system) - Automatic

	A	B	C	D	E	F	G	H	I	J	K	L	
1	m		0.5405										
2	Node description												
3	No	H	Qext	delH	Hupd.								
4	1	100	2	0	100								
5	2	98.48	-0.8	-0.1129	98.367								
6	3	98.732	0	-0.1488	98.583								
7	4	97.949	-1.2	0.1886	98.138								
8													
9	Pipe description					Continuity equations							
						Node numbers							
10	No	USnode	DSnode	k	h	kh^m	k/h^m	2	3	4			
11	1	1	3	0.6875	1.27	0.7818	0.60463	0	-1	0			
12	2	3	4	0.8032	0.78	0.7033	0.91721	0	-1	1			
13	3	4	2	0.5522	-0.53	0.3921	0.77777	-1	0	1			
14	4	1	2	1	1.52	1.2539	0.79749	-1	0	0			
15								num	0.8619	0.0784	1.0954		
16								den	1.5753	1.5218	1.695		
17													
18	Cell D5	(@HLOOKUP(A5,\$I\$10..\$K\$16,5)+C5)/@HLOOKUP(A5,\$I\$10..\$K\$16,6)/\$C\$1											
19	Cell E11	@VLOOKUP(B11,\$A\$4..\$B\$7,1)-@VLOOKUP(C11,\$A\$4..\$B\$7,1)											
20	Cell I15	+I11*\$F11+I12*\$F12+I13*\$F13+I14*\$F14											
21	Cell I16	@ABS(I11)*\$G11+@ABS(I12)*\$G12+@ABS(I13)*\$G13+@ABS(I14)*\$G14											
22													
23													



which is a system of nonlinear equations that can be solved using Newton Raphson method.

## DISCUSSION OF COMPUTATIONAL EXPERIMENTS

The series of exercises shown above provide detailed demonstration of several analysis techniques and solution methods. Spreadsheets made the calculations so visible and offers a great teaching tool allowing the student to change any input parameter and see the effect on the output. This kind of what-if analysis is very valuable to deepen the knowledge of the concepts of analysis and design of looped distribution networks. All combinations of analysis technique and solution method provide the same result since the solution of the analysis problem is unique as mentioned before. The ability to automate the solution by using spreadsheet macros and the efficient internal iteration provided by circular calculation enhance the solution procedure. The student should be able to evaluate the pros and cons of using a certain combination of analysis technique and solution method in terms of the required input data, number of equations, its nonlinearity, and the computational effort required.

## CONCLUSIONS

The paper demonstrates the use of spreadsheets as an educational tool in the area of analysis of networks. In addition to helping the student understand the concepts of analysis and design it clarifies the concepts behind solving the set of governing equations. Certain features inherent to spreadsheets were used to improve the efficiency of the solution, like the macros used to automate the solution steps and the circular calculation used to perform the iterations needed for the Hardy-Cross method. Spreadsheets are invaluable for the instructor also since it helps him design better assignments and test problems.

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