COMPUTER - AIDED WATER SUPPLY PIPING NETWORK DESIGN MODEL (WASDIM)

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ABSTRACT

Water Supply Distribution Network Model (WASDIM) based on the conventional apporaches of Darcy-Weisbach's headloss computation and Von-Karman's friction factor for turbulent flows and computer methods is presented. The model is a relaxation one of the Hardy-Cross type permitting accurate computation of the head losses and design flows in pipes of various diameters. Emphasis on the types of network-grid systems, branching systems or combined systems; and other available options-metric or imperials system of units, etc. in the software are adequately made. Two example test problems are presented. The first is a hypothetical one of grid systems only, solved manually and by WASDIM to demonstrate the model's accuracy and stablility. The second is a field case of Bille town, Degema LGA, River State, Nigeria, of combined systems also solved by WASDIM to illustrate its practical utility in dealing with a real life problem. The advantages of computer-aided water distribution modelling have been made and its use should be encouraged in the Nigeria water industry.

Key words:
Computer applications, grid-branching systems, water distribution model, and WASDIM.

1. INTRODUCTION

A water supply distribution network is primaily dictated by topography, street patterns, degree and type of development of the area and location of treatment and storage works. The distribution systems are generally classified as grid, branching or a combination of these (Clark et al. 1977). A grid system consists of a network of closed loops only while a branch system has numerous dead ends. For the sake of efficiency, a grid system is preferred to a branching system, because it can furnish a supply to any point from at least two directions.

As basic requirements, the performance of a distribution network can be assessed on the basic of the pressures available in the system for a specific flow rate (reh, 1962). Pressure should be adequate enough to meet consumer and fire-fighting needs. On the other hand, the same pressures should not be excessive as these have great cost implications. For instances, "as pressures increase, leakage increases, and money is thus spent to transport and process a product that is wasted" (Clark et al., 1977).

The water supply piping network model as presented herein is that of Harby-Cross (1936). The

method permits the accuate computation of the rates of flow through the system and the resulting the headlosses. It is a trial and error (relaxation method by which corrections are applied to assumed piezometric heads or assumed flow rates until an acceptable hydraulic balannce of the system is achieved. Because the procedure involves a number of trials, convergence will be dependent upon the accuracy of the value of heads or flow rates originally selected. Much more rapid convergence results from reasonable initial guessed valus.

The Hardy-Cross network analysis is based on the principles (Simon, 1981) that:

(i) in any system of flow, continuity must be preserved, and

(ii) the pressure drop between any two point in the circuit must be the same.

The system must be defined in terms of pipe sizes (diameters), lengths and roughness. Next is the assumption of initial values for either the flow rates in the individual pipes or piezometric heads as the junction points. The second option is adopted in modelling the WASDIM software program. Details are provided in the subsequent section on Mathematical Modelling of Piping System.

Apart from the Hardy-Cross relation method, other pipe network analysis techniques are in use. A summary of such techniques are presented in developments in water science by David Stephenson (1989). One of the more recent development is the application of linear theory in which the non-linear equations of flow and head loss are linearized resulting in a set of simultaneous equations (one for each node) which can be solved for head, H at each node (isaacs and Mills, 1980; Wood and Charles, 1972). the procedure is to estimate H at each node initially, then solve for new H's. This is repeated until satisfactory convergence is obtained.

2. MATHEMATICAL MODELLING OF PIPING SYSTEMS

Hydraulics of pipe flow involves mostly the computation of energy losses in pipes. Two main approaches are currently in use, namely; the empirical method and the scientific method (Simon, 1981). An example of the empirical method is the so-called Hazen-Williams equation, one of the early empirical equations that is still widely in use today, developed by plotting and analyzing experimental and field data on pipe flows. The Hazen-Williams equation has an inherent uncertainty in the determination of its coefficient off friction which is assumed to be a constant but indeed it is not.

The scientific approach is typified by the Darcy-Weisbach formula for headloss computation (Eaq.1) and Von-Karma's friction factor formula (Eq.2) for turbulent flow conditions. this is the approach adopted in the development of WASDIM computer-based model.

$$h_L = fLV^2/2Dg \quad (1)$$

and $$1/\sqrt{f} = 2 \log D/e + 1.14 \quad (2)$$

in which Hl is the head loss, f the friction factor, L the pipe length, D pipe diameter, V flow velocity, G acceleration due to gravity and E the roughness height for pipe.

In most technical applications pipelines are designed for possible maximum flows and such maximum flows will be maintained at fully turbulent conditions. Thus, the flows in the pipelines are obtained bu combining equations (1) and (2) as:

$$Q = [\pi/4\sqrt{2g}\,(2\log D/e + 1.14)D^{2.5}]\,(hL/L)^{1/2} \quad (3)$$

or $$Q = K\,(h_L/L)^{1/2} = K\sqrt{S} \quad (4)$$

in which all terms in the bracket in Eq (3) are known for a particular pipe and are called conveyance, K. S is the slope of the energy grade line.

In the network analysis vai Hardy-Cross method, for the initially assumed piezometric heads to be correct (which is a remote possibility), all continuity equations must be satisfied. Otherwise, an error in continuity equation. $\sum Q$ must appear at each junction in the form.

$$\sum Q = \sum \Delta Q \qquad (5)$$

On account of the error, ΔQ assumed piezometric heads must be adjusted by an amount, ΔH. The aggregate effect of ΔH on the excess Q at a junction may be evaluated by the weighted formula (Simon, 1981):

$$\Delta H = 2\Delta Q / \sum / Q / h_L / \qquad (6)$$

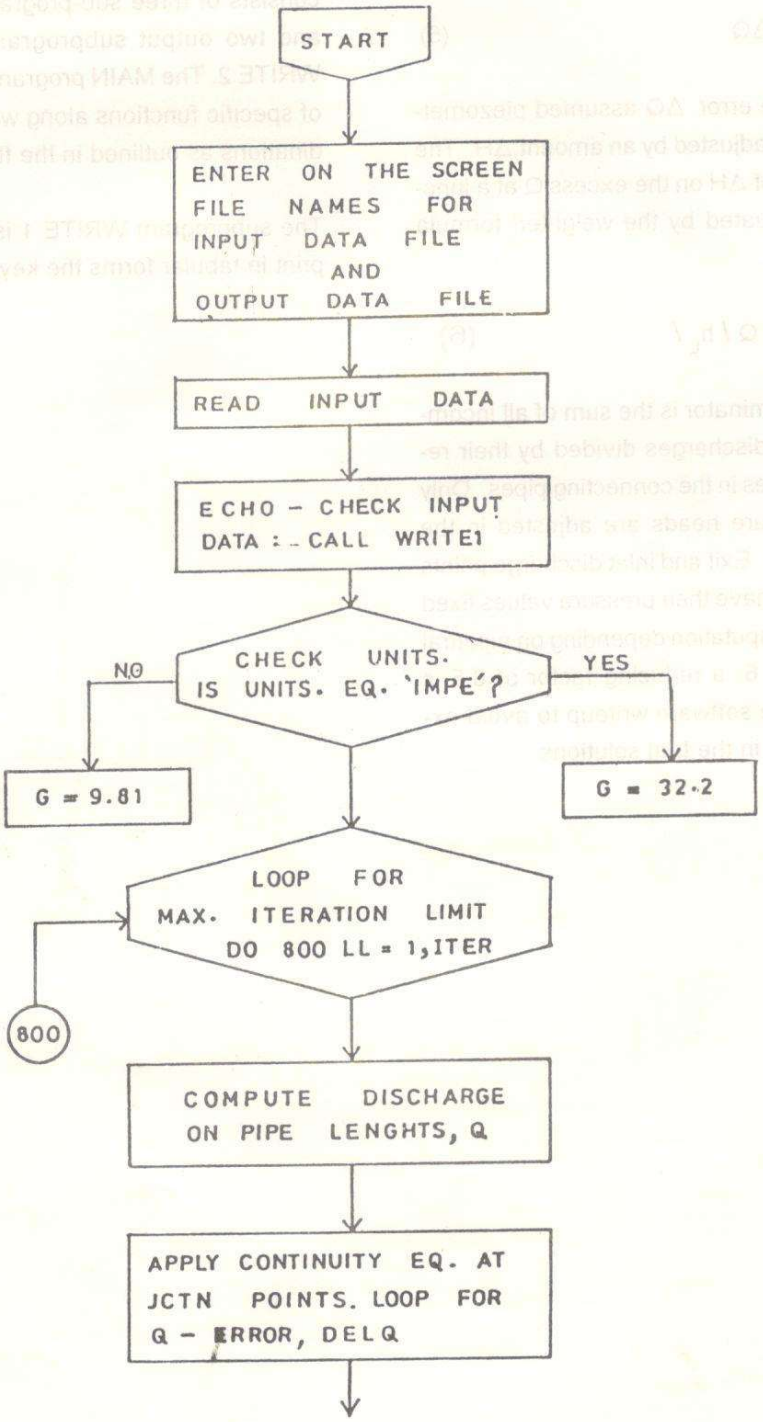
In which the denominator is the sum of all incoming and outgoing discharges divided by their respective head losses in the connecting pipes. Only the internal pressure heads are adjusted in the relaxation method. Exit and inlet discharge points or dead ends may have their pressure values fixed throughout the computation depending on extenral controls. For Eq. 6, a reducing factor of 0.5 is incorporated in the software writeup to avoid excessive oscillation in the trial solutions.

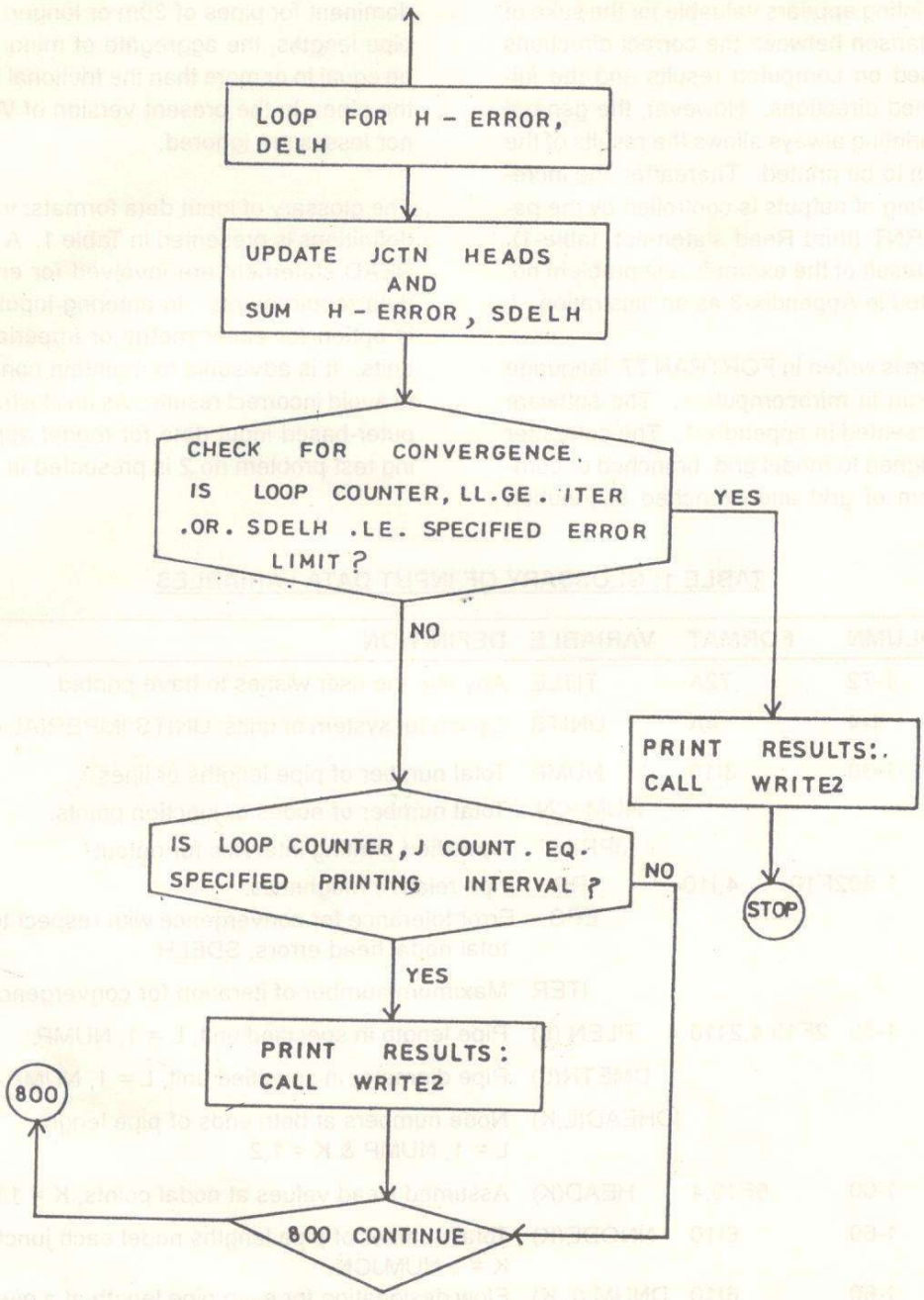
3. THE COMPUTER PROGRAM

The computer program is constructed using equations (3) - (6) in an iterative fashion based on the principles of Hardy - Cross relaxation method discussed in the preceeding sections. The program consists of three sub-programs, MAIN program and two output subprograms - WRITE 1 and WRITE 2. The MAIN program performs a number of specific functions along with its program coordinations as outlined in the flow chart A.

The subprogram WRITE 1 is used repeatedly to print in tabular forms the key

FLOW CHART A: WATER SUPPLY DISTRIBUTION NETWORK MODEL (MAIN PROGRAM)




LOOP FOR H - ERROR, DELH
UPDATE JCTN HEADS AND SUM H - ERROR, SDELH
CHECK FOR CONVERGENCE. IS LOOP COUNTER, LL.GE. ITER .OR. SDELH .LE. SPECIFIED ERROR LIMIT ?
YES
NO
PRINT RESULTS:. CALL WRITE2
STOP
IS LOOP COUNTER, J COUNT. EQ. SPECIFIED PRINTING INTERVAL ?
NO
YES
PRINT RESULTS: CALL WRITE2
800
800 CONTINUE

input data. The subroutine WRITE 2 outputs the computed results. Each time it is called, it prints dicharge values for each pipe length and nodal peizometric heads. However, at convergence of solution or exceedance of maximum iteration limit, it prints head loss values and tabulation of initially assumed heads and computed values of heads. The later printing appears valuable for the sake of quick comparison between the correct directions of flow based on computed results and the initially assumed directions. However, the general format for printing always allows the results of the first iteration to be printed. Thereafter, the incremental printing of outputs is controlled by the parameter JPRNT (third Read statement, table-1). The output result of the example test problem no. 2 is presented in Appendix-3 as an illustration.

The software is writen in FORTRAN 77 language and easily run in mirocomputers. The software listing is presented in appendix-1. The computer code is designed to model grid, branched or combined system of grid and branched distribution network. At each junction point up to six pipe lenghts or lines can be modelled. An aspect of the software model that may be subject to future revision is the inclusion of minor losses due to elbows, valves and other fittings that may affect headloss computations. In hydraulic design of pipelines headloss due to friction along the pipe is dominant for pipes of 30m or longer. For shorter pipe lengths, the aggregate of minor losses may be equal to or more than the frictional losses along the pipe. In the present version of WASDIM minor losses are ignored.

The glossary of input data formats: variables and definitions is presented in Table 1. A total of nine READ statement are involved for entering input data requirements. In entering input data, there is option for either metric or imperial system of units. It is advisable to maintain consistent units to avoid incorrect results. As an illustration a computer-based input data for model application using test problem no.2 is presented in appendix 2.

TABLE 1: GLOSSARY OF INPUT DATA VARIABLES

CARD	COLUMN	FORMAT	VARIABLE	DEFINITION
1	1-72	.72A	TITLE	Any title the user wishes to have printed.
2	1-4	4A	UNITS	Option for system of units: UNITS IMPERIAL or METRIC.
3	1-30	3I10	NUMP	Total number of pipe lengths or lines.
			NUMJCN	Total number of nodes or junction points.
			JPRINT	Specified printing intervals for output.
4	1-302F10.	4,I10	RR	Pipe relative roughness.
			EPS	Error tolerance for convergence with respect to computed total nodal head errors, SDELH.
			ITER	Maximum number of iteration for convergence.
5	1-50	2F10.4,2110	PLEN (L)	Pipe length in specified unit, L = 1, NUMP.
			DMETR(L)	Pipe diameter in specified unit, L = 1, NUMP.
			IDHEAD(L,K)	Node numbers at both ends of pipe length, L = 1, NUMP & K = 1,2.
6	1-60	6F10.4	HEAD(K)	Assumed Head values at nodal points, K = 1 NUMJCN.
7	1-60	6I10	NNODE(K)	Total number of pipe lengths nodel each junction, K = 1 NUMJCN.
8	1-60	6I10	DNUM (L,K)	Flow designation for each pipe length at a given junction, using index no. [not same as IDHEAD (L,2)] assigned to the pipe: + ve for inflow to a jctn and ve for outflow from a Jctn., IDNUM (L,K) L = 1, NUMJCN; K = 1 NNODE (L).
9	1-60	6I10	NODFX (K)	Nodal junction points with know heads or for which no adjustments will be made. input 0 for YES and 1 for NO ADJUSTMENT.

4. MODEL VERIFICATION

4.1 EXAMPLE TEST PROBLEM NO. 1

The first test problem is a case of an idealized water supply network with known solution (Simon, 1981). The problem description (in imperial units) is presented. a pipe network is fed from a water tower 1000ft above datum level. The network is composed of steel pipes with equivalent sand roughness of e = 0.0005ft. The pipe lenghts and diameters are as shown in table 2. Assuming that at the exit point (node 5, Fig. 1), the pressure is maintained at 750ft above datum level, calculate the discharge through the network using the hardy-Cross method.

Preparation of the input data for computer simulation is made using data in Fig.1, Table 2 and the input formats in Table 1. A total of twenty cycles of computations are made and the resulting piezometric error sum $\sum\Delta H$ at junctions (nodes) against corresponding numbers of iteration are noted. The error sum varies from 109.83 to 0.751 for the first to the twentieth iterations, respectively. a plot of the error sums against numbers of iteration (fig.2) illustrate the inherent stability or non-oscillatory nature of WASDIM software.

Comparisons of Simon's manually-based and WASDIM's computer-based computed values of the piezometric heads and discharges at fifth cycle of iteration are presented in tables 2 and 3, respectively. The percent diference in the computed heads gives a maximum value of 7.62 at node 2. For the discharge values both the manual and computer approaches gave similar results (table 3). However, the round-off errors in the manual computations account for any difference in either computed head or

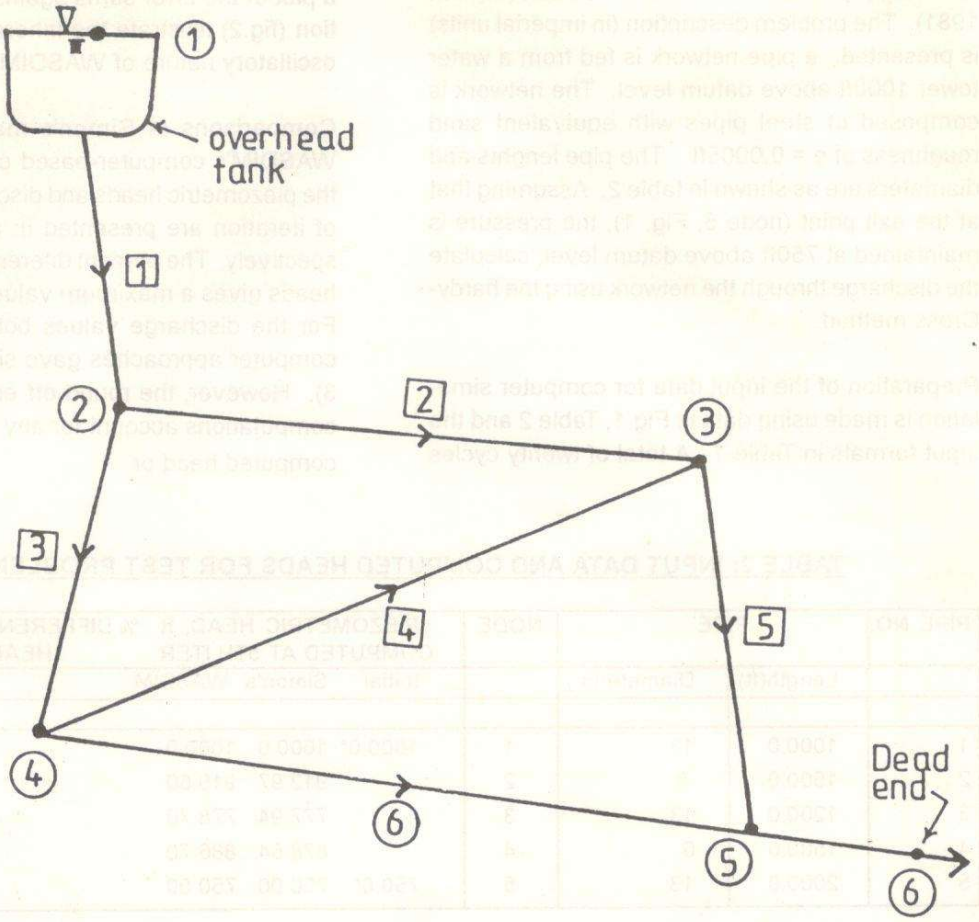
TABLE 2: INPUT DATA AND COMPUTED HEADS FOR TEST PROBLEM NO.1

PIPE NO.	PIPE		NODE	PIEZOMETRIC HEAD, ft COMPUTED AT 5TH ITER			% DIFFERENCE IN COMPUTED HEAD AT 5TH ITER
	Length(ft)	Diameter(in)		Initial	Simon's	WASDIM	
1	1000.0	13	1	1000.0*	1000.0	1000.0	0.0
2	1500.0	8	2	-	912.97	919.60	7.62
3	1200.0	13	3	-	777.94	778.70	0.34
4	1500.0	6	4	-	878.64	886.70	6.64
5	2000.0	13	5	750.0*	750.00	750.00	0.0

* Specified heads and should remain fixed at all times while the unspecified heads are computed.

TABLE 3: COMPUTED DISCHARGE VALUES ALONG THE NETWORK FOR TEST PROBLEM NO. 1

PIPE NO.	COMPUTED DISCHARGE VALUES, CFS			% IMPROVEMENT USING WASDIM @ 5TH & 20TH ITER
	SIMON @ 5TH ITER	WASDIM		
		@ 5TH ITER	@20TH ITER	
1	18.26	17.50	14.87	-17.69
2	4.96	5.10	5.45	6.42
3	10.52	10.12	9.24	-9.52
4	1.84	2.08	3.32	37.34
5	7.29	7.23	7.75	6.71
6	5.90	6.13	6.78	9.59



KEY

(1) Denotes node number or junction number.

[1] Denotes pipe length designation or line no.

→ Direction of flow based on initially assumed piezometric heads

Fig.1: Idealized Water Supply Distribution Network Depicting A Grid System only.

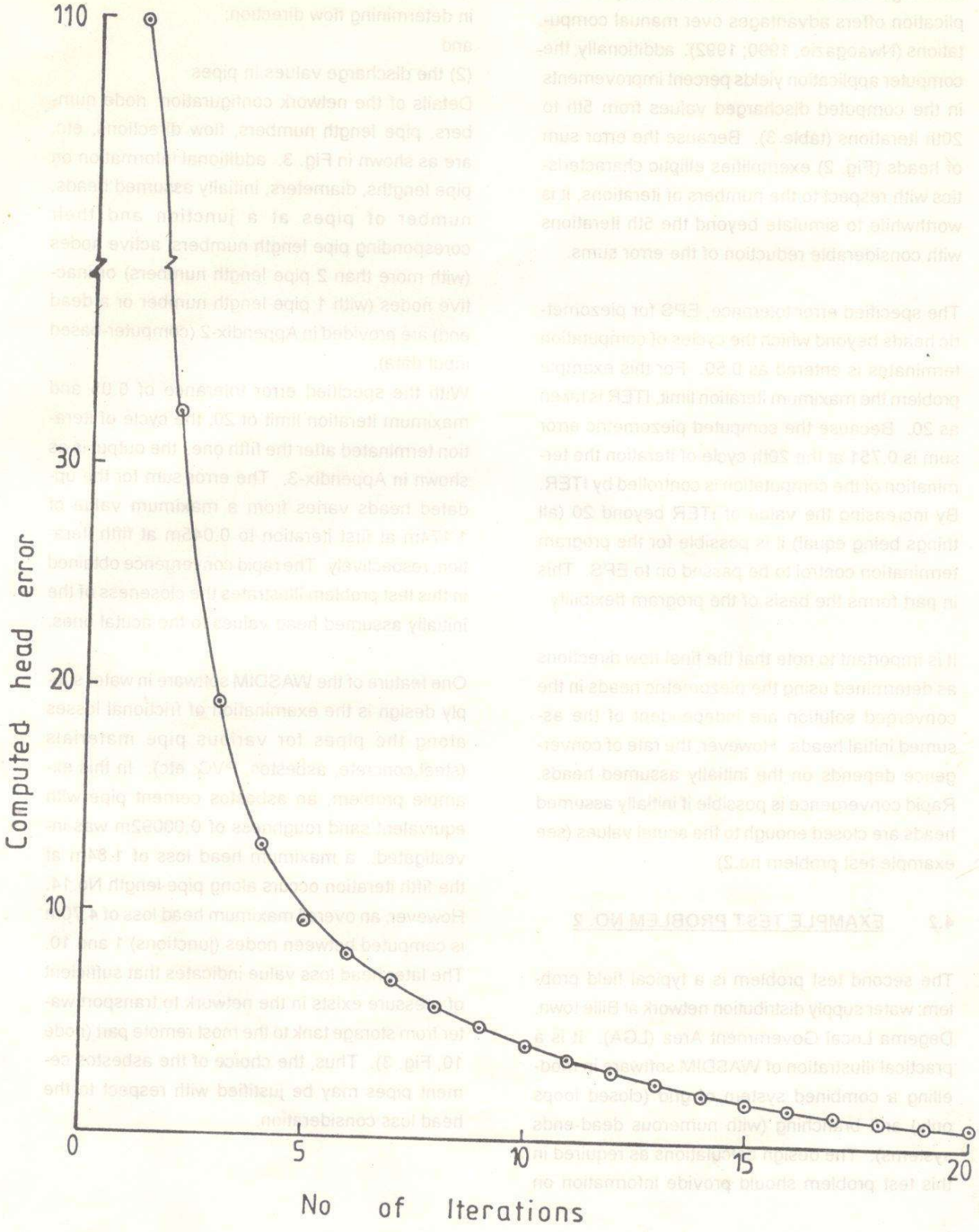


Fig. 2 : Computed piezometric head error sum at junctions against corresponding iteration number.

discharge values. This is one area computer-application offers advantages over manual computations (Nwaogazie, 1990; 1992). additionally, the computer application yields percent improvements in the computed discharged values from 5th to 20th iterations (table 3). Because the error sum of heads (Fig. 2) exemplifies elliptic characteristics with respect to the numbers of iterations, it is worthwhile to simulate beyond the 5th iterations with considerable reduction of the error sums.

The specified error tolerance, EPS for piezometric heads beyond which the cycles of computation terminates is entered as 0.50. For this example problem the maximum iteration limit, ITER is taken as 20. Because the computed piezometric error sum is 0.751 at the 20th cycle of iteration the termination of the computation is controlled by ITER. By increasing the value of ITER beyond 20 (all things being equal) it is possible for the program termination control to be passed on to EPS. This in part forms the basis of the program flexibility.

It is important to note that the final flow directions as determined using the piezometric heads in the converged solution are independent of the assumed initial heads. However, the rate of convergence depends on the initially assumed heads. Rapid convergence is possible if initially assumed heads are closed enough to the acutal values (see example test problem no.2)

4.2 EXAMPLE TEST PROBLEM NO. 2

The second test problem is a typical field problem: water supply distribution network at Bille town, Degema Local Government Area (LGA). It is a practical illustration of WASDIM software in modelling a combined system of grid (closed loops only) and branching (with numerous dead-ends systems). The design calculations as required in this test problem should provide information on the follqwing:

(1) heads at junctions which in turn are employed in determining flow direction;

and

(2) the discharge values in pipes

Details of the network configuration: node numbers, pipe length numbers, flow directions, etc. are as shown in Fig. 3. additional information on pipe lengths, diameters, initially assumed heads, number of pipes at a junction and their coresponding pipe length numbers, active nodes (with more than 2 pipe length numbers) or inactive nodes (with 1 pipe length number or a dead end) are provided in Appendix-2 (computer-based input data).

With the specified error tolerance of 0.05 and maximum iteration limit of 20, the cycle of iteration terminated after the fifth one. the output is as shown in Appendix-3. The error sum for the updated heads varies from a maximum value of 1.174m at first iteration to 0.045m at fifth iteration, respectively. The rapid convergence obtained in this test problem illustrates the closeness of the initially assumed head values to the acutal ones.

One feature of the WASDIM software in water supply design is the examination of frictional losses along the pipes for various pipe materials (steel,concrete, asbestos, PVC, etc). In this example problem, an asbestos cement pipe with equivalent sand roughness of 0.00092m was investigated. a maximum head loss of 1.84m at the fifth iteration occurs along pipe length No.14. However, an overall maximum head loss of 4.70m is computed between nodes (junctions) 1 and 10. The later head loss value indicates that sufficient of pressure exists in the network to transport water from storage tank to the most remote part (node 10, Fig. 3). Thus, the choice of the asbestos cement pipes may be justified with respect to the head loss consideration.

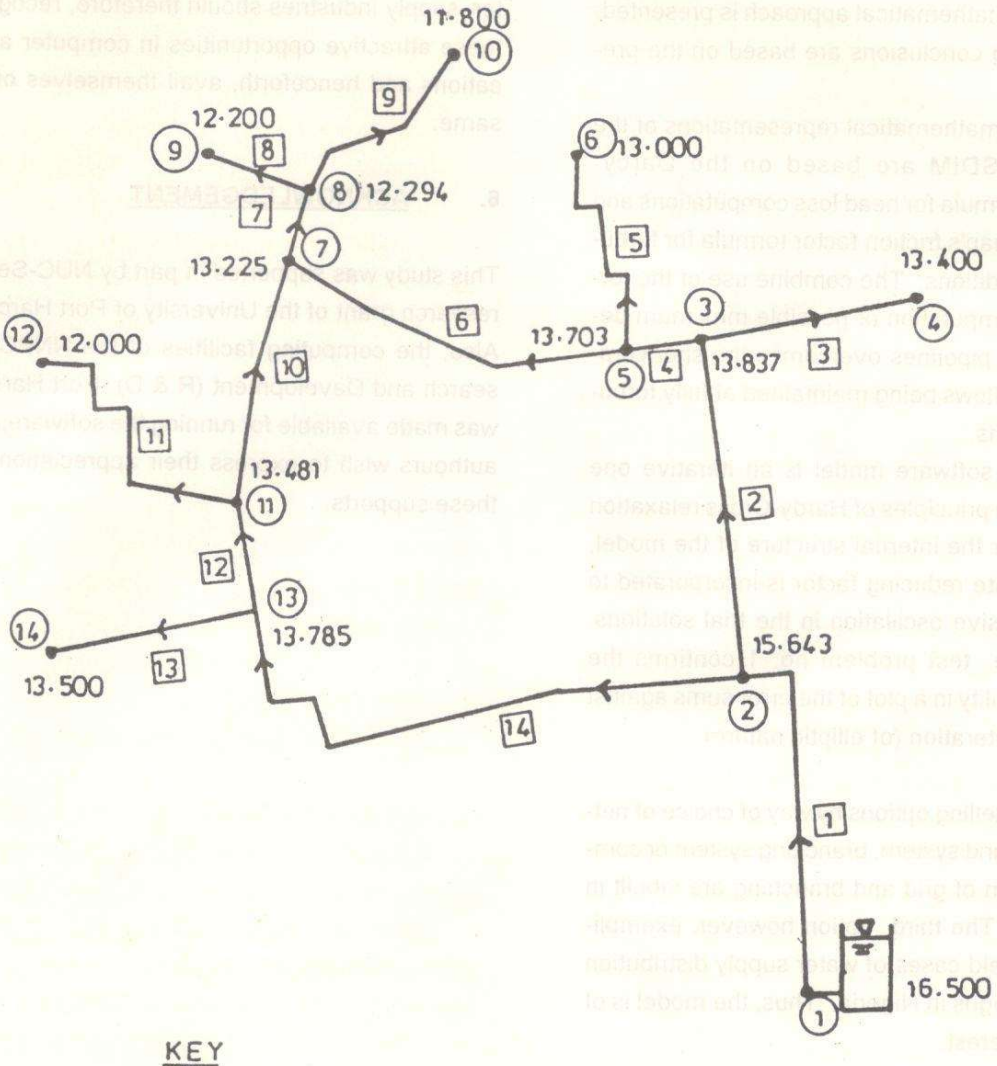


FIG. 3 WATER SUPPLY DISTRIBUTION NETWORK AT BILLE, DEGEMA L.G.A.

5. CONCLUSION

A water supply piping network model, utilizing computer-aided mathematical approach is presented. The following conclusions are based on the presentations:

(i) The mathematical representations of the model, WASDIM are based on the Darcy-Weisbach formula for head loss computations and on Von-Karman's friction factor formula for turbulent flow conditions. The combine use of the formulas for computation of possible maximum design flows in pipelines overcomes the shortcomings of such flows being maintained at fully turbulent conditions.

(ii) The software model is an iterative one based on the principles of Hardy-Cross relaxation method. For the internal structure of the model, an appropriate reducing factor is incorporated to avoid excessive oscillation in the trial solutions. An example test problem no. 1 confirms the model's stability in a plot of the error sums against numbers of iteration (of elliptic nature).

(iii) Modelling options by way of choice of network types: grid system, branching system or combined system of grid and branching are inbuilt in the model. The third option however, exemplifies many field cases of water supply distribution network designs in Nigeria. Thus, the model is of practical interest.

(iv) The example test problem no. 2 on Bille town, Degema LGA water supply design is a typical case of field problem. And the test problem demonstrates the utility of the model in selecting appropriate pipe material based on head loss consideration.

(v) Implementation of WASDIM software is simple and direct, requiring minimum input data and thus its use should be encouraged. Computer-aided water supply piping network analysis offers numerous advantages particularly, in determining maximum design flows in pipes for various pipe sizes and complex network of large size with high accuracy and speed. The Nigerian water supply industries should therefore, recognize these attractive opportunities in computer applications and henceforth, avail themselves of the same.

6. ACKNOWLEDGEMENT

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APPENDIX -1: COMPUTER PRORAM LISTING (WASDIM SOFTWARE)

```
C     * * * * * * * * * * * * * * * * * * * *
C                      MAIN PROGRAM
C          DESIGN OF WATER SUPPLY PIPING SYSTEM
C     USING THE CONVETIONAL APPROACHES OF DARCY-WEISBACH'S
C     HEADLOSS COMPUTATION & VON-KARMAN'S FRICTION FACTOR FOR
C        TURBULENT FLOW.  THE MODEL IS A RELAXATION  ONE OF
C     HARDY-CROSS TYPE WITH OPTIONS FOR METRIC OR IMPERIAL
C     SYSTEM OF UNITS.  TYPES OF NETWORK ANALYSIS INCLUDES:
C     GRID SYSTEM, BRANCHING SYSTEMS OR  COMBINED SYSTEM.
C                      DEVELOPED BY:
C                ENGR. DR. IFY L. NWAOGAZIE, MNSE
C                        MARCH, 1992.

      DIMENSION COVEY (50), DETH (50), DELQ (50), DMETR (50)
     1 HEAD (50),          HEAD 2 (50), Q (50), IDHEAD (50,2), IDNUM (50,5).
     2.NNODE (50),  PLEN (50), HLOSS (50),      NODFX (50), HDLX (50),
     3.ADJS (50)
      CHARACTER IFILE * 72, OFILE *72, TITLE *72, UNITS *4 DATA LR, LW, LDIN, NHD/5, 6, 50. 3/

C     WRITE  (*,*)' PLEASE ENTER INPUT FILE NAME'
      READ (*,1000) IFILE
      OPEN (LR, FILE  =  IFILE, STATUS ='OLD')
      WRITE (*,*)  ' PLEASE ENTER OUTPUT FILE NAME'
      READ (*1000)  OFILE
      OPEN (LW, FILE = O FILE, STATUS = NEW' )

C  -- ENTER TITLE YOU WISH TO BE PRINTED
C     READ (LR, 1000) TITLE
     -- ENTER SYSTEM OF UNITS: METRIC OR IMPERIAL.
      READ (LR, 1015) UNITS
      IF (UNITS. EQ.' IMPE' .OR. UNITS EQ. 'METR') GO TO 100
      WRITE (LW, 1032)
      STOP

C  -- INPUT TOTAL NO. OF PIPE LENGTHS, NODAL POINTS/JCTNS &
     ELAPSED INTRATION NO, BEFOR PRINTING
  100 READ (LR, 1010) NUMP, NUMJCN, JPRNT.

C --  INPUT RELATIVE ROUGHNESS FOR PIPE MATERIAL, SPECIFIED
      ERROR TOLERANCE & MAX. INERATION LIMIT.
     READ (LR,  1020) RR,  EPS, ITER

C  -- INPUT PIPE LENGTHS, DIAMETERS &
C     NODE NOS.  AT BOTH ENDS OF PIPE
C     LENGHTH
      DO 150 L  = 1, NUMP
  150 READ (LR, 1020) PLEN (L), DMETR (L), (IDHEAD (L,K) K=1, NHD)

C  -- INPUT ASSUMED HEAD VALUES AT SPECIFIED NODES.
     READ (LR, 1030) HEAD (K), K = 1, NUMJCN)
```

```
      --INPUT TOTAL NO. OF PIPE LENGTHS AT EACH JUNCTION
      READ (LR, 1010) (NNODE (K) ,K-1,NUMJCN)

C --  INPUT FLOW DESIGNATION FOR EACH PIPE USING INDEX NO.
      ASSIGNED TO PIPE: +V  FOR INFLOW & -VE FOR OUTFLOW
C     AT JUNCTION
      DO 200 L  =  1,  NUMJCN
      LCHK  = NNODE (L)
200   READ (LR, 1010) (IDNUM (L,K) ,K=1, LCHK)
C
C  -- SPECIFY JUNCTION POINTS WITH KNOWN HEADS OR FOR WHICH NO ADJUSTMENTS WILL
      BE MADE: INPUT 0 FOR YES & 1 FOR NO ADJUSTMENTS
      READ (LR,1010) (NODFX (K), K=1, NUMJCN)

      -- ECHO-CHECK INPUT DATA
      WRITE (LW,,1035)
      WRITE (LW,1038) TITLE

      WRITE (LW,1040) RR, EPS, ITER
      WRITE (LW,1050)
      CALL WRITE 1 (PLEN, NUMP)
      WRITE (LW,1060)
      CALL WRITE1 (DMETR, NUMP)
      DO 260 K = 1, NUMJCN
260   HEAD2 (K) = HEAD(K)
      WRITE (LW,1070)
      -- INITIALIZE FLOW DIRECTION ADJUSTER
      DO 270 J = 1, NUMP
270   ADJS(J) = 1.0
      IF (UNITS.EQ.'IMPE') G = 32.2
      IF (UNITS.EQ.'METR') G = 9.81

      -- LOOP  FOR  MAXIMUM ITERATION LIMIT
      JCOUNT = 0
      DO 800 LL = 1, ITER
      SDELH = 0.0
      -- COMPUTE HEADLOSS ALONG EACH PIPE LENGTH
      DO 280 L = 1 NUMP
      M1 = IDHEAD (L,1)
      M2 = IDHEAD (L,2)
      HDLX (L) = HEAD2 (M1) - HEAD 2  (M2)
      IF (HDLX (L) .LT. 0.0) ADJS(L) = -1.0
      HLOSS(L) = ABS (HDLX(L))
280   IF (HLOSS (L) .EQ. 0.0) HLOSS(L) = 0.0001

      -- COMPUTE CONVEYANCE & DISCHARGE VALUES FOP PIPE LENGTHS
      USING DARCY-WEISBACHI & VON KARMAN FRICTION FORMULAS.
      DO 300 K=1,NUMP
      COVEY (K)=0.25* (22./7.) *  SQRT (2.*G)) * 2.*LOG I10
      1 (DMETR (K)/RR)+1.14) *DMETR (K) **2.5
      SAV = PLEN (K)/COVEY (K) **2
300   Q (K) = SQRT (HLOSS (K)/SAV) * ADJS (K)
```

```
   --APPLY FLOW CONTINUITY EQ. AT EACH JUNCTION POINT.
   DO 500 L=1, NUMJCN
   SUMQ = 0.0
   ADJ = 1.0
   LAD = NNODE (L)
   LMT = NODFX (L)
   IF (LMT.EQ.1) GO TO 500
   DO 400 K = 1, LAD
   JCK = IDNUM (L,K)
   IF (JCK .LT. 0) GO TO 350
   NN = JCK
   GO TO 380
350  ADJ = -1.0
   NN = -JCK
380  SUMQ = SUMQ + ADJ*Q(NN)
400  CONTINUE
   DELQ (L) = SUMQ
500  CONTINUE

   --COMPUTE CHANGE IN HEAD, DELTA-H CORRESPONDING TO DELTA-Q; UPDATE HEADS &
     SUM DELTA-H FOR INTERNAL JUNCTIONS.

   DO 700 L=1, NUMJCN
   SQOVH = 0.0
   LAD = NNODE (L)
   LMT = NODFX (L)
   IF (LMT. EQ. 1) GO TO 700
   DO 600 K = 1, LAD
   MM = IDNUM (L,K)
   IF (MM = (MM LT. 0) MMM = MM

600  IF (HLOSS (MM) .NE. O.) SQOVH = SQOVH + ABS (Q(MM)/HLOSS(MM))
   IF (SQOVH .EQ. 0.0) GO TO 620
   DELH(L) = DELQ(L)/SQOVH
   GO TO 630
620  DELH(L) = 0.0
630  HEAD2(L) = HEAD2(L) + DELH(L)
   SDELH = SDELH + ABS(DELH(L))
700  CONTINUE

   --CHECK FOR CONVERGENCE & PRINT OUTPUT AT SPECIFIED ITERATION &/OR AT CONVER-
     GENCE.
   JCOUNT = JCOUNT + 1
   IF (LL.EQ.1) GO TO 780
   IF (LL .GE. ITER .OR. SDELH .LE. EPS) GO TO 850
   IF (JCOUNT - JPRNT) 800,780,780
780  CALL WRITE(NUMJCN,NUMP,LL,HEAD,
     HEAD2,H LOSS,Q ,LDIN, SDELH,1)
     JCOUNT = 0
800  CONTINUE
   GO TO 880
850  CALL WRITE2 (NUMJCN,NUMP,LL,
     HEAD,HEAD2,HLOSS,Q,LDIN,SDELH,2)
```

```
 880  CONTINUE
 ----- FORMAT STATEMENTS
 1000FORMAT (A)
 1010FORMAT (BI10)
 1015FORMAT (A4)
 1020FORMAT (2F10.4,3I10)
 1030FORMAT (6F10.4)
 1032 FORMAT (//1X,70('*')/5X,'INPUT DATA IS ENTERED INCORRECTLY: '
    1 'CORRECT INPUT IS EITHER IMPERIAL OR METRIC'/1X,70('*'))
 1035FORMAT (////3X,72('=')/20X,'HARDY-CROSS PIPE NETWORK ANALYSIS:'
    1 //5X,'USING DARCY-WEISBACH HYDRAULIC FORMULA & VON KARMAN'
    2 ' FRICTION FORMULA'/25X,'FORTURBULENT FLOW'//3X,72('='))
 1038FORMAT (//3X,A/3X,72('-'))
 1040FORMAT (/////8X,21('=')/8X,'INPUT DATA'8X,
    1 21('=')//8X,'RELATIVE ROUGHNESS FOR PIPE',
    2 'MATERIAL = ',E11.4/08X,' SPECIFIED ERROR TOLERANCE',
    3 '=',E11.4/08X,'MAXIMUM ITERATION LIMIT = ', I5)
 1050FORMAT(////32X,'PIPE LENGTHS' /32X,12('=')/9X,
    1 'INDEX',5X,'LENGTH',5X,'INDEX',5X,'LENGTH',5X,'INDEX',
    2 5X,'LENGTH'/9X,5('='),5X,6('='),
    3 5X,5 ('='),5X,6('='),5X,5('='),5X,6('='))
 1060FORMAT(////31X,'PIPE DIAMETERS'/31X,14('=')/9X,'INDEX',
    1 3X,' DIAMETER',5X,'INDEX',3X,'DIAMETER',5X,'INDEX',3X,
    2 'DIAMETER',/9X,5('='),3X,8('='),
    3 5X,5 ('='),3X,8('='),5X,('='),3X,8('='))
 1070FORMAT (/////7X,32('*')//8X,'COMPUTED RESULTS',
    1//7X,32('*'))
 STOP
 END

 SUBPROGRAM FOR OUTPUTTING INPUT DATA
 SUBROUTINE WRITE1 (SAVE,LMX)

    DIMENSION SAVE (LMX)
    DO 100 M = 1, LMX, 3
    JHK = MINO (M+2, LMX)
 100  WRITE (6,200) (J, SAVE(J), J=M, JHK)
 200  FORMAT (8X,I5,2X,E11.4,3X,I5,2X,E11.4,3X,I5,2X,E11.4)
      RETURN
      END

 SUBPROGRAM FOR OUTPUTTING COMPUTED RESULTS.
 SUBROUTINE WRITE2 (NUMJCN,NUMP,LL,HEAD,HEAD2,HLOSS,1 QX,LD,SDELH,JSWTCH)

 DIMENSIONHEAD (LD),HEAD2(LD),QX(LD),HLOSS(LD)
 DATA LW/6/
 100  WRITE (LW,400)LL
      CALL WRITE1 (QX,NUMP)
      WRITE (LW,220)LL
      CALL WRITE1 (HEAD2,NUMJCN)
      WRITE (LW,450) SDELH
      IF (JSWTCH - 1) 500,500,180
 180  WRITE (LW,230)LL
      CALL WRITE1 (HLOSS,NUMP)
      WRITE (LW,250)LL
```

```
      DO 200 NM = 1,NUMJCN
  200 WRITE (LW,300)NM, HEAD (NM), HEAD2 (NM)
  220 FORMAT (/////  32X,'CURRENT HEADS'/32,X 13('=')/24X,
     1 'ELAPSED NUMBER OF ITERATIONS = ',13/24X,
     2 34('=')/10X,'NODE',3X,'CRNT,HEAD',5X,'NODE',3X,
     3 'CRNT.HEAD',5X,'NODE',4X,'CRNT.HEAD',
     4 /10X,4('='),3X,9('='),5X,4('='),3X,9('='),
     5 5X,4('='),4X,9('='))
  230 FORMAT (/////30X,'HEAD LOSS VALUES'/30X,16('=')/24X,
     1 'ELAPSED NUMBER OF ITERATIONS = ',I3/24X,
     2 34('=')/9X,'INDEX',3X,'HEAD LOSS',4X,'INDEX',2X,
     3 'HEAD LOSS',5X,'INDEX',3X,'HEAD LOSS',
     4 /9X,5('='),3X,9('='),4X,5('='),2X,9('='),
     5 5X,5('='),3X,9('='))
  250 FORMAT (/26X,'ELAPSED NUMBER OF ITERATIONS = ',I3/26X,
     1 34('=')/20X,' JUNCTIONS',8X,'GUESSED 'HEAD',5X,'CURRENT',
     2 ' HEAD'/20X,9('='),8X,13('='),5X,12('='))
  300 FORMAT (/20X,I5,12X,E11.5,5X,E11.5)
  400 FORMAT (/////30X,'DISCHARGE VALUS'/30X,16('=')/24X,
     1 'ELAPSED NUMBER OF ITERATIONS = ',I3/24X,
     2 34 ('=')/09X,'INDEX',3X,'DISCHARGE',4X,'INDEX',2X,
     3 DISCHARGE';5X,'INDEX',3X 'DISCHARGE',
     4 /O9X,5('='),3X,9('='),4X,5('='),2X,9('='),
     5 5X,5 ('='),3X,9('='))
  450 FORMAT (////10X,39('=')/10X,'COMPUTED ERROR ON DELTA-H =',
     1 E11.5/9X,39('=')//)
  500 RETURN
      END
```

Appendix-2: COMPUTER - BASED INPUT DATA FOR TEST ROGRAM NO.2

PRELIMINARY DESIGN OF WATER SUPPLY DISTRIBUTION FOR BILLE, DEGEME LGA METR

14	14	4			
.0009144	0.05	20			
95.9	0.150	1	2		
96.9	0.100	2	3		
52.7	0.075	3	4		
12.6	0.100	3	5		
136.1	0.075	5	6		
76.8	0.100	5	7		
46.6	0.100	7	8		
20.4	0.075	8	9		
40.7	0.100	8	10		
68.2	0.100	11	7		
157.6	0.075	11	12		
27.7	0.100	13	11		
50.9	0.075	13	14		
96.4	0.100	2	13		
16.50	15.00	14.00	13.40	13.80	13.00
12.80	12.60	12.20	11.80	13.60	12.00
14.00	13.50				
1	3	3	1	3	1
3	3	1	1	3	1
3	1				
1	0	0			
1	-2	-14			
2	-3	-4			
3	0	0			
4	-5	-6			
5	0	0			
6	10	-7			
7	-8	-9			
8	0	0			
9	0	0			
12	-10	-11			
11	0	0			
14	-12	-13			
13	0	0			
1	0	0	1	0	1
0	0	1	1	0	1
0	1				

APPENDIX- 3: COMPUTER-BASED OUTPUT RESULTS FOR TEST PROBLEM NO.2

HARDY CROSS PIPE NETWORK ANALYSIS:

USING DARCY-WEISBACH HYDRAULIC FORMULA & VON KARMAN FRICTION FORMULA FOR TURBULENT FLOW

PRELIMINARY DESIGN OF WATER SUPPLY DISTRIBUTION FOR BILLE, DEGEMA LGA

INPUT DATA

RELATIVE ROUGHNESS FOR PIPE MATERIAL = .9144E-03
SPECIFIED ERROR TOLERANCE = .5000E-01
MAXIMUM ITERATION LIMIT = 20

PIPE LENGTHS

INDEX	LENGTH	INDEX	LENGTH	INDEX	LENGTH
1	.9590E+02	2	.9690E+02	3	.5270E+02
4	.1260E+02	5	.1361E+03	6	.7680E+02
7	.4660E+02	8	.2040E+02	9	.4070E+02
10	.6820E+02	11	.1576E+03	12	.2770E+02
13	.5090E+02	14	.9640E+02		

PIPE DIAMETERS

INDEX	DIAMETER	INDEX	DIAMETER	INDEX	DIAMETER
1	.1500E+00	2	.1000E+00	3	.7500E-01
4	.1000E+00	5	.7500E-01	6	.1000E+00
7	.1000E+00	8	.7500E-01	9	.1000E+00
10	.1000E+00	11	.7500E-01	12	.1000E+00
13	.7500E+01	14	.1000E+00		

COMPUTED RESULTS

DISCHARGE VALUES

ELAPSED NUMBER OF ITERATIONS = 1

INDEX	DISCHARGE	INDEX	DISCHARGE	INDEX	DISCHARGE
1	.2113E-01	2	.5834E-02	3	.2842E-02
4	.7235E-02	5	.2042E-02	6	.6553E-02
7	.3762E-02	8	.3730E-02	9	.8051E-02
10	.6219E-02	11	.2684E-02	12	.6901E-02
13	.2640E-02	14	.5849E-02		

CURRENT HEADS

ELAPSED NUMBER OF ITERATIONS = 1

NODE	CRNT. HEAD	NODE	CRNT. HEAD	NODE	CRNT. HEAD
1	.1650E+02	2	.1537E+02	3	.1391E+02
4	.1340E+02	5	.1377E+02	6	.1300E+02
7	.1307E+02	8	.1239E+02	9	.1220E+02
10	.1180E+02	11	.1353E+02	12	.1200E+02
13	.1387E+02	14	.1350E+02		

COMPUTED ERROR ON DELTA-H = .11742E+01

DISCHARGE VALUE

ELAPSED NUMBER OF ITERATIONS = 5

INDEX	DISCHARGE	INDEX	DISCHARGE	INDEX	DISCHARGE
1	.1609E-01S	2	.7788E-02	3	.2453E-02
4	.5904E-02	5	.1929E-02	6	.4585E-02
7	.8105E-02	8	.1827E-02	9	.6339E-02
10	.3539E-02	11	.2584E-02	12	.6028E-02
13	.2006E-02	14	.7935E-02		

CURRENT HEADS

ELAPSED NUMBER OF ITERATIONS = 5

NODE	CRNT. HEAD	NODE	CRNT. HEAD	NODE	CRNT. HEAD
1	.1650E+02	2	.1564E+02	3	.1384E+02
4	.1340E+02	5	.1370E+02	6	.1300E+02
7	.1322E+02	8	.1229E+02	9	.1220E+02
10	.1180E+02	11	.1348E+02	12	.1200E+02
13	.1379E+02	14	.1350E+02		

COMPUTED ERROR ON DELTA-H = .42950E-01

HEAD LOSS VALUES

ELAPSED NUMBER OF ITERATIONS = 5

INDEX	HEAD LOSS	INDEX	HEAD LOSS	INDEX	HEAD LOSS
1	.8705E+00	2	.1782E+01	3	.4472E+00
4	.1332E+00	5	.7140E+00	6	.4896E+00
7	.9284E+00	8	.9599E-01	9	.4960E+00
10	.2591E+00	11	.1483E+01	12	.3052E+00
13	.2886E+00	14	.1841E+01		

ELAPSED NUMBER OF ITERATIONS = 5

JUNCTIONS	GUESSED HEAD	CURRENT HEAD
1	.16500E+02	.16500E+02
2	.15000E+02	.15643E+02
3	.14000E+02	.13837E+02
4	.13400E+02	.13400E+02
5	.13800E+02	.13703E+02
6	.13000E+02	.13000E+02
7	.12800E+02	.13225E+02
8	.12600E+02	.12294E+02
9	.12200E+02	.12200E+02
10	.11800E+02	.11800E+02
11	.13600E+02	.13481E+02
12	.12000E+02	.12000E+02
13	.14000E+02	.13785E+02
14	.13500E+02	.13500E+02