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Optimal Design of Sewer Networks Using Genetic Algorithm

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By

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بسم الله الرحمن الرحيم

﴿قَالُوا سُبْحَانَكَ لَا عِلْمَ لَنَا إِلَّا مَا عَلَّمْتَنَاۖ
إِنَّكَ أَنْتَ الْعَلِيمُ الْحَكِيمُ﴾

صدق الله العلي العظيم

سورة البقرة/أيه (٣٢)

Dedication

I dedicate this humble work

To my father and mother, who gave me affection and love; I say to them: you gave me life, hope, and the emergence of a passion for learning and knowledge;

To my brothers, my sister, my family members, my friends and the martyrs of Iraq;

Also, To everyone who taught me a character and became a lamp illuminates the road ahead of me.

CERTIFICATION

I certify that this thesis titled ***"Optimal Design of Sewer Networks Using Genetic Algorithm"***, was prepared by ***"Safa'a Sabry Mohammed"*** under my supervision at the Civil Engineering Department, Kerbala University as a partial requirement for the degree of Master of Science in Civil Engineering (Infrastructure).

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Abstract

Sewerage pipeline networks are one of the essential infrastructures in modern cities serving domestic housing, manufacturing plants, hospitals, schools and other vital utility activities by disposing unwanted wastewater and preventing contamination of the water environment. In recent years, the global population has increased significantly in parallel with commercial and industrial activities. This has led to an increase in water consumption and consequential increases in the quantity of the wastewater produced, meaning that there is a need to construct new sewer networks in various places.

This research illustrates the application of a new hybrid Genetic Algorithm with Heuristic Programming (GA-HP) technique in order to find the optimal design for sewer networks. The objective was to minimize the construction cost function, which is represented by excavation depth and pipe diameter. The proposed GA-HP model has fulfilled the optimum design task into two stages. Firstly, the Genetic Algorithm (GA) was applied to obtain the diameters needed for the preliminary design of the network. Secondly, Heuristic Programming (HP) preliminary designs were used to obtain the optimal slope for those diameters and to determine other characteristics such as the velocity, relative depth of water, excavation depths and total cost of the network.

A MATLAB code was used to perform the GA-HP optimization model. The performance of eight different selection methods (RWS, RRWS, LRS, ERS, TRS, SUS, TOS and RMS), seven different crossover methods (One-point, N-point, Uniform, Flat Arithmetic, Intermediate and Shuffle), and different population sizes (50,100, 200, 300 and 400), have been examined using the proposed model to determine their impact on convergence behaviour. Tournament Selection method (TOS) and the One-point Crossover method proved to be the most efficient in relation to the optimal design. The proposed GA-HP model is tested using some benchmark problems of sewer networks from the literature .The results show that the GA-HP model is superior to all previous methods.

In order to ensure the efficiency of the proposed GA-HP model for the design of large networks, it was examined with two case studies located in Karbala Holy city, and compared the cost of the manual designs with the designs obtained from the present model for networks. The saving percentages were (28.1%) and (28.45%) for relatively small and large networks, respectively.

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List of symbols

Symbols	Description
ACO	Ant Colony Optimization
AGA	Adaptive Genetic Algorithm
BIE	Bounded Implicit Enumeration
CA	Cellular Automata
DP	Dynamic Programming
ERS	Exponential Ranking Selection
GA	Genetic Algorithm
HP	Heuristic Programming
LP	Linear Programming
LRS	Linear Ranking Selection
MIP	Mixed Integer Programming
MOGA	multi-objective Genetic Algorithm
NLP	Non-Linear Programming
QP	Quadratic Programming
RGA	Rebirthing Genetic Algorithm
RMS	Random Selection
RRWS	Rank Roulette Wheel Selection
RWS	Roulette Wheel Selection
SA	Simulated Annealing
SUS	Stochastic Universal Sampling
SWMM	Name of package program (Storm Water Management model)
TGA	Tree Growing Algorithm
TOS	Tournament Selection
TRS	Truncation Selection
TS	Tabo Search
PSO	Particle Swarm Optimization

CHAPTER ONE

Chapter One

Introduction

1.1. General

Population growth in cities and accompanied by urban, industrial and commercial expansion certainly requires thinking about the best methods to get rid of residues of used water for all public actions or resulting from rain-water and flood-water. This should be carried out in a healthy and safely way with lower costs. It had to be using sewage projects, which are considered in the present day of vital projects and necessary of urban, health and cultural, that made a study of this subject tangible significance, leading to the expansion of studies and research in this area.

Sewers play an important role in wet weather and wastewater management. Without efficient drainage, storm water may cause urban flooding with severe consequential problems, such as public inconvenience, economic and environmental damage, infectious disease, and even threat to public safety. Therefore, it is vital to maintain reliable performance of storm sewer systems. However, in the face of tight budgets and additional stringent regulations, sewer engineers are confronted with a significant challenge and urged to pursue cost-effective strategies for design, operation and management of sewers. This study will focus on the first of these issues, which is the cost-effective design of sewer networks.

Design of sewer projects, like all the major development work, requires a complex study takes into consideration all aspects of life and public activities in the area, in addition to air, geographical and other considerations.

Sewer systems are classified on the basis of moveable wastewater quality into two types: separate networks that transfer waste water and rainwater separately, combined networks whereby wastewater and rainwater are transferred together. Choosing the most suitable type for any region or city is based on various factor.

Hydraulic design of network depends primarily on calculation or estimation of the highest expected discharge during the design return period throughout the determination of the probability of incidence. This will be useful in the design of the network throughout finding diameters and slopes of pipes by using the hydraulic equations.

The choice of the sewer pipe layout in the network is an important factor in the design, which depends on several factors: topography of the area, which is the most important factor, location of treatment plant project for wastewater, and location of natural drainers for rain water that define the outlets of the network. Expert designer engineer can choose the pipes layout of sewer networks. However, experience alone is not sufficient to give the optimal choice for the diameters and slopes of network pipes that are designed based on the chosen layout. Moreover, the previous design methods were simple and rely on some hydraulic simplifications that could make the resulting designs are so far from the optimal. For example, excessive dimensions may entail high costs or may be inefficient, causing some bottlenecks and lead to material damage in the city.

So it may be used to engineer a number of design alternatives give him a chose the best, but the size of the massive calculations required by such designs imposes a limited number of attempts only compared to the large number of alternatives that can be designed any sewer network. Especially if these calculations are manual, these designs may make the engineer have to accept some simplifications. Therefore, any design accomplishes this way may stay far from optimal design.

1.2. State of problem

The cost of sewer networks design includes into two of the main costs are pipe diameter and excavation costs, which in addition, often create contradictory objectives in the design. Any decrease in pipe size is likely to result in an increase in pipe slope and subsequent excavation costs. In contrast, decreasing the excavation costs requires a modest slope for pipes, resulting in the need for pipes with a larger diameter to make the design workable. Therefore, finding an economical design for sewer networks requires an optimal balance between costs relating to excavation and pipe diameter, a difficult task for the design engineer to achieve.

1.3. Objectives

The main objectives of this study are to find optimal sewer design to minimize capital investment on infrastructure whilst ensuring a good system performance under specific design criteria by developing a new model for this purpose using a new technique hybridized the Genetic algorithm with Heuristic programming.

1.4. Methodology of the Current Study

The sequence steps have been followed to achieve the above objective:

1. Fieldwork:
    a. Selection the location case studies.
    b. Data collection and preparation which are included topographic maps, layout, ground elevation, manual design for networks of case studies, and data for the construction cost of networks.
    c. Derivation of cost function from data of the construction cost of sewer networks by regression analysis method with the SPSS program.

2. Theoretical:
    a. Formulation of objective function, and define the constraints and limitations for this objective function.
    b. Build GA-HP model by programming code in MATLAB, using Genetic Algorithm (GA) combined with Heuristic Programming (PH) within objective function and constrains.
    c. Developed the GA-HP model by using different selection and crossover methods for part Genetic Algorithm in this model.
3. Application the proposed model with two international problems and test different selection and crossover methods, to find any methods more effective and best-performing for the proposed model.
4. After Developing the proposed model, application it with two case studies in Karbala city, Iraq. The first case study has 90 pipes and 91 manholes, the second case study has 354 pipes and 355 manholes.

1.5. Layout of the thesis

- Chapter one describes the overview of sewer networks, state of problem, objective for research, the layout of dissertation and assumptions
- Chapter two reviews some of the recent work done on the optimization methods for optimal design of sewer networks.
- Chapter three describes the theory of sewer design includes the design period, flows estimation, and hydraulic equations. Also, it describes the theory of methods used in the model includes Heuristic Programming and Genetic Algorithms.
- Chapter four explains the methodology of the work through three points, objective function, problem constraints, and formulation of new techniques GA-HP model.

- Chapter five presents the cost equations, layout, characteristics, and constraints for every benchmark problems and cases study.
- Chapter six presents and discusses the results obtained from proposed GA-HP model.
- Chapter seven explains the main conclusions and recommendations for future work.

CHAPTER TWO

Chapter Two

Literature Review

This chapter aims at providing a systematic and up-to-date review of achievements in sewer optimization field. It also discussing problems and key issues in the context of future research needs in sewer optimization.

2.1. History

Since the first successful efforts to control the flow of water were probably made in Mesopotamia and Egypt, where the remains of the ancient irrigation work still exist. The use of drainage systems by humans has a long history dating back to the early third millennium B.C. during the Indus civilization. Not far behind were the Mesopotamians (Adams, 1980).

2.2. Optimum solution methods for sewer networks

A great deal of researchers studied sewer networks in different direction and methods. Some of them studied the subject of analysis and design of sewer networks in general, while other tried to investigate particular problems in design or find the optimal designs using different optimization methods.

This chapter highlighted the most relevant research related to the present study, which were available during the research period. These researches have been classified depending on methods of optimization as follows:

2.2.1. Heuristic Programming (HP)

Heuristic programming (HP) gives the impression of artificial intelligence by solving problems using protocols or experience-based guidelines. Contrary to the principle of using strict algorithm-based computing, heuristics, in many key senses, is a shortcut to a quantified logic type of programming. It enables researchers to accomplish a goal by substituting certain types of machine-learning programs for logical algorithms.

(Liebman, 1967) suggested a heuristic method for optimization the layout of a sewer system assuming fixed size diameters. He identified factors involved in finding the optimal layout of a network by topography of area that the network is to be implemented, network outlet location, direction of flow, and detailed map of the area for which the network is to be designed contains (location of streets and street intersections). The best layout is found by a search procedure. At each step, one branch of the network is changed. The change is retained if it results a decrease in the cost. The method suffers from several shortcomings in which the most important one is that the network is not designed hydraulically, and therefore, may not be feasible.

(Charalambous and Elimam, 1990) employed Heuristic Algorithm to design sewer networks that can handle the introduction of lift stations and the use of standard diameters. They used either the Manning or the modified Hazen-Williams hydraulic equation in the proposed model. They found that the Heuristic Algorithm provided good and logical (rather than optimal) designs of sewer networks. They also found that HP provides the flexibility for altering design parameters throughout avoiding the tedious tasks of performing the required engineering computations in choosing standard pipe diameters and their corresponding slopes.

2.2.2. Linear Programming (LP)

Linear programming (LP) is an optimization technique applicable for the solution of problems in which the objective function and constraints appear as a linear function of the decision variables.

(Deininger, 1966, Dajani et al., 1972) used Linear Programming (LP) and Separable-Convex Linear Programming, respectively, to find the optimum design of wastewater collection systems.

(Fisher et al., 1971) applied Integer Linear Programming methods to determine continuous pipe diameters for very small networks, with full flow condition and using Manning formula. They concluded that the optimization technique as applied to the selection of pipe sizes and slopes cannot be considered as substantial improvement with respect to conventional methods because the uncertainties involved in the determination of the objective function, further investigations are necessary to improve the technique of sewer design, but they should be aimed at deviating from the conventional principle of considering the actual transient flow situation as a series of steady-state conditions.

(Dajani and Hasit, 1974) used LP optimization method to solve their network design problem. They linearized their non-linear objective function in order to obtain a linear numerical solution for the problem using ‘piecewise linearization technique’. Three alternative formulation of the drainage network design problem were presented. The first formulation assumes both full-conduit flow and continuum of pipe sizes, where solved it by using Separable-Convex variation of Linear Programming. The second formulation maintains the full-flow assumption and feasible pipes sizes to discrete, commercially available diameters. The third formulation allows partial flow and discrete diameters, where solved it by using Separable-Convex and Mix-Integer of Linear Programming. They found out that lowest cost is obtained in the first formulation.

(Dajani et al., 1977) presented three alternative mathematical programming formulations: Separable Convex Linear, Dynamic and Geometric Programming to optimize the design of an existing layout (i.e.

diameters, elevations, and slopes). In the first model, they used Separable Convex Linear Programming, with full flow condition and using Manning formula. They concluded its main advantage of Separable Programming was the flexibility with respect to design criteria, objective functions and topographic conditions. On other hand, they found that the major disadvantage was its solution set contains continuous pipe sizes which are not commercially available.

(Elimam et al., 1989) applied linearized Linear Programming and Heuristics to design large-size networks (pipes sizes diameter and slope). Their approach provides continuous pipe diameters, with partial flow condition and using modified Hazen-Williams formula. They concluded that the developed model had been extensively and successfully used to design several large sewer networks.

(Swamee and Sharma, 2013) used (LP) technique for the estimation of pipe diameters and sewer depths. They used the Darcy-Weisbach formula as the resistance equation and commercially available pipe diameters directly in the problem formulation, without transforming nonlinear objective function or constraint equations into linear functions. They also incorporated commercially available pipe sizes directly in the problem formulation. Furthermore, they used the commercial sewer pipe sizes directly in the design of sewer system, which eliminates the problem of rounding off the estimated pipe sizes to the nearest commercial sizes as required in some optimization techniques, which forfeits the purpose of system optimization to a large extent. They focused equally on economic considerations and hydraulic feasibility and moving away from conventional design guidelines based only on self-cleaning velocity concepts for a node to node sewer link hydraulic design.

(Safavi and Geranmehr, 2016) proposed the Mixed-Integer Linear Programming (MILP) for optimizing sewer networks with given layout by using the Manning formula and a fast, robust mathematical method. They defined the objective function as the sum of the costs for pipe purchase, earthwork and pipe-installing, and manhole construction expressed in linear terms and subjected to minimum and maximum allowable slopes, velocities, and relative depths for both minimum and maximum sewage discharge rates in each pipe. They also transformed their non-linear constraints into the linear format. They concluded that MILP might be claimed to be a practicable method for the optimal design of sewer networks in which all the real-life constraints are duly considered. They also suggested adding a Graphical User Interface (GUI) for the proposed method to help engineers designing optimized sewer networks easily.

2.2.3. Non-Linear Programming (NLP)

Non-Linear Programming (NLP) could be defined as the art of obtaining the set of design or decision variables that provides an optimal solution for problems in which the objective function and/or some or all constraints imply non-linear relations.

(Lemieux et al., 1976) developed NLP to optimize the design of stormwater sewer systems with the cost function includes the purchase, installation and excavation costs of every pipe expressed as a convex function. They assumed flow full with a free surface condition by using Manning equation. They used pipe diameters as continuous variables, found that using the diameter of pipe as continuous in mathematical programming does not give an optimal design for sewer, but lead to an efficient design because of the continuous diameter rounded to the largest commercial diameter. They also concluded that the main factors influencing the optimal solution are: (1) excavation in soil or rock, (2) inlet time at a node, (3) ground slope, and (4) Manning's coefficient (n).

NLP techniques can generally deal with non-linear objective functions and constraints, but entail much increased computational difficulty due to the discontinuous and nondifferentiable objective function. Moreover, most of them could not deal with discrete diameters (Price, 1978, Gidley, 1986). Because of various difficulties encountered with their application, mathematical programming techniques, like LP and NLP, had limited success and soon fell out of favor with researchers when more advanced optimization techniques are emerged.

2.2.4. Dynamic Programming (DP)

While dealing with practical problems we come across a number of situations where the variable decision vary with time, and these situations are considered to be dynamic in nature. These problems are known to be multistage decision problems and are deal with using special mathematical techniques called Dynamic Programming (DP).

(Merritt and Bogan, 1973) employed DP to optimize the design (diameters, elevations, and slopes) of an existing layout. A sensitivity analysis evaluation was carried out to study the effect of design parameters. The design has been limited by constraints includes minimum and maximum allowable velocities, available commercial diameters, minimum and maximum allowable excavations depth, value of Manning’s coefficient, and inlet pipe diameters, which shall be less than or equal the outlet pipe diameter in the manhole.

The researchers also used the assumpations in the design includes; ground slope between two manholes are constant and uniform, invert slope between two manholes are constant and uniform, and increasing the construction cost of a network with increase of pipe diameter and excavation depth. They found out that Dynamic Programming (DP), despite being powerful in solving such problems, does not ensure finding the optimum solution for that it depends mainly on the number of input and output state variables given, represented by upstream (U/S) and downstream (D/S) invert elevations respectively.

(Argaman et al., 1973) also utilized DP to optimize layout and design of wastewater networks. The main shortcoming of the method was the need for large computer space and long computation time, as the dimensions of the network increase. They proposed that large systems may be decomposed to smaller subsystems, each of which is optimized internally, and later combined into a single optimal.

(Tang et al., 1975) presented two models for the optimum design of storm sewer networks using DP and Discrete Differential Dynamic Programming (DDDP). The proposed models also accounted for the risk due to uncertainties in the design, that is for the costs of expected flood damages. They found out that DDDP significantly reduced the computer time and computer storage than those needed in DP.

(Mays and Yen, 1975) used DP and DDDP to optimize the design of two hydraulic models of storm sewer systems. The first model was serial sewer system while the second was a branched sewer system. They concluded that DDDP approach is proffered to the DP approach for large systems because it utilizes less computer time and memory, even though a global optimum is not guaranteed. They also stated that there are four major factors that affect the efficiency of DDDP applied to sewer systems, namely, the location of the initial trial trajectory, the initial width of the corridor, the number of lattice points and the rate of reduction of state increment.

(Mays and Wenzel, 1976) showed that a serial DDDP approach of formulating the problem is found superior to the Non-serial approach because of the ease of handling large storm sewer systems with many levels of branching.

(Mays et al., 1976) presented two models for the optimum design of storm sewers using DDDP. The first model was concerned with the simultaneous selection of layout and design of sewer systems. The second model was to optimize the design of given layouts only. They concluded that DDDP did not always guarantee giving global optimum solution always. They also found that when DDDP was used to optimize the layout of the network, a trace back of the optimum route has to be made at each stage to solve the connectivity at that stage. Consequently, there is no guarantee of selecting the layout at each stage that is optimal for the entire system.

(Gupta et al., 1983) used the modified DP approach in their work to determine continuous pipe diameters for the network, with partial flow condition and using Modified Hazen-Williams formula. They concluded that the algorithm required small computer memory, little execution time and led to optimal global solution of a complete gravity wastewater collection systems.

(Kulkarni and Khanna, 1985) applied dynamic programming to optimize the design of gravity wastewater collection systems includes the continuous pipe diameters for limited size networks, the slope of pipes and the pump location that lead to the least cost for an implement, with partial flow condition using Modified Hazen-Williams formula. They concluded that the using of an intermediate pump in gravity wastewater collection systems had obtained cost savings of 7.75-28% over optimal gravity systems without an intermediate pump in that case study.

(Omran, 1986) also used DDDP to design and analyze storm sewer networks. He analyzed the behavior of flow in storm sewers during the storm period on the basis of unsteady non-uniform flow conditions. The complexity of such flow conditions was overtaken by dividing the base time of hydrographs of inlets into many short intervals. In addition, he succeeded in tracing different hydraulic cases that might happen in such systems.

(Jurji, 1988) employed DDDP and the Rosenbrocks sequential search technique that depended on the principles of non-linear programming and proposed by (Resonbrock, 1960) to design sewer networks and compare designs results.

(Nagoshe et al., 2014) applied DP to optimize the design of sewerage networks includes pipe sizes and slopes, with partial flow condition using Manning formula. They concluded that Substantial savings in the design of sewerage networks could be obtained as compared to the conventional design. The design of large sewerage networks becomes very cumbersome as the number of option becomes very large when designing the sewerage network by dynamic programming.

2.2.5. Spreadsheet Method

(Brown and Koussis, 1987) used a Shell system programmed by Shell Oil in LOTUS[1] spreadsheet to design storm sewer networks. They found that the proposed method provides reasonably precise designs at a very modest computational effort. They also concluded that using the LOTUS environment provides greater ease and efficiency that are necessary for routine usage.

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[1] Lotus 1-2-3 is a discontinued spreadsheet program from Lotus Software (later part of IBM). It was the IBM PC's first killer application, was hugely popular in the 1980s and contributed significantly to the success of the IBM PC.

(Miles and Heaney, 1988) used LOTUS 1-2-3 spreadsheet package to develop a model for the design of storm sewer networks. They concluded that the heuristic method utilized in the spreadsheet design procedure was capable of producing "optimal" designs which were better than those generated by the formal optimization algorithms such as DP.

(Afshar and Zamani, 2002) also used the spreadsheet to design of sewer networks and estimate the cost of constructing the network.

2.2.6. Cellular Automata (CA)

A cellular automata (CA) is a discrete model studied in computability theory, mathematics, physics, complexity science, theoretical biology and microstructure modeling. Cellular automata is also called cellular spaces, tessellation automata, homogeneous structures, cellular structures, tessellation structures, and iterative arrays (Wolfram, 1983).

(Guo et al., 2007) presented a model for optimal design of storm sewer networks employing CA combined with a sewer hydraulic simulator (the EPA StormWater Management Model (SWMM)). They tested the model in two problems (one small artificial sewer network and one large real sewer network). They found that the CA method demonstrated its ability to attain near-optimal designs in a remarkably small number of computational steps in comparison with its performance in that of a genetic algorithm.

(Afshar et al., 2011) applied CA to find the optimal design of sewer networks includes pipe diameters and excavation depths. The nodes of the network were employed as the CA cell, with the corresponding elevations as CA cell states. They found that the CA model resulted in a near-optimal design in comparison with other methods in which it required less effort of computational.

Using CA-based hybrid methods by (Afshar and Rohani, 2012) proposed discrete and continuous approaches to find the optimal design of sewer networks. The discrete approach used the commercial diameters, whilst applied continuous diameter at continuous approach. The optimal design problem for sewer networks was first analyzed into two sub-optimization problems, which were solved iteratively in a two-stage manner. In the first stage, the excavation depths at network nodes were calculated by solving a nonlinear sub-optimization problem when assumed the pipe diameters of the network were fixed. In the second stage, calculate the pipe diameters by solving a second nonlinear sub-optimization problem after fixing the excavation depths which determined from the first stage. They proved that the CA-based hybrid methods were more effective and efficient than the most powerful optimization methods through the obtained results.

(Afshar et al., 2016) improved the efficiency of CA to find optimal design of sewer networks by employing Adaptive Refinement. In the proposed model, the continuous decision variables were discretized to turn the original mixed-integer problem to a discrete problem which was then solved by a two-stage CA method. Therefore, an adaptive refinement approach was suggested to reduce the computational cost of the CA method without adverse effect on the final solution quality. They found that the proposed model resulted in a quality solution with much more reduction in the computational effort.

2.2.7. Metaheuristic Algorithms for Optimization

In recent years, meta-heuristic techniques, mostly hinted at by nature, have been rigorously developed and widely applied to complex engineering problems like water networks (Reca et al., 2008). The famous meta-heuristic methods include:

2.2.7.1. Tabu Search (TS) and Simulated Annealing (SA)

Tabu Search (TS) is a meta-heuristic that guides a local heuristic search procedure to explore the solution space beyond local optimality. One of the main components of Tabu Search is its use of adaptive memory, which creates a more flexible search behavior. Simulated annealing (SA) on other hand, is a random-search technique that exploits an analogy between the way in which a metal cools and freezes into a minimum energy crystalline structure (the annealing process) and the search for a minimum in a more general system. It forms the basis of an optimization technique for combinatorial and other problems.

(Yeh et al., 2011) and (Yeh et al., 2013) applied TS, and SA to the optimization of sewer network designs includes commercial pipe sizes and slope of pipe, partial flow condition using Manning formula. They used the sewer network design of a central Taiwan township, which contains significantly varied elevations, and the optimal designs from TS and SA were compared with the original official design. They concluded that TS and SA were successful in finding the optimal design of sewer network whose elevations are significantly varied. They also concluded that SA was found to be more reliable and efficient than TS for optimal design solutions to sewer network problems.

(Karovic and Mays, 2014) using SA was developed within Microsoft Excel to determine the least cost combination of pipe sizes and slopes for given layout, with partial flow condition and using Manning formula. They concluded that the using of an optimization technique during design can significantly decrease the construction cost of a branching storm sewer system. They also found that significant cost savings could be realized if storm sewer systems are designed using an optimization procedure as opposed to the conventional (non-optimized) straight slope method.

2.2.7.2. Genetic Algorithm (GA)

Genetic algorithms (GAs) are adaptive and structured random search methods that may be used to search and solve optimization problems. GAs work with a population of individuals, each representing a possible solution to a given problem. They are based on the principles of natural selection and survival of the fittest (Holland, 1975; Goldberg, 1989).

(Goldberg and Kuo, 1987, Murphy and Simpson, 1992, Murphy et al., 1993, Simpson et al., 1993), were the first whom to applied GA in pipeline network systems for water distribution.

(Simpson et al., 1994) presented a model for optimizing pipe networks by employing the GA in which results then compared with other optimization techniques. They found that GA technique was very effective in finding the global optimum solutions in relatively few evaluations compared to the size of the search space.

(Dandy et al., 1996) developed an improved GA formulation for pipe network optimization by the combination of (1) variable exponent fitness scaling, (2) an adjacency mutation operator, and (3) Gray code representation. The results showed that the performance of the improved GA significantly better than the simple GA and other optimization methods.

(Liang et al., 2004) applied the GA and TS techniques for optimizing the design of gravity wastewater collection networks. They developed a strategy of dynamic search and an adaptive rule for assisting the search procedures in finding better designs. They found that the conventional design results in deeper elevations at outlet compared with both GA and TS designs. Also, GA design leads to larger diameters compared with TS design for many pipes. They also found that TS attained the cost savings greater than GA.

(Afshar et al., 2006) employed the GA with the TRANSPORT module of the US Environmental Protection Agency storm water management model version 4.4H (SWMM4.4H) to find the optimal design of storm sewer networks that includes the pipe diameters and elevations at each node. They employed two different approaches for formulating the problem of optimal design of sewer networks with varying degrees of success for obtaining the near-optimal design. In the first approach, they optimized the pipe diameters and nodal elevations by GA. In the second approach, they optimized only the nodal elevations by GA, and left computation of pipe diameters to SWMM module.

(Afshar, 2012) applied RGA to find the optimal design of storm sewer networks. The finer discretization of the design variables would increasingly enlarge the scale of the problem, while coarse discretization could adversely affect the final solution, leading to higher computation cost. They used Rebirthing procedure as a remedy for the problem just outlined. The method was based on the idea of limiting the originally wide search space to a smaller one once a locally converged solution is obtained. They designed the smaller search space for containing the locally optimal design at its center. The resulting search space was refined, and a completely new search was conducted for finding a better design. They concluded that the method was shown to be very effective, efficient and insensitive to the population size of the genetic search and the search space size of the optimization problem.

(Haghighi and Bakhshipour, 2012) developed an AGA to find the optimal design of sewer networks includes pipe diameter, slopes and indicates of the pump. They focused on handling the non-linear and discrete constraints of the problem. Through the proposed method, all the constraints of sewer system were systematically satisfied. Therefore, there was neither need for discarding or repairing infeasible chromosomes nor for applying penalty factors to the cost function. They found that the adaptive constraints handling method computationally makes the optimization more efficient in terms of speed and reliability.

(Cozzolino et al., 2015) employed GA coupled with a steady and uniform flow hydraulic module for finding the optimal design of rural drainage networks. They used GA for the choice of the channels' geometric characteristics that minimize the construction cost, while the uniform flow stage discharge formula was used for evaluating the hydraulic performance of the channels and the degree of satisfaction of constraints.

2.2.7.3. Ant Colony Optimization (ACO)

Ant Colony Optimization (ACO) is a metaheuristic inspired by the indirect communication of real ants by means of trials of a chemical substance called pheromone. Artificial ants are simple agents that use numerical information (artificial pheromone information) to communicate their experience while solving a particular problem to other ants. These principles provide a common framework for most applications of ant algorithms to combinatorial optimization problems. Therefore, algorithms derived from the ACO metaheuristic are called ACO algorithms.

(Afshar, 2006) applied adaptive refinement ACO algorithm to solve optimal design of storm sewer networks includes commercial pipe diameters and slope, partial flow condition and Manning formula. They concluded that ACO algorithm was very effective and efficient to find the optimal design. They also found that ACO algorithm was able to find optimal or near-optimal designs with reduced computational effort and storage requirements making it a suitable choice for the optimization of large-scale continuous design problems.

(Afshar and Mariño, 2006) used ACO algorithm to find the optimal layout of sewer networks includes commercial pipe diameters and slope, partial flow condition and Manning formula. They used two different formulations to represent the optimal layout of sewer networks in the appropriate form required to apply the ant algorithm. In the first formulation, selected link was taken as the decision points of the problem, and on the other formulation, the nodes of the network were taken as the decision points of the problem. They applied the proposed model to find the optimal layout of a sewer network for three benchmark problems. They concluded that ACO algorithm superior to other optimization methods. They also concluded that the second formulation was superior to the first formulation for optimal layout of sewer networks.

(Afshar, 2007, Afshar, 2010b) applied partially constrained ACO algorithm, a parameter free Continuous Ant Colony Optimization (CACO) algorithm, respectively, for the optimal design of sewer networks includes size pipe diameters and slope.

(Moeini and Afshar, 2012, Moeini and Afshar, 2013) used Tree Growing Algorithm (TGA) and ACO algorithm for the optimal layout and design of sewer networks. They used TGA to find the optimal layout while ACO algorithm to find size pipe diameters and pipe slope. They solved three benchmark problems by the proposed model. They concluded that the proposed model was efficient in finding the optimal layout and designing sewer networks.

(Moeini and Afshar, 2016) applied Arc Based Ant Colony Optimization (ABACO) algorithm to find the optimal design of sewer networks includes size pipe diameters and pipe slope.

2.2.7.4. Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) is a computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of quality. It solves a problem by having a population of candidate solutions, here dubbed particles, and moving these particles around in the search-space according to simple mathematical formulae over the particle's position and velocity. Each particle's movement is influenced by its local best known position but is also guided toward the best known positions in the search-space, which are updated as better positions are found by other particles. This is expected to move the swarm toward the best solutions.

(Afshar, 2008) used Particle Swarm Optimization (PSO) technique for finding the storm water network design.

(Izquierdo et al., 2008) used PSO technique to find the optimal design of sewer networks and compared the results with those obtained from DP for the same network. They found the PSO was better from DP. They also concluded that PSO technique is a promising method to find the optimal design of sewer networks, according to the results presented.

2.2.7.5. Hybrid Genetic Algorithm

GA is one of the latest optimization techniques for design sewer networks. However, this approach can be prohibitively time-consuming especially for designing large networks. Firstly, GAs normally take a large number of generations for achieving improved performance. Secondly, many forms of GA depend on the initial populations that randomly are generated, which are often the poor solutions. These researchers hybridized GA for overcoming this intractable problem and obtaining the optimal solution in the least number of generations.

(Weng and Liaw, 2005) established a combinatorial optimization model by employed the GA. The proposed model called the Sewer System Optimization Model for Layout and Hydraulics (GA/SSOM/LH), for optimizing the layout and design of a real urban sewer network. They used the proposed model to find the optimal layout and hydraulic design simultaneously. They applied a Bounded Implicit Enumeration (BIE) and a 0-1 Mixed Integer Programming (MIP) algorithm at SSOM approach for determining the pipe diameters and slopes, achieving design objective and satisfying the constraints for network layout. They concluded that the hybrid algorithms proved the suitability to solve the more complex optimization problems at the sewer networks.

(Guo et al., 2006) employed hybrid GA and CA to solve optimal design of sewer networks problem. The model fulfilled the design chore at two stages. The first stage applied principles of CA for obtaining a set of preliminary solutions. The second stage employed preliminary solutions at multi-objective Genetic Algorithm (MOGA) to find final optimal design. They concluded that the CA based approach used a remarkably small number of computational steps to create a good initial population for the following genetic algorithm runs. They also concluded that this method significantly outperformed the non-heuristic based GA in terms of its optimization performance and efficiency.

(Pan and Kao, 2009) developed a model coupled GA with Quadratic Programming (QP) to solve optimal design of sewer networks problem. In that work, the non-linear functions were converted into quadratic forms and solved the issue by employing QP which combined with GA, the QP calculated the excavation depths, slopes of pipe, and network cost for each chromosome. They concluded that the GA-QP model and DDDP alternatives might be inapplicable or impracticable.

(Rohani and Afshar, 2014) developed a hybrid model combined GA with General Hybrid Cellular Automata (GHCA) to find the optimal design of sewer networks with lift station for given layout. They proposed two alternative versions of the GA-GHCA model. In the first model, the GA approach decided the locations of pump and heads of pumping, while the GHCA approach determined the pipe diameters and excavation depths for the network optimally. In the second model, the GA approach decided only the locations of pump and the GHCA approach determined the pipe diameters, excavation depths, and the heads of pumping at the predefined locations optimally. They found that the proposed model was more efficient and effective than alternative methods for the optimal design of sewer networks with a lift station.

2.3. Summary

In the current study, a hybrid Genetic Algorithm with Heuristic Programming (GA-HP) model was developed for sewer network design. The proposed GA-HP model has fulfilled the optimal design task into two stages. Firstly, the GA was applied to obtain the diameters needed for the preliminary design of the network. Secondly, HP preliminary designs were used to obtain the optimal slope for those diameters and to determine other characteristics such as the velocity, relative depth of water, excavation depths and total cost of the network. Most of the variables and sewer constraints were accurately formulated in HP, thus significantly improve the efficiency of the method. Even though the notable features of this approach, and the implementation of the new model GA-HP, are much more complex than previous methods such as GA alone or DDDP. There are many methods used to the optimal design of sewer networks such as ACO, GA, AGA, RGA, CA, … etc., the results of these methods will be compared with the model proposed in this research.

CHAPTER THREE

Chapter Three

Theoretical Aspect

This chapter deals with the theoretical aspect of the research, which consists of the design period, the estimate of network discharges, simplifying hydraulic equations, and explaining the concepts of the Heuristic Programming (HP) and the Genetic Algorithm (GA).

3.1. Wastewater collection design

A fundamental prerequisite to begin the design of wastewater facilities is a determination of the design capacity. This, in turn, is a function of the wastewater flow rates. The determination of wastewater flow rates consists of five parts (Davis, 2010):

1. Selection of a design period.
2. Estimation of the population and commercial and industrial growth.
3. Estimation of wastewater and stormwater flows.
4. Estimation of infiltration and inflow.
5. Estimation of the variability of the wastewater flow rates.

3.1.1. Design period:

The design period (also called the design life) is not the same as the life expectancy. The design period is the length of time it is estimated that the facility will be able to meet the demand, that is, the design capacity. The life expectancy of a facility or piece of equipment is determined by wear and tear. Typical life expectancies for equipment range from 10 to 20 years. Buildings, other structures, and pipelines are assumed to have a useful life of 50 years or more (Davis, 2010).

New wastewater and stormwater works are generally made large enough to meet the demand for the future. The number of years selected for the design period is based on the following:

- Regulatory constraints.
- The rate of population growth.
- The interest rate for bonds.
- The useful life of the structures and equipment.
- The ease or difficulty of expansion.
- Performance in early years of life under minimum hydraulic load.

Design periods that are commonly employed in practice and commonly experienced life expectancies are shown in Table 3-1.

Table 3-1: Design periods for wastewater works (Davis, 2010)

Type of facility	Characteristics	Design period, yr	Life expectancy, yr
Treatment plants			
Fixed facilities	Difficult and expensive to enlarge/replace	20 - 25	50 +
Equipment	Easy to refurbish/replace	10 - 15	10 - 20
Collection systems			
Trunk lines and interceptors > 60 cm	Replacement is expensive and difficult	20 - 25	60 +
Laterals and mains ≤ 30 cm	Easy to refurbish/replace	To full development[a]	40 - 50

[a] Full development (also called ”build-out”) means that the land area being serviced is completely occupied by houses and/or commercial and institutional facilities.

3.1.2. Estimation of wastewater flows

Wastewater may be classified into the following components:

- Domestic or sanitary wastewater. Wastewater discharged from residences, commercial (e.g., banks, restaurants, retail stores), and institutional facilities (e.g., schools and hospitals).
- Industrial wastewater. Wastewater discharged from industries (e.g., manufacturing and chemical processes).
- Infiltration and inflow (I/I). Water that enters the sewer system from groundwater infiltration and storm water that enters from roof drains, foundation drains, and submerged manholes.
- Storm water. Runoff from rainfall and snow melt.

3.1.2.1. Domestic wastewater flow

- Residential districts:

The quantity of domestic wastewater from an area will generally be about (60) to (90) percent of the water supplied to the area (Steel, 1979). The higher percentages apply to cold countries which have cold weather. In warm, dry climates where water is used for evaporative cooling of homes and landscape irrigation for example lawn sprinkling, the lower percentage is more likely (Metcalf and Eddy, 2003). Hence, if the water use of a community is known the probable output of domestic wastewater can be estimated. Estimate of wastewater facilities should allow for future growth of the area.

(GLUMRB, 2004) recommends that the sizing of facilities receiving flows from new wastewater collection systems be based on an average domestic daily flow of 380 liters per capita per day (lpcd) plus wastewater flows from commercial, institutional, and industrial facilities.

Regulations requiring the use of water saving devices (Table 3-2) can significantly reduce the wastewater flow.

Table 3-2: Typical changes in water consumption with use of water saving devices (AWWA, 1998)

Use	Without water conservation. Lpcd	With water conservation. Lpcd
Showers	50	42
Clothes washing	64	45
Toilets	73	35

- Commercial districts and institutional facilities:

Estimates for commercial wastewater flows range from 7.5 to 14 m^3/ha*d (cubic meters per hectare per day) (Metcalf and Eddy, 2003). For small districts with a limited number of well-defined businesses and institutions, Tables 3-3 and 3-4 can provide a basis for estimating commercial and institutional flows.

Table 3-3: Typical wastewater flow rates from commercial sources in the United States (Metcalf and Eddy, 2003).

Source	Unit	Flow rate, L/unit . d	
		Range	Typical
Airport	Passenger	10 - 20	15
Apartment	Bedroom	380 - 570	450
Automobile service station	Vehicle	30 - 60	40
	Employee	35 - 60	50
Bar/cocktail lounge	Seal	45 - 95	80
	Employee	40 - 60	50
Boarding house	Person	95 - 250	170
Conference center	Person	40 - 60	30
Department store	Restroom	1,300 - 2,300	1,500
	Employee	30 - 60	40
Hotel	Guest	150 - 230	190
	Employee	30 - 60	40
Industrial building (sanitary wastewater only)	Employee	60 - 130	75
Laundry (self-service)	Machine	1,500 - 2,100	1,700
	Customer	170 - 210	190
Mobile home park	Mobile home	470 - 570	530
Motel with kitchen	Guest	210 - 340	230
Motel without kitchen	Guest	190 - 290	210
Office	Employee	25 - 60	50
Public restroom	User	10 - 20	15
Restaurant without bar	Customer	25 - 10	35
Restaurant with bar	Customer	35 - 15	40
Shopping center	Employee	25 - 50	40
	Parking space	5 - 10	8
Theater	Seal	10 - 15	10

Table 3-4: Typical wastewater flow rales front institutional sources in the United States(Metcalf and Eddy, 2003)

Source	Unit	Flow rale, L/unit . d	
		Range	Typical
Assembly hall	Guest	10 - 20	IS
Hospital	Bed	660 - 1.500	1,000
	Employee	20 - 60	40
Prison	Inmate	300 - 570	450
	Employee	20 - 60	40
School[a]			
With cafeteria, gym, and showers	Student	60 - 120	100
With cafeteria only	Student	40 - 80	60
School, boarding	Student	280 - 380	320

[a] Flow rates are L/unit-school day.

3.1.2.2. Industrial wastewater flows

Industrial flows will vary with the type and size of the industry, the degree of water reuse, and the on-site treatment methods that are used, when the type of industry and the water requirements for it are known, estimated the wastewater flow about 85-95 percent of the water used. A typical design value for estimating the flows from industrial districts that have few wet processes is in the range 7.5 to 14 m^3/ha·d for light industrial development and 14 to 28 m^3/ha·d for medium industrial development. While the specified type of industry is unknown, an allowance of (50 m^3/hectare/day = 0.58 l/hectare/sec) is often used (Metcalf and Eddy, 2003).

3.1.2.3. Infiltration and inflow

There is always some entry of groundwater into sewers through broken pipes, defective joints, and similar entry points. The amount of infiltration depends mostly on the groundwater level and the care exercised in the construction of the sewer. If the groundwater table is below the sewer, infiltration will occur only when the water is moving down through the soil.

If the water table is high, infiltration rates of (3 to 15 m^3/hectare/day = 0.06 to 0.17 l/hectare/sec) of area sewer may occur. Infiltration sometimes estimation between (0.1 to 10 m^3/day) per centimeter of diameter per kilometer of sewer (Linsley and Franzini, 1979). Estimate of inflow from roof leaders and other sources must be based on local conditions.

3.1.2.4. Variation in wastewater flowrates

The flow of domestic and industrial wastewater varies throughout the day and the year, the daily peak from the small residential areas will usually occur in midmorning and will vary from (200) to more than (500) percent of the average flowrate, depending on the number of persons contributing.

Commercial and industrial wastewater is delivered somewhat more uniformly throughout the day, with peak rates varying from (150) to (250) percent of the flowrate (Linsley and Franzini, 1979).

Because the variation in wastewater flows will change with the size of the city, the amount of industrial wastewater, and other local conditions, the typical values quoted above are only a guide. On the other hand, some designers use the following formula to estimate the maximum rate of domestic sewage flow from small areas (Steel, 1979):

$$\boldsymbol{M = 1 + \frac{14}{4+P^{1/2}}} \qquad \textbf{\textit{... (3-1)}}$$

in which M is the ratio of the maximum sewage flow to the average, and P is the population served in thousands. Some engineers use 22 as the numerator of the fraction. The ratio of the maximum sewage flow to the average (M) must be large than 2.7.

3.1.3. Estimation of storm-water flow

The amount of storm water to be transported is determined with the rational method.

The rational method

All presently used techniques for estimating storm flow are based upon the use of rainfall data-either implicitly or explicitly. The rational method relates the flow to the rainfall intensity, the tributary area, and a coefficient which represents the combined effects of ponding, percolation, and evaporation. The total volume which falls upon an area, A, per unit time under a rainfall of intensity, i, is:

$$\boldsymbol{Q \quad = i \times A} \qquad \textbf{\textit{... (3-2)}}$$

Of this total, a portion will be lost by evaporation, percolation, and ponding. The portion lost is not constant, but may be determined for differing conditions of temperature, soil moisture, and rainfall duration. The actual amount which appears as runoff may then be calculated from:

$$Q = C \times i \times A \qquad \text{... (3-3)}$$

in which C is the runoff coefficient, i.e., the fraction of the incident precipitation which appears as surface flow. Table (3-5) shows the coefficients for various surfaces.

Table 3-5: Runoff coefficients for various surfaces (Steel, 1979).

Type of surface	C
Watertight roofs	0. 70 - 0. 95
Asphaltic cement streets	0. 85 - 0. 90
Portland cement streets	0. 80 - 0. 95
Paved driveways and walks	0. 75 - 0. 85
Gravel driveways and walks	0. 15 - 0. 30
Lawns, sandy soil	
2 % slope	0. 05 - 0. 10
2 - 7 % slope	0. 10 - 0. 15
> 7 % slope	0. 15 - 0. 20
Lawns, heavy soil	
2 % slope	0. 13 - 0. 17
2 - 7 % slope	0. 18 - 0. 22
> 7 % slope	0. 25 - 0. 35

The rational method makes the following assumptions:

- Precipitation is uniform over the entire basin.
- Precipitation does not vary with time or space.
- Storm duration is equal to the time of concentration.
- A design storm of a specified frequency produces a design flood of the same frequency.
- The basin area increases roughly in proportion to increases in length.
- The time of concentration is relatively short and independent of storm intensity.
- The runoff coefficient does not vary with storm intensity or antecedent soil moisture.

- Runoff is dominated by overland flow.
- Basin storage effects are negligible.

3.2. Sewer network hydraulics

Sewer networks are usually designed using the Manning equation, written as follows:

$$\boldsymbol{V = \frac{1}{n} R^{2/3} S^{1/2}} \qquad \textbf{\textit{... (3-4)}}$$

where:

V = Velocity of flow in (m/s),

n = Coefficient of Manning equation (s/m$^{(1/3)}$),

R = Hydraulic radius in (m), and

S = Slope of pipe (dimensionless).

The flow in sewer pipes is generally a partial flow as shown in figure (3-1). In order to calculate flow and velocity by using chart as shown in figure (3-2), and it is important to express the area and hydraulic radius as a function of the diameter of the pipe and the flow depth in the pipe. This can be established according to the following relationships:

$$\boldsymbol{A = 0.125(\theta - \sin\theta)D^2} \qquad \textbf{\textit{... (3-5)}}$$

$$\boldsymbol{R = \frac{(\theta - \sin\theta)}{4\,\theta} D} \qquad \textbf{\textit{... (3-6)}}$$

The continuity equation is written as follows:

$$\boldsymbol{Q = A\,V} \qquad \textbf{\textit{... (3-7)}}$$

where:

θ = central angle of water surface in radians: $0 \le \theta \le 2\pi$.

D = diameter of pipe in m.

A = cross-sectional area of flow in m^2.

Q = flow of sewage (discharge), m^3/s.

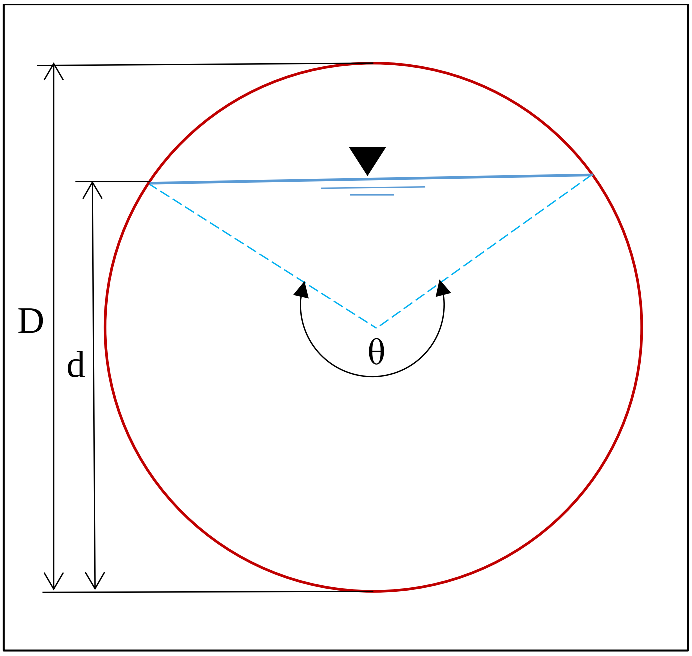


Figure 3-1: Cross-section of pipe in partial filled condition.

Substituting Eq. (3-5) into (3-4) and then substituting this equation and Eq. (3-4) into (3-6) produces the following equation for flow:

$$\boldsymbol{Q = \frac{0.05}{n}\theta^{(-2/3)}(\theta - \sin\theta)^{(5/3)}D^{(8/3)}S^{(1/2)}} \qquad \textbf{\textit{... (3-8)}}$$

The depth of flow in a pipe is also relative to the central angle of the water surface, *θ*, by the following expression:

$$\boldsymbol{d = 0.5\,D\left[1 - \cos\left(\frac{\theta}{2}\right)\right]} \qquad \textbf{\textit{... (3-9)}}$$

where:

d = depth of flow in m.

Substituting Eq. (3-5) for the hydraulic radius into Eq. (3-4) produces the following equation for slope:

$$\boldsymbol{S = 6.35\left[V.n.\theta^{(2/3)}.(\theta - \sin\theta)^{(-2/3)}.D^{(-2/3)}\right]^2} \qquad \textbf{\textit{... (3-10)}}$$

It is typical practice to compute the minimum slope based on the flow of a half-full pipe (d/D=0.5) at minimum velocity (Desher and Davis, 1986).

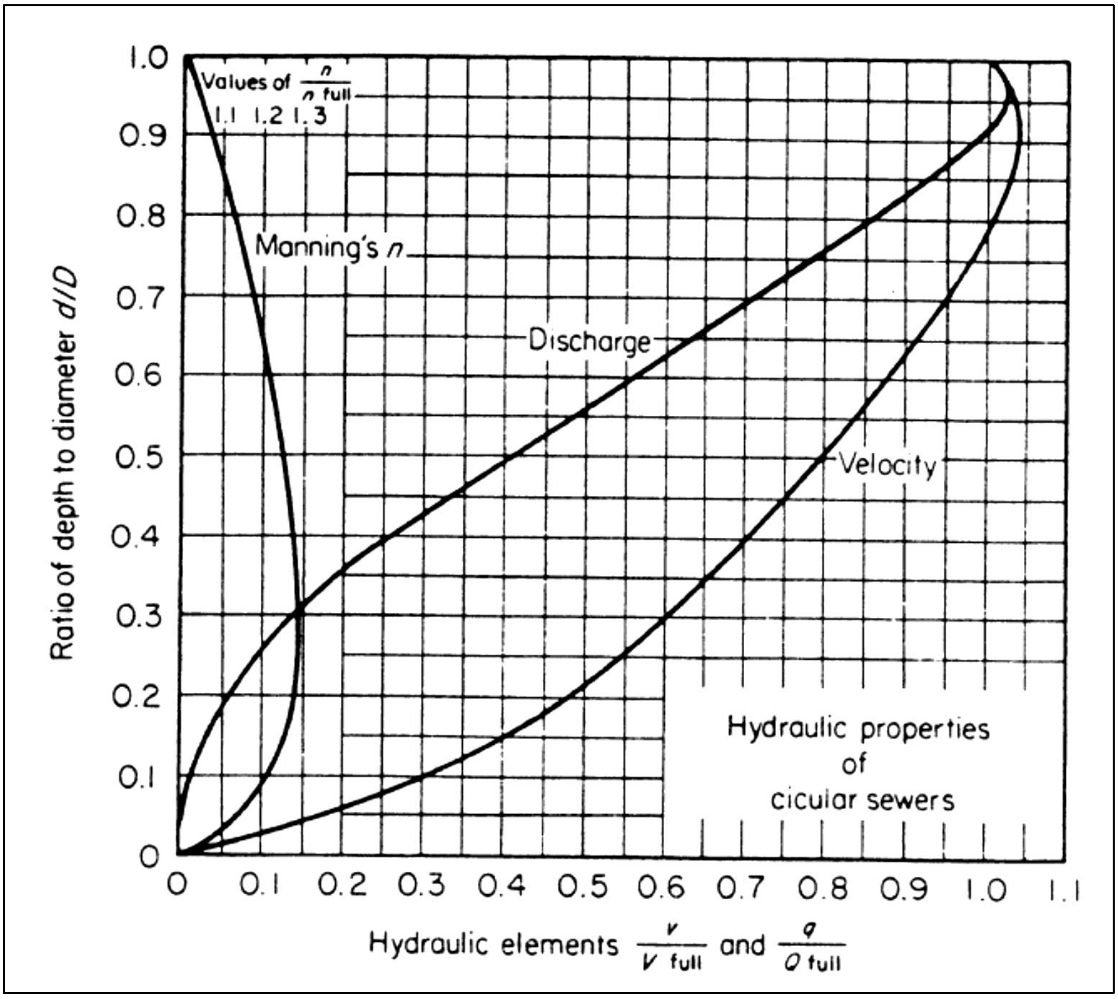


Figure 3-2: Hydraulic elements of a circular pipe.

3.3. Heuristic Programming

Heuristic programming gives the impression of artificial intelligence by solving problems using protocols or experience-based guidelines. Contrary to the principle of using strict algorithm-based computing, heuristics, in many key senses, is a shortcut to a quantified logic type of programming. Heuristic programming enables researchers to accomplish a goal by substituting certain types of machine-learning programs for logical algorithms. The current work used Heuristic Programming (HP) to compute a fitness function to guide the choice of optimum slope for a pipe depending on overlapping multi-logical algorithms, backtrack techniques and numerical solutions for some equations.

3.4. Genetic Algorithm

3.4.1. Description of genetic algorithms

Genetic algorithms are computerized search and optimization algorithms based on the mechanics of natural genetics and natural selection. Professor Jone Holland at the University of Michigan, An arbor envisaged the concept of these algorithms in the mid-sixties and published his seminal works (Holland, 1975). Therefore, a number of his students and other researchers have contributed to developing this field.

Genetic algorithm, as powerful and broadly applicable stochastic search and optimization techniques, are perhaps the most widely known types of evolutionary computation methods. As stated by (Goldberg, 1989), the structure of the genetic algorithm differs from more traditional optimization methods in four major ways:

1. The genetic algorithm typically uses a coding of the decision variable set, not the decision variables themselves.
2. The genetic algorithm searches from a population of decision variable sets, not a single decision variable set.
3. The genetic algorithm uses the objective function itself, not derivative information.
4. The genetic algorithm uses probabilistic, not deterministic, search rules.

The second characteristic is especially important for multiple objective optimizations. Working with a population of decision variable sets makes it possible to optimize simultaneously for several solutions along the trade-off curve surface.

3.4.2. Outline of the basic genetic algorithm

1. [Start] Generate random population of *n* chromosome (suitable solutions for the problem).
2. [Fitness] Evaluate the fitness *f(x)* of each chromosome *x* in the population.
3. [New population] Create a new population by repeating following steps until the new population is complete:
    a) [Selection] Select two parent chromosome from a population according to their fitness (the better fitness, the bigger chance to be selected).
    b) [Crossover] With a crossover probability crossover the parents to form a new offspring (children). If no crossover was performed, offspring is an exact copy of parents.
    c) [Mutation] With a mutation probability mutate new offspring at each locus (position in chromosome).
    d) [Accepting] Place new offspring in a new population.
4. [Replace] Use new generated population for a further run of algorithm.
5. [Test] If the end condition is satisfied, stop, and return the best solution in current population.
6. [Loop] Go to step 2 such as shown in figure (3-3).

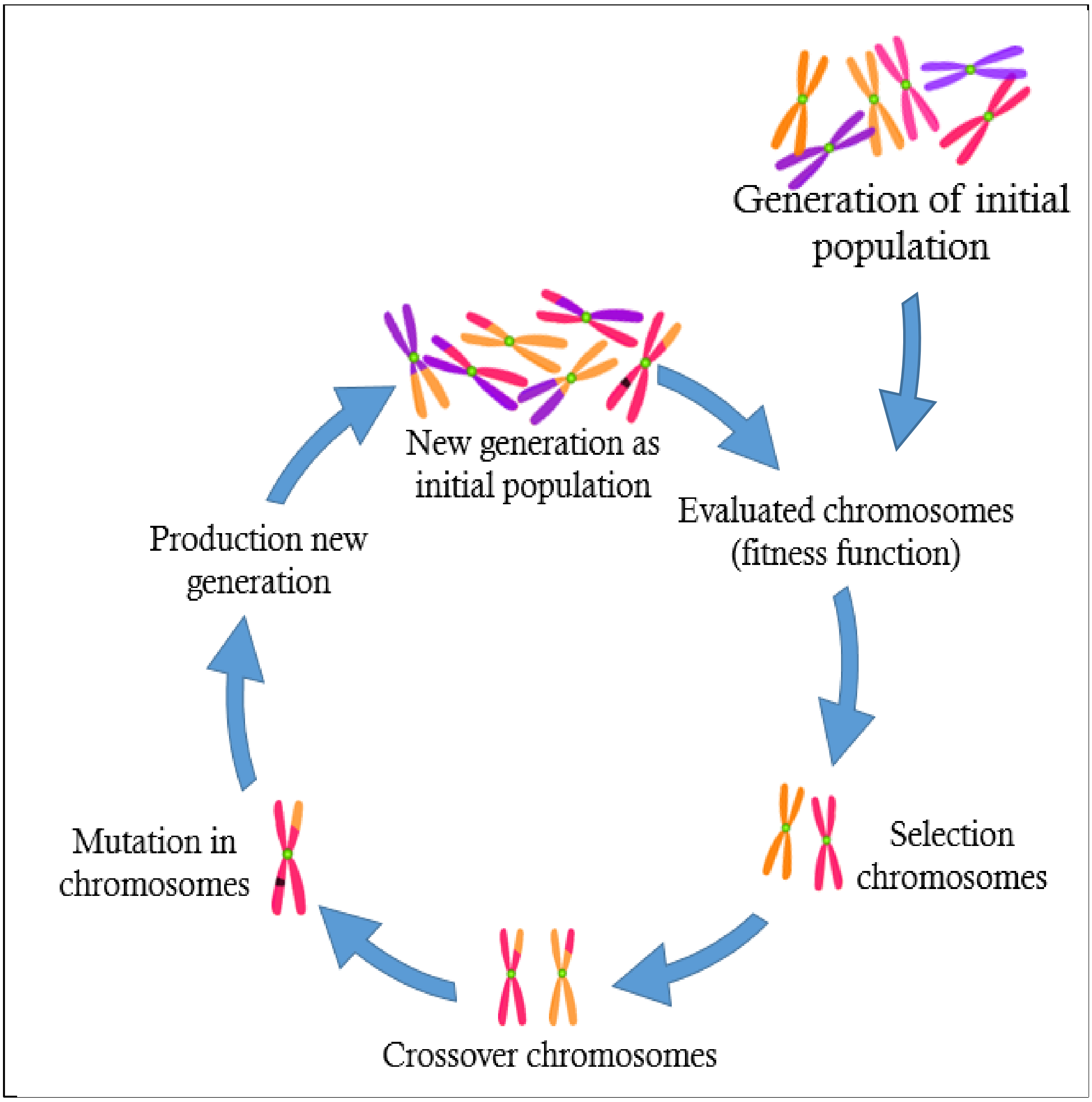


Figure 3-3: shown the principles of genetic algorithm.

3.4.3. Working principles of genetic algorithm

To illustrate the working principles of GAs, firstly consider an unconstrained optimization problem. Later, we shall discuss how GAs can be used to solve a constrained optimization problem. Let us consider the following minimization problem:

Minimize *f(x)* , $x_i^{(L)} \leq x_i \leq x_i^{(U)}$, $i = 1,2, \dots \dots \dots, N.$

Although a minimization problem is considered here, a maximization problem can also be handled using GAs. The working of GAs is completed by performing the following tasks:

3.4.3.1. Encoding:

In order to use GAs to solve the above problem, variables x_i's are first coded in integer-coded or some string structures (binary-coded). The decision variables present the commercial diameters for each pipe. It is important to mention here that the coding of the variables is absolutely necessary. There exist some studies where GAs are directly used on the variables themselves, but here we shall ignore the exceptions and discuss the working principle of a simple genetic algorithm.

3.4.3.2. Fitness:

GAs mimics the survival-of-the-fittest principle of nature to make a search process. Therefore, GAs are naturally suitable for solving maximization problems. Minimization problems are usually transformed into maximization problems by some suitable transformation. In general, a *fitness function F(x)* is first derived from the objective function and used in successive genetic operations. Certain genetic operations require that the fitness function be non-negative, although certain operators do not have this requirement. For maximization problems, the fitness function can be considered to be the same as the objective function or $F(x) = f(x)$. For minimization problems, the fitness function is an equivalent maximization problem chosen such that the optimum point remains unchanged. A number of such transformations are possible. The following fitness is often used:

$$\boldsymbol{F(i) = \frac{1}{objective\ function(i)}} \qquad \textbf{...(3-11)}$$

The transformation does not alert the location of the minimum, but converts a minimization problem to an equivalent maximization problem. The fitness function value of a string is known as the string's fitness.

The operation of GAs begins with a population of random strings representing design or decision variables. Thereafter, each string is evaluated to find the fitness value. The population is then operated by three main operators (a- reproduction (selection), b- crossover, c- mutation) to create a new population of points. The new population is further evaluated and tested for termination. If the termination criterion is not met, the population is iteratively operated by the above three operators and evaluated. This procedure is continued until the termination criterion is met. One cycle of these operations and the subsequent evaluation procedure is known as a *generation* in GA's terminology.

3.4.4. Reproduction

Reproduction is usually the first operator applied on a population. Reproduction selects good strings in a population and forms a mating pool. That is why, the reproduction operator is sometimes known as the *selection operator*.

Selection two parent chromosomes are selected from a population according to their fitness (the better the fitness, the bigger the chance of being selected). This work considered eight different selection methods, as follows:

3.4.4.1. Roulette Wheel Selection (RWS)

Parents are selected according to their fitness. The better the chromosomes are, the more chances to be selected they have. Imagine a roulette wheel where are placed all chromosomes in the population, every has its place big accordingly to its fitness function, like as shown in the figure (3-4). Also known as Fitness Proportionate Selection. The roulette wheel is spun n times, each time selecting an instance of the chromosomes chosen by the roulette-wheel pointer. Its probability ($p(i)$) of being selected is (Jebari and Madiafi, 2013):

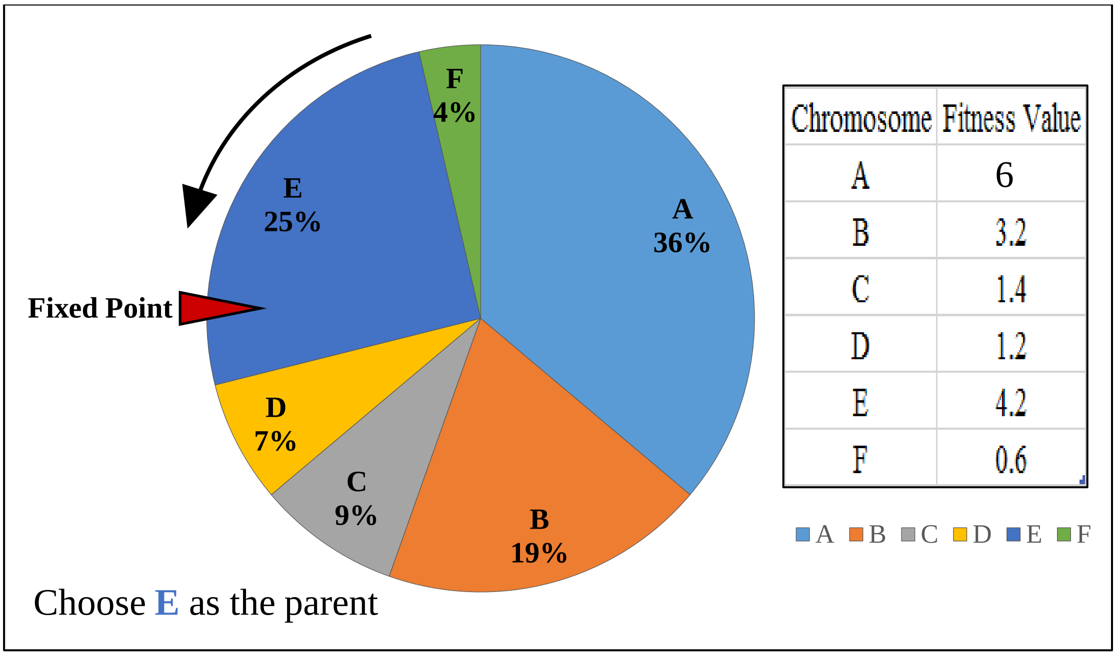
$$\boldsymbol{p(i)} = \frac{\boldsymbol{f(i)}}{\sum_{\boldsymbol{j=1}}^{\boldsymbol{n}} \boldsymbol{f(j)}} \qquad \textbf{... (3-12)}$$

where:

f(i) is the fitness of chromosome i.

n is the number of individuals in the population.

This roulette-wheel selection scheme can be simulated easily. Using the fitness value Fi of all strings, the probability of selection a string pi can be calculated. Thereafter, the cumulative probability (*pi*) of each string being copied can be calculated by adding the individual probabilities from the top of the list. Thus, the bottom-most string in the population should have a cumulative probability (*pn*) equal to 1. The roulette-wheel concept can be simulated by realizing that the i-th string in the population represents the cumulative probability values from (*pn*-*i*) to (*pi*). The first string represents the cumulative values from zero to *pi*. Thus, the cumulative probability of any string lies between (0 - 1). In order to choose n strings, n random numbers between zeros to one are created at random. Thus, a string that represents the chosen random number in the cumulative probability range (calculated from the fitness values) for the string is copied to the mating pool. This way, the string with a higher fitness value will represent a larger range in the cumulative probability value and therefore has a higher probability of being copied into the mating pool. On the other hand, a string with a smaller fitness value represents a smaller range in cumulative probability value and has a smaller probability of being copied into the mating pool.



Chromosome	Fitness Value
A	6
B	3.2
C	1.4
D	1.2
E	4.2
F	0.6

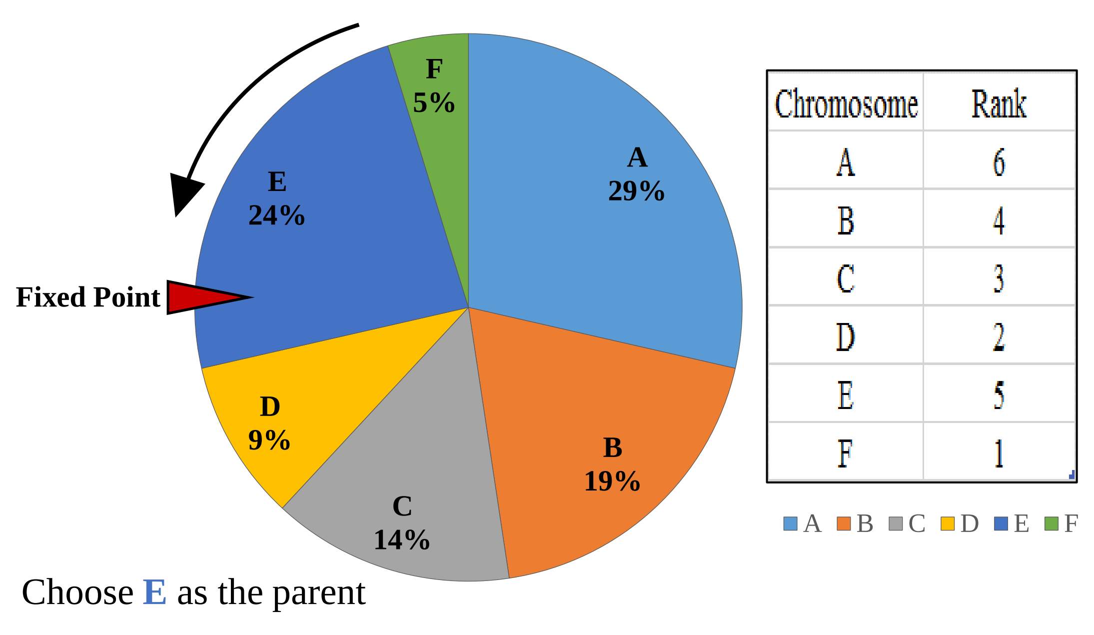
Choose **E** as the parent

Figure 3-4: Selection strategy with roulette-wheel mechanism.

3.4.4.2. Rank Roulette Wheel Selection (RRWS)

Rank Selection is similar to Roulette wheel selection, however instead of selecting individuals based on fitness values, this based on the chromosomes’ rank. The rank of 1 is granted for the worst chromosome has the least fitness, while the best chromosome has the largest fitness is given the rank of n.

Rank Selection is mostly used when two cases, the first case the individuals in the population have very close fitness values (this happens usually at the end of the run), the second case the individuals in the population have the fitness values differs very much (this happens usually at the start of the run). In the first case, leads to each individual having an almost equal share of the pie and hence each individual no matter how fit relative to each other has an approximately same probability of getting selected as a parent. In the second case, leads to the many individuals having very few chances to be selected. This in turn leads to a loss in the selection pressure towards fitter individuals, making the GA to make poor parent selections in such situations. The figure (3-5) shown the Rank selection method.



Chromosome	Rank
A	6
B	4
C	3
D	2
E	5
F	1

Choose E as the parent

Figure 3-5: Selection strategy with rank roulette-wheel mechanism.

In this, remove the concept of a fitness value while selecting a parent. However, every individual in the population is ranked according to their fitness. The selection of the parents depends on the rank of each individual and not the fitness. The higher ranked individuals are preferred more than the lower ranked ones.

3.4.4.3. Linear Ranking Selection (LRS)

Ranking selection was first suggested by Baker to eliminate the serious disadvantages of proportionate selection. By means of linear ranking the selective pressure can be controlled more directly than by scaling and consequently the search process can be accelerated remarkably.

Linear Ranking Selection is based on the individual' rank instead of their fitness. The rank of 1 is granted for the worst individual, while the best individual is given the rank of n. The selection probability is linearly assigned to the individuals according to their rank (Blickle and Thiele, 1995):

$$\boldsymbol{p(i) = \frac{1}{n}\left(\eta^- + \left((\eta^+ - \eta^-) \times \frac{Rank(i)-1}{n-1}\right)\right)} \qquad \text{... (3-13)}$$

where

$$\boldsymbol{(\eta^- + \eta^+ = 2) \rightarrow (\eta^- = 2 - \eta^+)} \qquad \text{... (3-14)}$$

$p(i)$ = the selection probability of an individual,

η^+ = the selective pressure

($\eta^- \geq 0$) and ($1 \geq \eta^+ \geq 2$) must be fulfilled.

Table (3-6) contains the selection probability of the individuals for various values of the selective pressure (η^+) assuming a population of 6 individuals.

Table 3-6: Example of scaled rank with different η^+ values.

Population	Objective value	Rank	The selection probability	
			η^+=2	η^+=1.1
A	6.0	6	33.3	18.3
B	3.2	4	20.0	17.0
C	1.4	3	13.3	16.3
D	1.2	2	6.67	15.7
E	4.2	5	26.7	17.7
F	0.6	1	0.00	15.0

3.4.4.4. Exponential Rank Selection (ERS)

This is based on the chromosomes’ rank instead of their fitness. The rank of 1 is granted for the worst chromosome, while the best chromosome is given the rank of *n*. Thus, based on its rank, each chromosome (*i*) has the probability of being selected given the expression (Jebari and Madiafi, 2013):

$$\boldsymbol{p(i) = 1.0 \times e^{\left(\frac{-rank(i)}{c}\right)}} \qquad \text{... (3-15)}$$

where

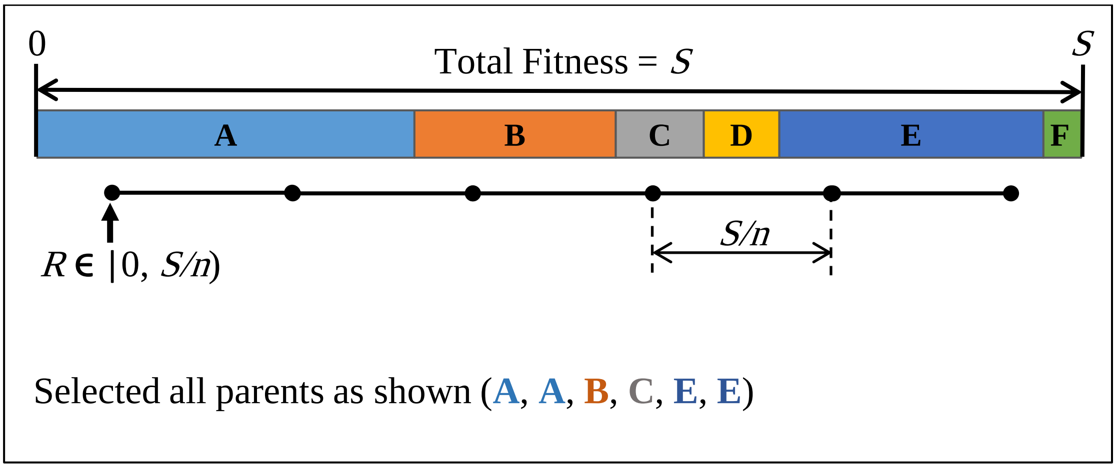
$$\boldsymbol{c = \frac{(2n\times(n-1))}{(6(n-1)+n)}} \qquad \text{... (3-16)}$$

3.4.4.5. Truncation Selection (TRS)

In truncation selection the candidate solutions are ordered by fitness, and some proportion, T, (e.g. T=1/2, 1/3, etc.), of the fittest individuals are selected and reproduced 1/T times. Truncation selection is less sophisticated than many other selection methods, and is not often used in practice. Only the individuals above the threshold T are selected as parents. T indicates the proportion of population to be selected as parents and takes values ranging from 50% - 10%. Individuals below threshold do not produce offsprings (Hancock, 1997).

3.4.4.6. Stochastic Universal Sampling (SUS)

Stochastic Universal Sampling is introduced by (Baker, 1987), is quite similar to Roulette wheel selection. However instead of spinning the roulette wheel *n* times as described in Roulette Wheel Selection, in this technique one can spin the Roulette Wheel just once, but after determining *n* points in the Wheel, where *n* is a population size. Then choose *n* chromosomes that situated in front of the determined points as shown in the figure (3-6).



Selected all parents as shown (**A**, **A**, **B**, **C**, **E**, **E**)

Figure 3-6: Selection strategy with Stochastic Universal Sampling mechanism.

3.4.4.7. Tournament Selection (TOS)

In this method, the selection of a single chromosome is achieved through two steps: (1) Random selection of a set of chromosomes from the population. The selected chromosomes of cardinality $k \leq n$, $k < +\infty$ are placed in a group called *tournament-mate*. (2) Selecting the fittest chromosomes from those in this tournament-mate group such as shown in figure (3-7). This procedure is repeated n times for the whole population (Blickle and Thiele, 1995).

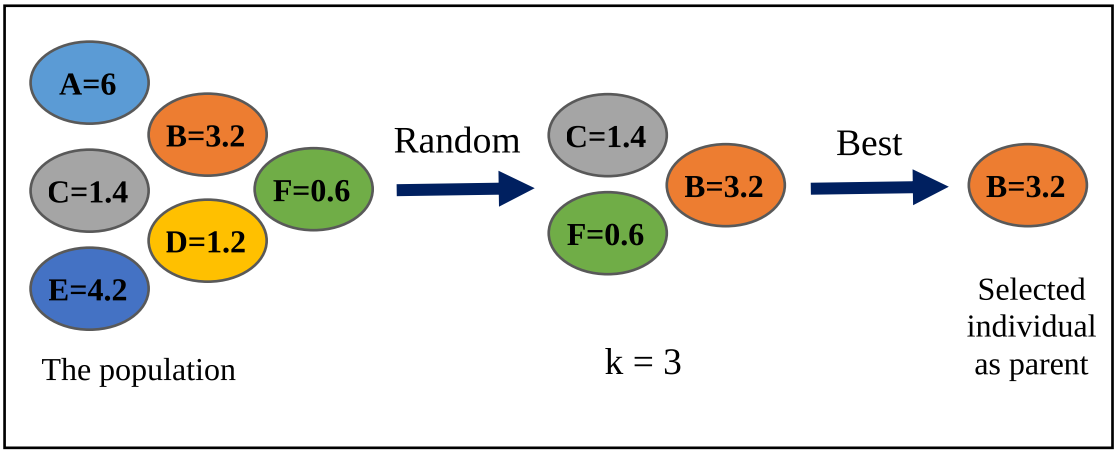


Figure 3-7: Selection strategy with tournament mechanism.

3.4.4.8. Random Selection (RMS)

In this strategy we randomly select parents from the existing population. There is no selection pressure towards fitter individuals and therefore this strategy is usually avoided.

3.4.5. Crossover

The basic operator for producing new chromosomes by exchanging information among chromosomes of the mating pool in the GA is that of crossover. Like its counterpart in nature, crossover produces new individuals that have some parts of both parent's genetic material. Crossover occurs between two selected chromosomes with some specified probability, usually in range of 0.50 – 1.00 (i.e., selected chromosomes have this probability of being used in crossover). Many crossover methods are described following:

3.4.5.1. One-Point Crossover (OPC)

One-point crossover is the most popular crossover and it is widely used. Crossover operator randomly selects one crossover point and then copies everything before this point from the first parent, and then everything after the crossover point from the second parent. The crossover would then look as shown in figure (3-8).

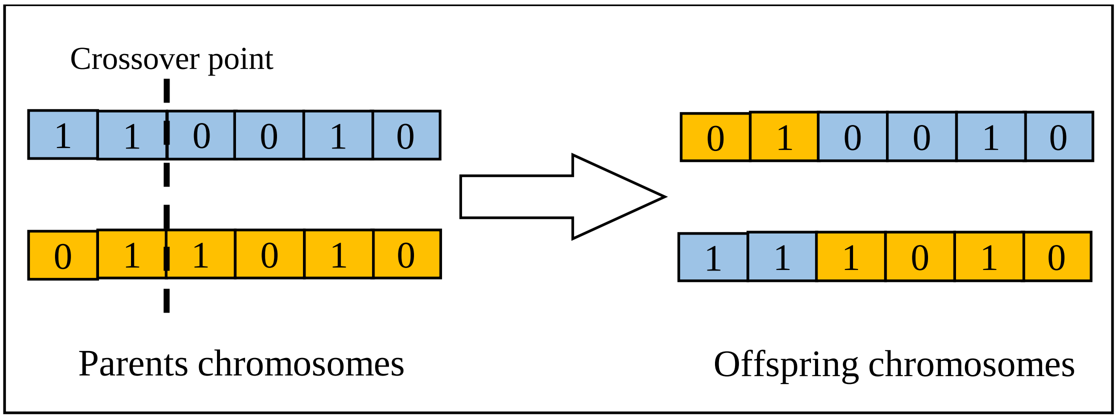


Figure 3-8: Explanation of one-point crossover.

3.4.5.2. N-Points Crossover (NPC)

It uses the random crossover point to combine the parents same as per one-point crossover. To provide the great combination of parents it selects more than one crossover points to create the offspring or child. The crossover would then look as shown in figure (3-9).

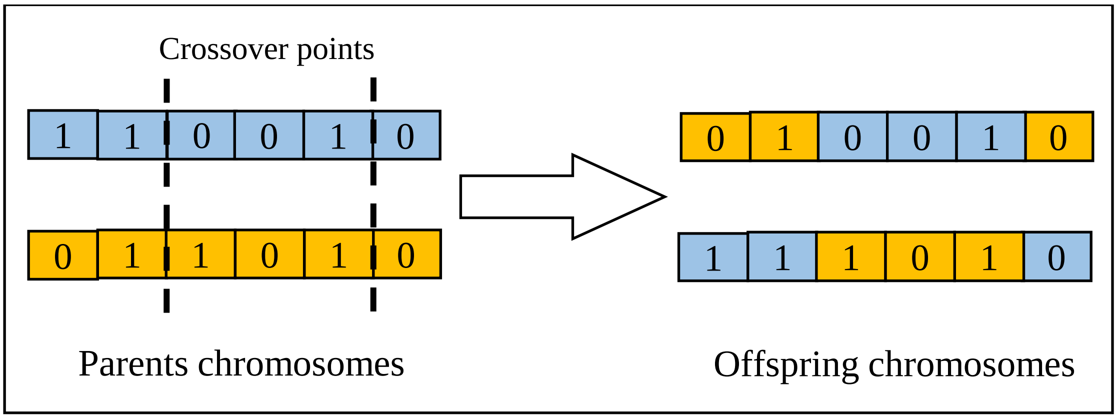


Figure 3-9: Explanation of two-point crossover.

3.4.5.3. Uniform Crossover (Mask crossover)

This crossover decides the percentage of the parental contribution to the chromosome of the offspring. If the mixing ratio is 0.33, this means 33% of genes in the offspring will come from parent 1, the other 67% coming from parent 2. The crossover would then look as shown in figure (3-10).

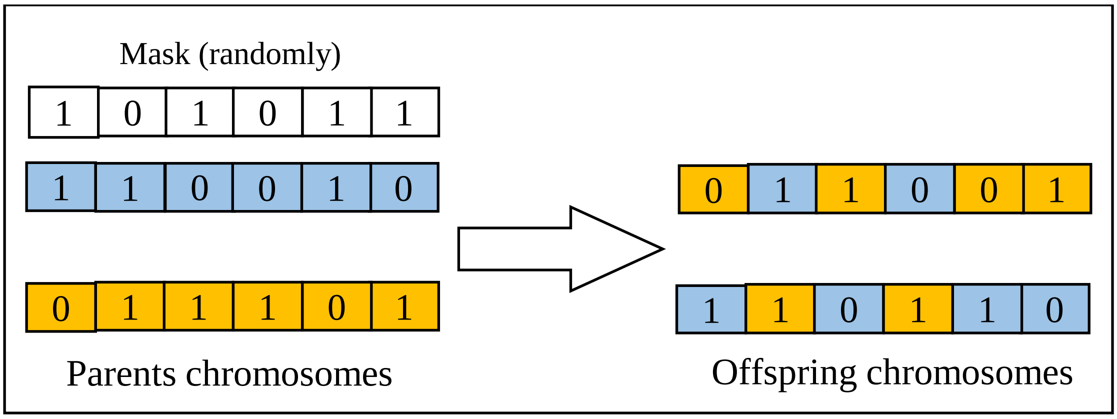


Figure 3-10: Explanation of uniform crossover.

3.4.5.4. Flat Arithmetic Crossover (FAC)

In flat arithmetic crossover (FAC), arithmetic creates offspring that are the weighted arithmetic mean of two parents. Offspring can occur as long as they follow linear constraints and boundaries. Alpha is a random value between [0, 1]. If parent 1 and parent 2 are the parents and parent 1 has the better fitness value, the function returns the offspring as follows (Kaya and Uyar, 2011):

$$offspring_1 = \alpha \times parent_1 + (1-\alpha) \times parent_2 \qquad \textbf{... (3-17)}$$

3.4.5.5. Intermediate Crossover (IMC)

This method creates offspring by taking a weighted average of the parents. Intermediate crossover (IC) is controlled by a single parameter ratio:

$$offspring_1 = parent_1 + rand \times ratio \times (parent_2 - parent_1) \qquad \textbf{... (3-18)}$$

If *Ratio* is in the range [0,1] then the offspring produced are within the hypercube defined by the parents' locations on opposite vertices. *Ratio* can be a scalar or a vector of length of a number of variables. If *Ratio* is a scalar, then all the offspring will lie on the line between the parents. If *Ratio* is a vector, then the offspring can be at any point within the hypercube (Kaya and Uyar, 2011).

3.4.5.6. Shuffle Crossover (SHC)

Shuffle Crossover helps in creation of offspring which have independent of crossover point in their parents. It uses the same 1-Point Crossover technique in addition to shuffle.

Shuffle Crossover selects the two parents for crossover. It firstly randomly shuffles the genes in the both parents but in the same way. Then it applies the 1-Point crossover technique by randomly selecting a point as crossover point and then combines both parents to create two offspring. After performing 1-point crossover the genes in offspring are then unshuffled in same way as they have been shuffled. The crossover would then look as shown in figure (3-11).

3.4.6. Mutation

A random mutation with some specified probability of mutation, *Pm*, is carried out for each of the strings that have undergone crossover. In an integer coded GA, random mutation changes the value of the selected gene to the integer's random value between coded intervals [1, 2, 3, 4…]. Here, a random mutation operator with $P_m = 0.5$ is employed by which only one gene in a chromosome is randomly selected for mutation.

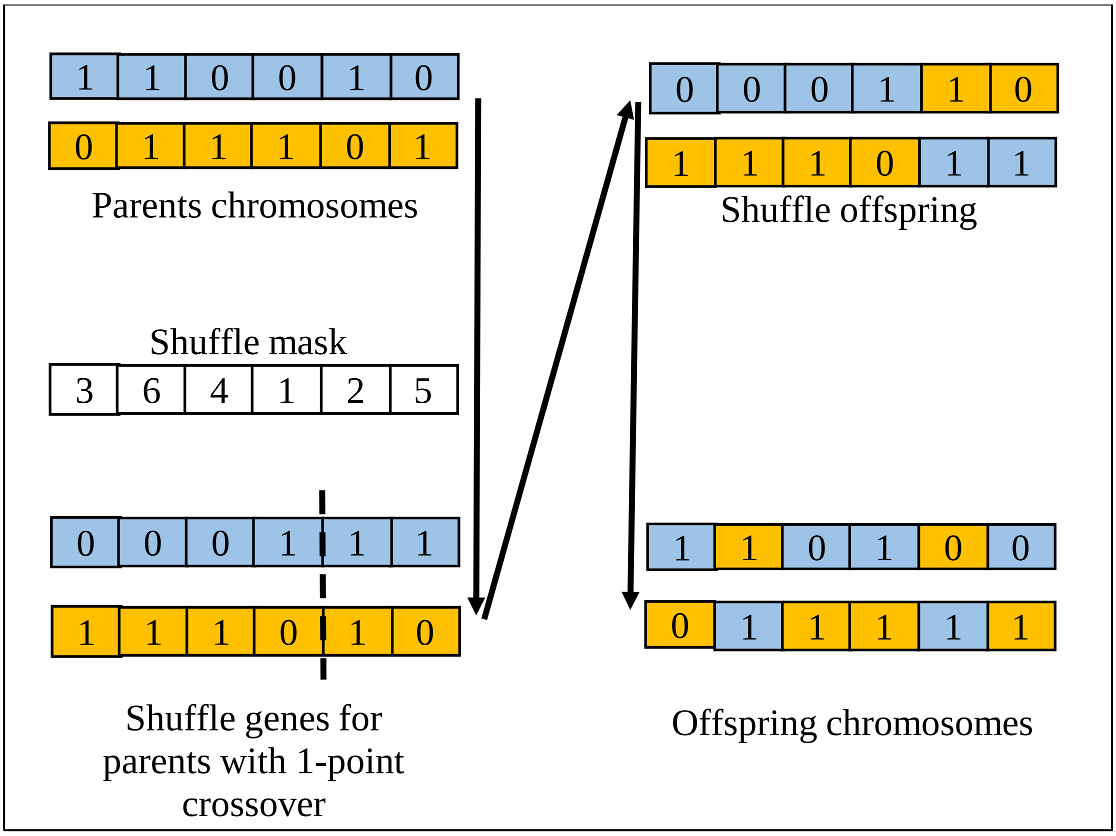


Figure 3-11: Explanation of shuffle crossover.

CHAPTER FOUR

Chapter Four

Formulation of Optimization

This chapter explains the methodology of work through three points, objective function, problem constrains, and formulation of new techniques GA-HP model.

4.1. Objective function

The objective function has represented the subject of finding the optimal design for sewer networks. The objective function will be minimization function because it is construction cost for network represented by cost of pipes, excavations, and manholes. The objective of designing a sewer network is generally formulated as:

$$\boldsymbol{Min.\,C_{total}} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \boldsymbol{f_i}\left(\boldsymbol{d_i}, \boldsymbol{\overline{Z}_i}, \boldsymbol{C_i}\right) \times \boldsymbol{L_i} \qquad \textbf{... (4-1)}$$

where:

C_{total} = total cost for the sewer network.

d_i = diameter of pipe in *i*th link; (*i*=1, 2, ……… *n*),

n = no. of pipes in network,

$\overline{Z}_i$ = average depth of excavation for *i*th link,

L_i = length of pipe in *i*th link,

C_i = unit cost of pipe and excavation for *i*th link.

Genetic algorithms are basically unconstrained optimisation techniques. If used to solve constrained problems like sewer networks in GA, the constrained problem has to be converted to an unconstrained one. A penalty method is usually used for this purpose, which includes constraints in the objective function via a penalty cost, leading to the following form of penalised objective function:

$$\boldsymbol{Min\,C_{total}} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \boldsymbol{f_i}\left(\boldsymbol{d_i}, \boldsymbol{\overline{Z}_i}, \boldsymbol{C_i}\right) \times \boldsymbol{L_i} + \boldsymbol{\delta}.\boldsymbol{f}(\boldsymbol{G}) \qquad \textbf{... (4-2)}$$

by which *f* is some function of the violation of constraint matrix G, with a typical component, δ, representing the parameter of the penalty, and g_{ij} representing the *jth* violation of constraint at pipe i.

A variety of function forms of *f* have been used by different researchers. One of the most frequently used function form of *f* is the maximum function, this using the maximum violations of constraint as seen in Equation (4-3).

$$\boldsymbol{Min\, C_{total}} = \sum_{i=1}^{n} \boldsymbol{f_i\left(d_i, \overline{Z}_i, C_i\right) \times L_i} + \sum_{j=1}^{9} \boldsymbol{\delta_j} \sum_{i=1}^{n} (\boldsymbol{g_{ij}}) \qquad \textbf{... (4-3)}$$

4.2. Constraints

In the current research, the constraints were used to prepare the proposed GA-HP model for optimal design of sewer networks. The objective function in Eq. (4-1) is subject to the following constraints:

1. Commercially Available Pipe Diameter

   The pipe diameter must be chosen from those commercially available.

   $$\boldsymbol{D_i \in D_{com.}} \qquad \textbf{... (4-4)}$$

   where:

   D_i = pipe diameter for link *i*, and

   $D_{com.}$ = the commercially available pipe diameters.

2. Minimum Pipe Diameter Constraints

   Standards dictate that for reasons of both convenience and contingency, any sanitary sewer diameter must not be smaller than a certain minimum diameter.

   $$\boldsymbol{D_i \geq D_{min.}} \qquad \textbf{... (4-5)}$$

   where:

   $D_{min.}$ = minimum allowable diameter.

3. Diameter Progression Constraints

The diameter of any ith pipe must be equal to, or greater than, the diameter of a (i-1)th pipe which is just upstream of it and flows into it.

$$\boldsymbol{D_i \geq D_{i-1}} \qquad \textbf{... (4-6)}$$

where:

D_{i-1} = diameter of the [i -1]th pipe.

4. Minimum Velocity Constraints

   Velocities in the pipe must be greater than the minimum permissible velocity to prevent sedimentation.

$$\boldsymbol{V_i \geq V_{min.}} \qquad \textbf{... (4-7)}$$

where:

V_i = velocity in ith pipe at peak flow, and

V_{min} = minimum allowable velocity at peak flow.

5. Maximum Velocity Constraints

   Velocities in the pipe must be less than the maximum permissible velocity to prevent pipe abrasion. In addition, if the flow velocity is too great, the resulting forces can cause pipe joints to fail, and other undesirable effects due to high-velocity flow.

$$\boldsymbol{V_i \leq V_{max.}} \qquad \textbf{... (4-8)}$$

where:

$V_{max.}$ = maximum allowable velocity.

6. Minimum Pipe Cover Constraints

   For underground sewers, it is necessary to have adequate cover depth. Pipelines are normally designed for a specific range of depths and need to be strong enough to provide protection against imposed loads. The cover depth of a sewer pipe should be greater than the minimum sewer pipe cover depth. The minimum cover depth criteria adopted depends on local factors and specifically on the pipe material used.

$$\boldsymbol{GL_i - CL_i \geq C_{min.}} \qquad \textbf{... (4-9)}$$

where:

GL_i = ground elevation at the upstream of link *i*,

CL_i = crown level at the upstream of link *i*, and

C_{min} = minimum allowable cover.

7. Maximum Pipe Depth Constraints

   Construction of an underground sewer network is difficult if the sewer is too deep the maximum allowable pipe depth dependant on subsoil conditions.

$$\boldsymbol{GL_i - IL_i \leq Z_{max.}} \qquad \text{... (4-10)}$$

where:

IL_i = Invert level at the upstream of link *i*, and

$Z_{max.}$ = maximum allowable pipe depth.

8. Sink Progression Constraints

   The exiting crown elevation of a pipe is never placed higher than the lowest incoming crown elevation at a manhole to avoid the possibility of deposits at the bottom of a manhole.

$$\boldsymbol{C.L_i \geq C.L_{i-1}} \qquad \text{... (4-11)}$$

$C.L_{i-1}$ = crown level at the downstream of link *i-1*, and

9. Minimum Pipe Slope Constraints

   It is necessary to specify the minimum pipe slope to avoid adverse slopes caused by inaccurate construction or settlement; a minimum pipe slope should be considered for sewer pipes.

$$\boldsymbol{S_i \geq S_{min.}} \qquad \text{... (4-12)}$$

where:

S_i = Slope in link *i*.

$S_{min.}$ = Minimum allowable slope.

10. Maximum Pipe Slope Constraints

    The slopes of each pipe should be within a maximum permissible value:

$$S_i \le S_{max}. \qquad \dots (4\text{-}13)$$

where:

S_{max} = Maximum allowable slope.

4.3. Limitations and assumptions

1. The sewer system is a tree network converging towards downstream.
2. The sewer system operates entirely by gravity in which no negative slope is allowed for any sewers in the tree network.
3. The direction of the flow in a sewer is uniquely determined from topographic considerations.
4. The direction of flow is fixed for every pipe.
5. Gravity sanitary sewer flow is considered to be an open-channel flow because the surface of the flow is at atmospheric pressure.
6. The sewer flows in all pipes are assumed to be steady uniform flow.
7. Hydraulic losses at the nodes (manholes) are neglected.

4.4. Formulation of the GA-HP model

In order to solve the formulation problem presented in Section 4.2, a new technique is proposed in this study. It is a combination of Genetic Algorithm and Heuristic Programming called GA-HP. The following steps are suggested in the proposed GA-HP search for the perfect sewer network design:

1. **Encoding the design variables:** the genetic algorithm requires that any trial solution of the design problem be represented by a coded string of finite length, similar to the structure of the chromosome of a genetic code. Each chromosome from a population signifies one design, the associated pipe diameters coded as genes. The length of a chromosome is equal to the number of network pipes; any gene in a chromosome represents a pipe diameter coded with integer coding. A

selection of commercial pipes were considered and represented as integer coding, as shown in Table (4-1).

Table 4-1: Integer coding.

Diameter (mm)	Integer coding
254.0	1
304.8	2
381.0	3
.	.
.	.
.	.
D_n	N

2. **Generation of initial population:** this step generates an initial random population of chromosomes, which represent trial solutions to the sewer network design problem. Here, different population sizes ranging from 30 and 200 are used to investigate the effect of population size on the performance of the proposed GA in the GA-HP model.
3. **Decoding the population:** the population of the strings is decoded using the mapping defined in step 1, to produce a population of trial solutions to the corresponding storm water network problem.
4. **Calling sub-routine HP algorithm:** for every chromosome located within the parent pool, the HP algorithm is used to determine the pipe slope, pipe burial depth and network cost of each generated chromosome as follows:
   a. **Computation of optimal slope:** this step calculates the ground, and minimum, and maximum slopes for each chromosome, selecting the optimal slope from the sewer network characteristics using a multi-logical backtrack algorithm, such as that presented in the flow chart in figure (4-1).

b. **Computation of hydraulic characteristics for the network:** this step calculates velocity, relative flow depth, crown elevation and constraint violations. All these characteristics are calculated using steady flow analysis.

c. **Computation of penalty costs:** the GA assigns a penalty cost to each chromosome if a suggested solution does not satisfy one or more of the constraints.

d. **Computation of total network costs:** the total cost is computed by the sum of the pipe installation, manholes and penalty costs.

5. **Computation of fitness:** this is the fitness for each chromosome in the population. This step computes the fitness function, described as the inverse of the total cost.

6. **Generation of a new population:** this creates a new population by repeating the following steps until the new population is complete:

6.1. **Selection:** two parent chromosomes are selected from a population according to their fitness (the better the fitness, the bigger the chance of being selected). This work considered eight different selection methods.

6.2. **Crossover:** regarding crossover probability, parents crossover to form new offspring (children). If no crossover is performed, the offspring are an exact copy of the parents. Here, seven different crossover methods were considered where $P_c = 1$.

6.3. **Mutation:** a random mutation with some specified probability of mutation, Pm, is carried out for each of the strings that have undergone crossover. In an integer coded GA, random mutation changes the value of the selected gene to the integer's random value between coded intervals [1, 2, 3, 4…]. Here, a random mutation operator with Pm = 0.5 is employed by which only one gene in a chromosome is randomly selected for mutation.

7. **Production of successive generations:** the three operators described above, produce a new generation of storm water network trial designs.
8. **Convergence of the basic GA-HP model:** steps 3–7 are repeated until the convergence criteria for the basic GA search, set by the user, are met. Here, the basic GA search is considered to be converged if the best solution from the search is not improved by number of generations.

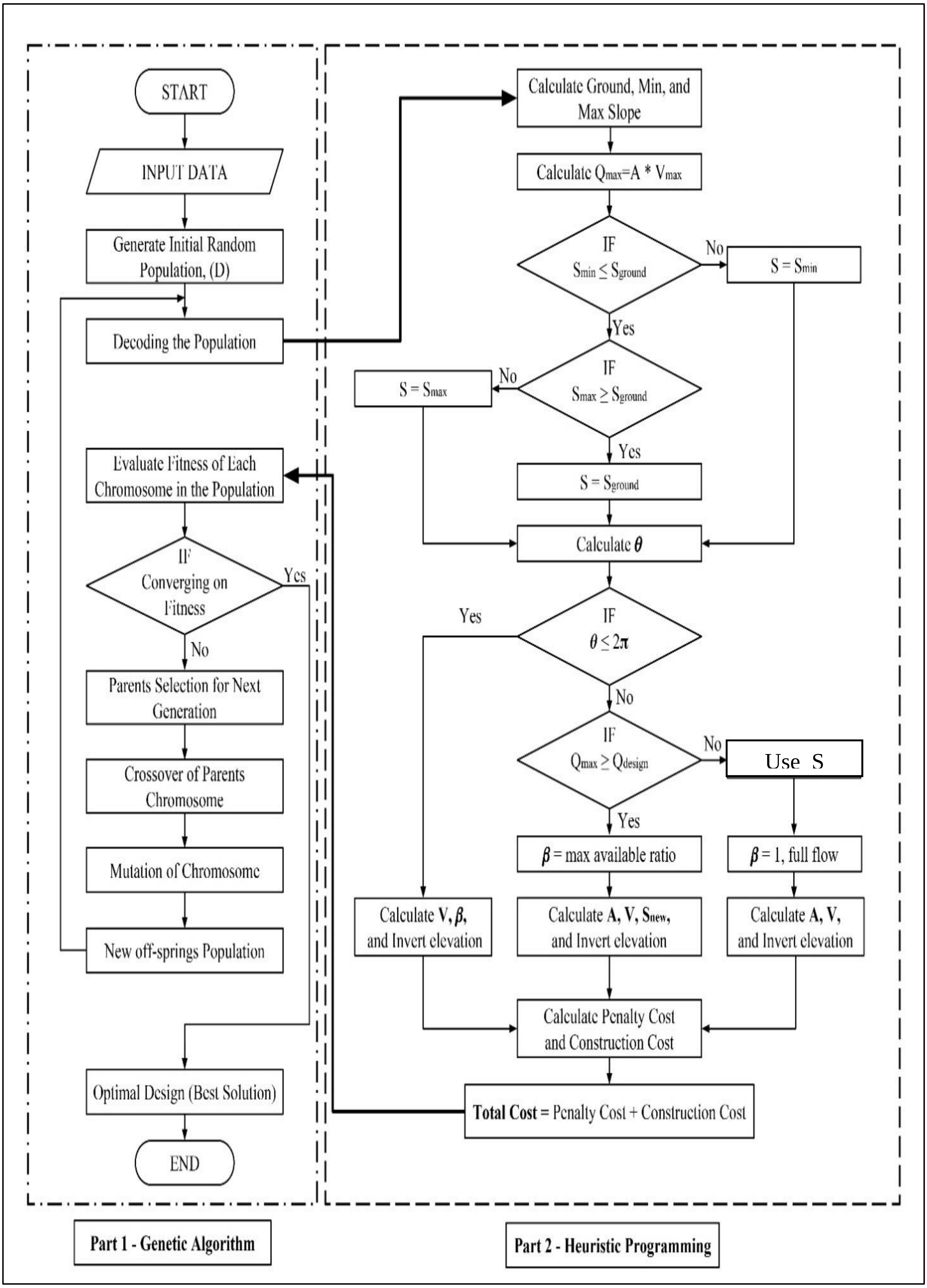


Figure 4-1:Flow chart of the proposed GA-HP model.

CHAPTER FIVE

Chapter Five

Benchmark Problems and Case Studies

In this chapter presents the cost equations, layout, characteristics, and constraints for every benchmark problems and case studies.

5.1. Benchmark problems

5.1.1. First benchmark problem

The first problem is a storm sewer network, originally designed by (Mays and Yen, 1975), and solved by many researchers. The network includes 21 nodes and 20 links, as shown in figure (5-1). Table (5-1) presents the data characteristics for this example. The cost function proposed by (Meredith, 1972) is:

$$C_p = \begin{cases} 10.98D_i + 0.8Z - 5.98 & \forall\, D_i \le 3' \;\; s \;\; Z \le 10' \\ 5.94D_i + 1.166Z + 0.504DZ - 9.64 & \forall\, D_i \le 3' \;\; s \;\; Z \ge 10' \\ 30.0D_i + 4.9Z - 105.9 & \forall\, D_i > 3' \end{cases} \quad \text{... (5-1)}$$

$$C_m = 250 + Z_m^2 \quad \text{... (5-2)}$$

where:

C_p = the unit pipe installation cost (\$/ft),
D_i = the pipe diameter (ft),
Z = the average excavation (ft),
C_m = the cost of manhole construction (\$), and
Z_m = the manhole depth (ft).

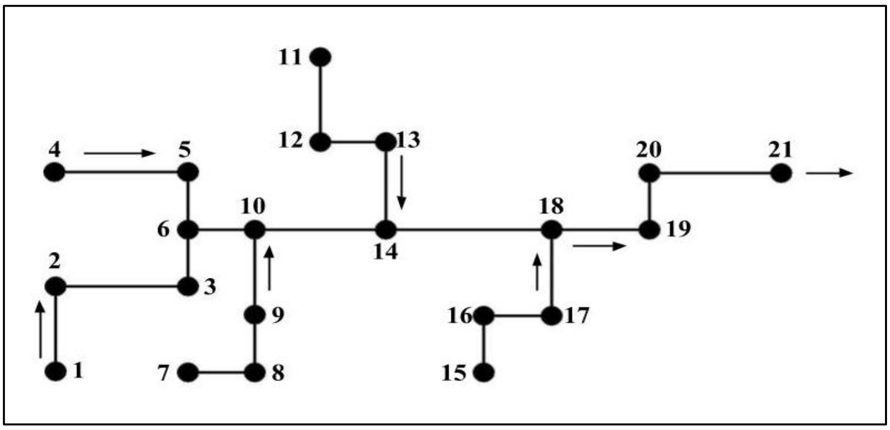


Figure 5-1: Layout of first example (Mays and Yen, 1975).

Table 5-1: Characteristics of first example (Mays and Yen, 1975).

Link ID	Ground Elevation (m)		Length (m)	Q_{design} (Cms)
	Upstream	Downstream		
01 02	152. 4000	150. 8760	106. 6800	0. 1132
02 03	150. 8760	148. 4876	121. 9200	0. 1982
03 06	148. 4876	146. 3040	106. 6800	0. 2548
04 05	149. 3520	147. 8280	121. 9200	0. 1132
05 06	147. 8280	146. 3040	131. 0761	0. 2265
06 10	146. 3040	143. 2560	167. 6796	0. 6229
07 08	149. 3520	147. 8280	147. 6375	0. 2265
08 09	147. 8280	144. 7800	137. 1600	0. 3398
09 10	144. 7800	143. 2560	106. 6800	0. 4530
10 14	143. 2560	141. 7320	152. 4000	1. 2459
11 12	147. 8280	144. 7800	152. 4000	0. 2548
12 13	144. 7800	143. 2560	106. 6800	0. 4530
13 14	143. 2560	141. 7320	106. 6800	0. 5663
14 18	141. 7320	138. 6480	172. 2120	2. 0104
15 16	142. 6464	141. 4272	121. 9200	0. 1132
16 17	141. 4272	140. 2080	091. 4400	0. 1699
17 18	140. 2080	138. 6480	105. 2291	0. 2548
18 19	138. 6480	137. 4648	121. 9200	2. 4635
19 20	137. 4648	136. 5504	152. 4000	2. 5201
20 21	136. 5504	135. 6360	186. 5376	2. 6617

The network constraints are described as a minimum cover depth of 2.4 m, minimum and maximum velocity of 0.6 m/s and 3.6 m/s, respectively, and a maximum relative flow depth that some researchers have assumed to be equal to 0.9, other researchers assuming it to be equal to 0.82; this study uses both 0.9 and 0.82. The Manning coefficient is considered as 0.013. Pipe sizes are chosen from a set of available pipe diameters (254 mm, 304.8 mm, 381 mm, 457.2 mm, 533.4 mm, 762 mm, 914.4 mm, 1066.8 mm and 1219.2 mm).

Mays and Yen (1975) & (1976) used this example to test the proposed Discrete Differential Dynamic Programming (DDDP) model, an iterative technique by which the recursive DP equation is used to search for an improved path through the discrete state in the neighbourhood of a trial solution.

The problem was later solved by Robinson and Labadie (1981) with a different version of the Dynamic Programming model, Miles and Heaney (1988) using a spreadsheet template, (Afshar et al., 2006) applying Genetic Algorithm (GA), (Afshar, 2006) employing Ant Colony Optimization (ACO), and (Yeh et al., 2013) using Tabu Search (TS) and Simulated Annealing (SA). The many researchers also solved this problem with different optimization methods.

5.1.2. Second benchmark problem

The second problem is part of the Kerman sewerage system in Iran, consisting of 21 nodes and 20 pipes, as shown in figure (5-2). The characteristics of this network are provided in table (5-2). The cost functions of excavation, manhole and pipe installation are as follows and are assigned as per (Mansouri and Khanjani, 1999):

$$\boldsymbol{C_p = 1.93e^{3.43D_i} + 0.812Z^{1.53} + 0.437DZ^{1.47}} \qquad \text{... (5-3)}$$

$$\boldsymbol{C_m = 41.46\,Z_m} \qquad \text{... (5-4)}$$

where:
C_p = the unit pipe installation cost ($/m),
D_i = the pipe diameter (m),
Z = the average excavation (m),
C_m = the cost of manhole construction ($), and
Z_m = the manhole depth (m).

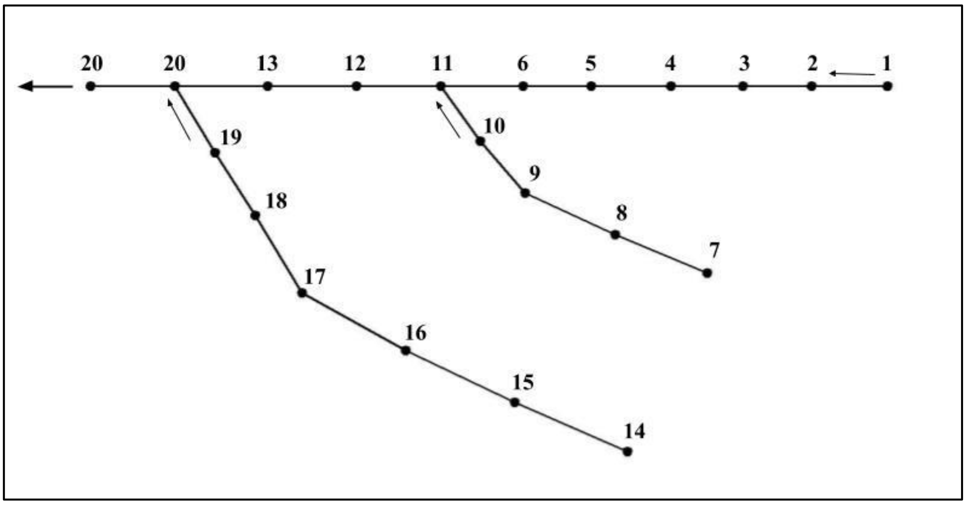


Figure 5-2: Layout of second example (Mansouri and Khanjani, 1999).

The network constraints are described as a minimum velocity of 0.3 m/s, a maximum velocity of 3 m/s, a minimum depth of flow of 0.1, a maximum depth of flow of 0.82 and a minimum depth of cover of 2.45m. The Manning coefficient is 0.013.

Table 5-2: Characteristics of second problem (Mansouri and Khanjani, 1999).

Link ID	Ground Elevation (m)		Length (m)	Q_{design} (Cms)
	Upstream	Downstream		
01 02	74. 59	73. 66	260	0. 0279
02 03	73. 66	72. 10	460	0. 0304
03 04	72. 10	71. 19	260	0. 0324
04 05	71. 19	69. 85	300	0. 0340
05 06	69. 85	68. 24	450	0. 0366
06 11	68. 24	67. 28	400	0. 0387
07 08	70. 70	69. 90	300	0. 0549
08 09	69. 90	69. 30	270	0. 0562
09 10	69. 30	68. 40	310	0. 0580
10 11	68. 40	67. 28	440	0. 0596
11 12	67. 28	66. 22	470	0. 0967
12 13	66. 22	65. 82	350	0. 1012
13 20	65. 82	65. 42	340	0. 1047
14 15	73. 00	71. 50	400	0. 0211
15 16	71. 50	70. 10	400	0. 0264
16 17	70. 10	68. 60	400	0. 0300
17 18	68. 60	66. 80	500	0. 0319
18 19	66. 80	66. 10	400	0. 0403
19 20	66. 10	65. 42	590	0. 0446
20 21	65. 42	64. 50	320	0. 1659

5.2. Case studies

The two case studies that will be used in this research are located in Karbala city, Iraq. The center of Karbala province is located in the Middle Euphrates region. Also, it is located 105 km southwest of Baghdad, on the edge of the desert in the Western Euphrates and on the left side of Al-Husseiniya creek. For more accuracy, the city is located between longitudes (43˚ 15′ 0″ E - 44˚ 15′ 0″ E), and latitudes (32˚ 7′ 30″ N - 32˚ 46′ 5″ N) as shown in figure (5-3). It is bordered to the north and west by Anbar province, to the south by Najaf province, to the east and northeast by Babil province. The ground level to the city is about (30-44) meters above sea level.

As mention previously the purpose of this research is to design a sanitary sewage system for a proposed case studies in Karbala, Iraq. The city of Karbala was chosen for several reasons. Two of those most important reasons were that the city's semi-flat slope would probably result in the challenge of limiting slopes in the optimization program, and it is the center of the visitors' polarization because of the shrine of Imam Hussein in it.

The network constraints are described as a minimum cover depth of (1.0) m, a minimum and maximum velocity of (0.6) m/s and (3.0) m/s, respectively, and a maximum relative flow depth of (0.85). The Manning coefficient is considered as 0.013. Pipe sizes are chosen from a set of available pipe diameters (200 mm, 250 mm, 315 mm, 400 mm and 600 mm).

Figure (5-3) shows the location of the two case studies which were chosen to study in this research. First case study is called Shohdaa Al-Mudhafen district, while the second case study is called Al-Amil district.

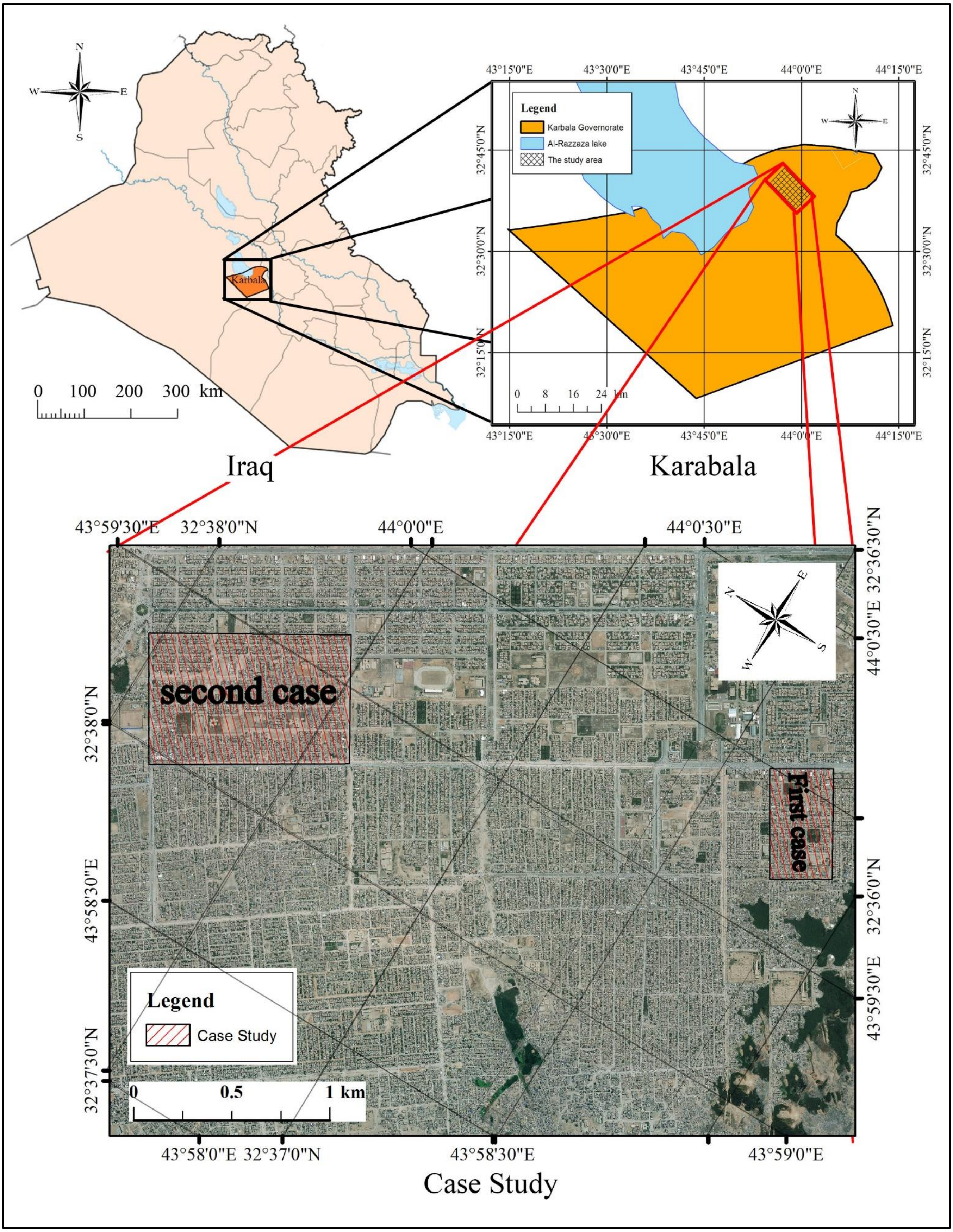


Figure 5-3: Geographical location of the study area relative to Karbala, Iraq.

5.2.1. Cost functions

In this research, Iraqi cost functions were used in the design process, as these functions were not ready before, but were found by collecting information for the cost of buying and installing pipes, the cost of earthworks, and the cost of manholes construction for different depths and sizes. This information has been obtained in tables (5-3) to (5-5) from the Directorate of the Karbala.

The cost functions were derived from this information by regression analysis method with the SPSS program. It is clear that pipes diameters made of a specific material determine the price of the unit of length for that diameter of pipes in the commercial markets. However, the use of these pipes in the sewer works makes them subject to cost functions that incorporate excavation depth and country conditions as additional factors to determine the construction price for unit length. Since the excavation depths and the prices of pipes may vary widely in the same network, it is difficult to obtain one function that covers the movement of prices for all diameters and excavation depths with the accuracy required. Therefore, it is better to find the cost functions in three limited parts by different diameters, as shown in the following:

1. **0.2 m ≤ D_i ≤ 0.315 m & 1 m ≤ Z_i ≤ 6 m**

$$C_p = -5490\, {D_i}^2 + 3182.6\, D_i - 5.03\, Z_i + 71.43\, Z_i\, D_i - 378 \quad \text{... (5-5)}$$

2. **0.4 m ≤ D_i ≤ 0.9 m & 1 m ≤ Z_i ≤ 8 m**

$$C_p = 482.3\, {D_i}^2 + 2.565\, D_i + 14.7\, Z_i + 19.06\, Z_i\, D_i + 46.35 \quad \text{... (5-6)}$$

3. **1 m ≤ D_i ≤ 1.8 m & 4 m ≤ Z_i ≤ 8 m**

$$C_p = 1792.14\, {D_i}^2 - 3639.2\, D_i - 30.5\, Z_i + 226.03\, Z_i\, D_i + 2268.03 \quad \text{... (5-7)}$$

Table 5-3: The cost of the dirt works of pipes (ID / meter length) (DND-DKS, 2017).

Excavation depth (m)	Commercial pipe diameters (mm)																	
	200	250	315	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800
	Cost (ID / meter length) × 1000																	
1-2	40	75	80	100	125	140	×	×	×	×	×	×	×	×	×	×	×	×
2-3	50	85	90	115	140	155	×	×	×	×	×	×	×	×	×	×	×	×
3-4	×	100	110	125	160	170	225	250	×	×	×	×	×	×	×	×	×	×
4-5	×	×	125	150	175	190	250	275	300	750	900	1000	1150	1300	1500	1650	×	×
5-6	×	×	150	175	200	220	275	300	340	1000	1100	1250	1350	1600	1750	1900	2000	2400
6-7	×	×	×	200	225	250	300	325	380	1250	1350	1500	1650	1900	2000	2250	2500	2800
7-8	×	×	×	250	275	300	325	360	425	1500	1550	1650	1900	2100	2250	2500	3000	3250

Table 5-4: Cost of buying pipes (ID / meter length) (DND-DKS, 2017).

Pipe diameters (mm)	200	250	315	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800
Cost (1000 ID / m length)	12.5	20	30	65	90	140	165	210	275	450	500	600	660	750	800	850	1000	1250

Table 5-5: Cost of construction manholes (ID/ each manhole) (DND-DKS, 2017).

Type of manhole	Dimension (cm)	Depth (m)	Cost (1000 ID)
AS	90 x 60	1 - 1.69	1000 – 1350
BS	Φ 110	1.7 - 2.99	1500 – 2000
BD	Φ 110	> 2.99	1750 – 2500
CS	Φ 150	1 – 3.24	2000 – 2450
CD	Φ 150	> 3.24	2700 - 3000
CD1			10,000 – 25,000

On the other hand, one equation is derived representing the construction cost of manholes for all depths and sizes as shown in the following:

$$\boldsymbol{C_m = -24.3\, Z_m^2 + 1411.7\, Z_m + 22.9\, DM - 6.74\, Z_m DM - 1830.2} \quad \text{... (5-8)}$$

where:

C_p = the unit pipe installation cost (1000 ID /m),

D_i = the pipe diameter (m),

Z = the average excavation (m),

C_m = the cost of manhole construction (unit.),

Z_m = the manhole depth (m),

DM = the equivalent diameter of manhole (mm) equal (83 mm for type AS, 110 mm for type manholes BS and BD, and 150 mm for type CS and CD).

The previous equations have high R-squared values equal 0.98, 0.99, 0.99 and 0.967, for Eqs. (5-5, 5-6, 5-7 and 5-8), respectively. Also, the high values indicate that the equations are closer to the representation of realistic values for the cost.

5.2.2. Sewer networks of cases study

5.2.2.1. First case study

The first case study is located in the city center, part from Shohdaa Al-Mudhafen quarter. It is located between latitudes (32° 36′ 5″ N - 32° 36′ 24″ N), and longitudes (43° 59′ 19″ E - 44° 0′ 5″ E), it forms about (0.195) km^2 as shown in figure (5-3). It includes 91 nodes and 90 pipes, the total length of a network (3.605 km), and the layout of network present such as figure (5-4). The total cost of manual design for network as build equal (529.7 million ID). Table (5-6) presents the data characteristics for this network and information of design by manually.

Table 5-6: Characteristics and manual design for the first case study(GIS-DKS, 2017).

Link ID	Ground Elevation (m)		L. (m)	Invert Elevation (m)		Dia. (mm)	Slope m/m
	U/S	D/S		U/S	D/S		
01 02	36. 55	36. 25	25	35. 10	35. 00	250	0. 0040
02 03	36. 25	36. 50	40	35. 00	34. 84	250	0. 0040
03 04	36. 50	36. 67	40	34. 84	34. 68	250	0. 0040
04 05	36. 67	37. 21	40	34. 68	34. 52	250	0. 0040
05 06	37. 21	37. 40	40	34. 52	34. 36	250	0. 0040
06 12	37. 40	37. 54	50	34. 36	34. 16	250	0. 0040
07 08	36. 45	36. 58	25	35. 20	35. 10	250	0. 0040
08 09	36. 58	36. 81	40	35. 10	34. 94	250	0. 0040
09 10	36. 81	37. 14	40	34. 94	34. 78	250	0. 0040
10 11	37. 14	37. 52	40	34. 78	34. 62	250	0. 0040
11 12	37. 52	37. 54	40	34. 62	34. 46	250	0. 0040
12 16	37. 54	37. 24	50	34. 16	33. 96	250	0. 0040
13 14	36. 69	36. 85	40	35. 44	35. 28	250	0. 0040
14 15	36. 85	37. 08	40	35. 28	35. 12	250	0. 0040
15 16	37. 08	37. 24	40	35. 12	34. 96	250	0. 0040
16 17	37. 24	37. 04	40	33. 96	33. 80	250	0. 0040
17 18	37. 04	36. 67	40	33. 80	33. 64	250	0. 0040
18 19	36. 67	36. 55	40	33. 64	33. 48	250	0. 0040
19 43	36. 55	36. 27	40	33. 48	33. 32	250	0. 0040
20 21	36. 68	36. 51	40	35. 42	35. 26	250	0. 0040
21 22	36. 51	36. 50	40	35. 26	35. 10	250	0. 0040
22 23	36. 50	36. 27	40	35. 10	34. 94	250	0. 0040
23 24	36. 27	36. 27	40	34. 94	34. 78	250	0. 0040
24 25	36. 27	35. 75	40	34. 66	34. 50	250	0. 0040
25 31	35. 75	36. 52	45	34. 50	34. 32	250	0. 0040
26 27	36. 55	36. 98	40	35. 30	35. 14	250	0. 0040
27 28	36. 98	37. 12	40	35. 14	34. 98	250	0. 0040
28 29	37. 12	37. 00	40	34. 98	34. 82	250	0. 0040
29 30	37. 00	36. 78	40	34. 82	34. 66	250	0. 0040
30 31	36. 78	36. 52	40	34. 66	34. 50	250	0. 0040
31 37	36. 52	36. 80	50	34. 32	34. 12	250	0. 0040
32 33	36. 30	37. 20	40	35. 05	34. 89	250	0. 0040
33 34	37. 20	37. 05	40	34. 89	34. 73	250	0. 0040
34 35	37. 05	37. 00	40	34. 73	34. 57	250	0. 0040
35 36	37. 00	36. 87	40	34. 57	34. 41	250	0. 0040
36 37	36. 87	36. 80	40	34. 41	34. 25	250	0. 0040
37 40	36. 80	36. 66	50	34. 12	33. 92	250	0. 0040
38 39	36. 48	35. 71	40	34. 62	34. 46	250	0. 0040
39 40	35. 71	36. 66	40	34. 46	34. 30	250	0. 0040
40 41	36. 66	36. 51	40	33. 92	33. 76	250	0. 0040
41 42	36. 51	36. 50	40	33. 76	33. 60	250	0. 0040
42 43	36. 50	36. 27	40	33. 60	33. 44	250	0. 0040
43 48	36. 27	36. 21	50	33. 255	33. 09	315	0. 0033
44 45	36. 27	35. 75	20	34. 58	34. 50	250	0. 0040
45 46	35. 75	36. 98	40	34. 50	34. 34	250	0. 0040

Table 5-6: Continued.

Link ID	Ground Elevation (m)		L. (m)	Invert Elevation (m)		Dia. (mm)	Slope m/m
	U/S	D/S		U/S	D/S		
46 47	36. 98	37. 12	40	34. 34	34. 18	250	0. 0040
47 48	37. 12	36. 21	50	34. 18	33. 98	250	0. 0040
48 49	36. 21	36. 05	45	33. 09	32. 942	315	0. 0033
49 60	36. 05	35. 98	45	32. 942	32. 793	315	0. 0033
57 58	36. 42	36. 32	30	35. 17	35. 05	250	0. 0040
54 55	36. 70	36. 69	30	35. 45	35. 33	250	0. 0040
55 56	36. 69	36. 63	35	35. 33	35. 19	250	0. 0040
56 58	36. 63	36. 32	40	35. 19	35. 03	250	0. 0040
58 59	36. 32	36. 21	50	35. 03	34. 83	250	0. 0040
50 51	36. 68	36. 68	30	35. 43	35. 31	250	0. 0040
51 52	36. 68	36. 63	40	35. 31	35. 15	250	0. 0040
52 53	36. 63	36. 27	40	35. 15	34. 99	250	0. 0040
53 59	36. 27	36. 21	30	34. 99	34. 87	250	0. 0040
59 60	36. 21	35. 98	50	34. 83	34. 63	250	0. 0040
60 65	35. 98	35. 80	50	32. 793	32. 628	315	0. 0033
61 62	36. 44	36. 34	50	35. 19	34. 99	250	0. 0040
62 63	36. 34	36. 24	45	34. 99	34. 81	250	0. 0040
63 64	36. 24	36. 04	45	34. 81	34. 63	250	0. 0040
64 65	36. 04	35. 80	50	34. 63	34. 43	250	0. 0040
65 91	35. 80	35. 42	50	32. 628	32. 463	315	0. 0033
73 74	34. 80	34. 55	35	33. 44	33. 30	250	0. 0040
74 75	34. 55	34. 34	40	33. 25	33. 09	250	0. 0040
75 76	34. 34	34. 62	40	33. 09	32. 93	250	0. 0040
76 84	34. 62	34. 89	40	32. 93	32. 77	250	0. 0040
77 78	35. 26	35. 10	35	33. 99	33. 85	250	0. 0040
78 79	35. 10	35. 13	35	33. 85	33. 71	250	0. 0040
79 80	35. 13	35. 28	40	33. 71	33. 55	250	0. 0040
80 81	35. 28	35. 22	40	33. 55	33. 39	250	0. 0040
81 82	35. 22	35. 09	40	33. 39	33. 23	250	0. 0040
82 83	35. 09	34. 85	30	33. 23	33. 11	250	0. 0040
83 84	34. 85	34. 89	30	33. 11	32. 99	250	0. 0040
84 85	34. 89	35. 58	50	32. 77	32. 57	250	0. 0040
66 67	35. 66	35. 78	35	34. 41	34. 27	250	0. 0040
67 68	35. 78	35. 92	35	34. 27	34. 13	250	0. 0040
68 69	35. 92	35. 97	40	34. 13	33. 97	250	0. 0040
69 70	35. 97	35. 94	40	33. 97	33. 81	250	0. 0040
70 71	35. 94	35. 77	40	33. 81	33. 65	250	0. 0040
71 72	35. 77	35. 61	30	33. 65	33. 53	250	0. 0040
72 85	35. 61	35. 58	30	33. 53	33. 41	250	0. 0040
85 91	35. 58	35. 42	45	32. 57	32. 39	250	0. 0040
86 87	34. 35	34. 54	35	33. 10	32. 96	250	0. 0040
87 88	34. 54	34. 75	40	32. 96	32. 80	250	0. 0040
88 89	34. 75	35. 00	40	32. 80	32. 64	250	0. 0040
89 90	35. 00	35. 14	40	32. 64	32. 48	250	0. 0040
90 91	35. 14	35. 42	50	32. 48	32. 215	250	0. 0040

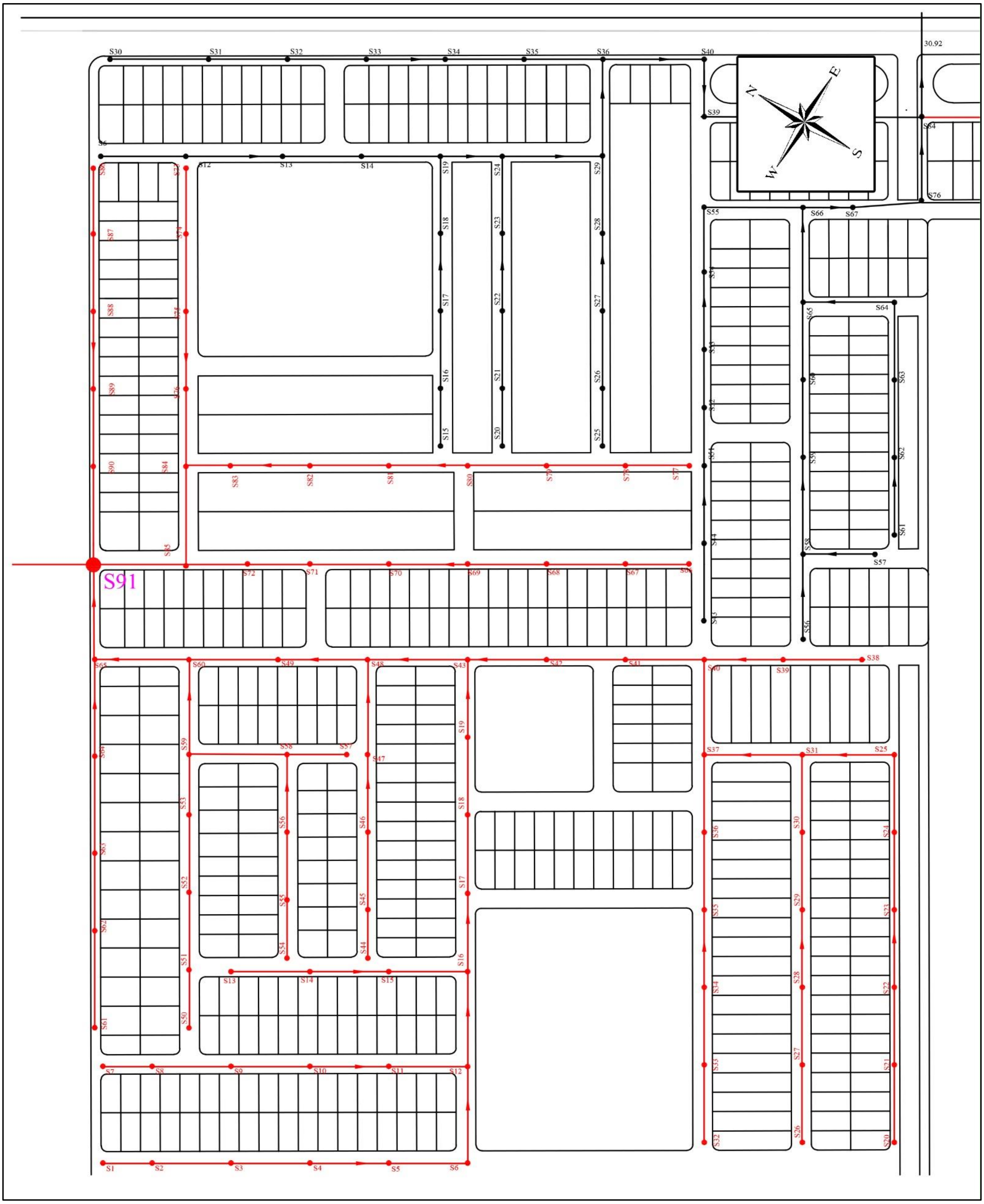


Figure 5-4: Layout of the first case study (part from Shohdaa Al-Mudhafen district) (GIS-DKS, 2017).

5.2.2.2. Second case study

The second case study located in Al-hur subdistrict, third sector from Al-Amil quarter. It is located between latitudes (32˚ 37′ 24″ N - 32˚ 38′ 2″ N), and longitudes (43˚ 59′ 2″ E - 43˚ 59′ 37″ E), it forms about (0.66) km^2 as shown in figure (5-3). It includes 355 nodes and 354 pipes, the total length of network (13.506 km), and the layout of network present such as figure (5-5). The total cost of manual design for network as build equal (2,190 million ID). Table (5-8) presents the data characteristics as build for this network and information of design by manually.

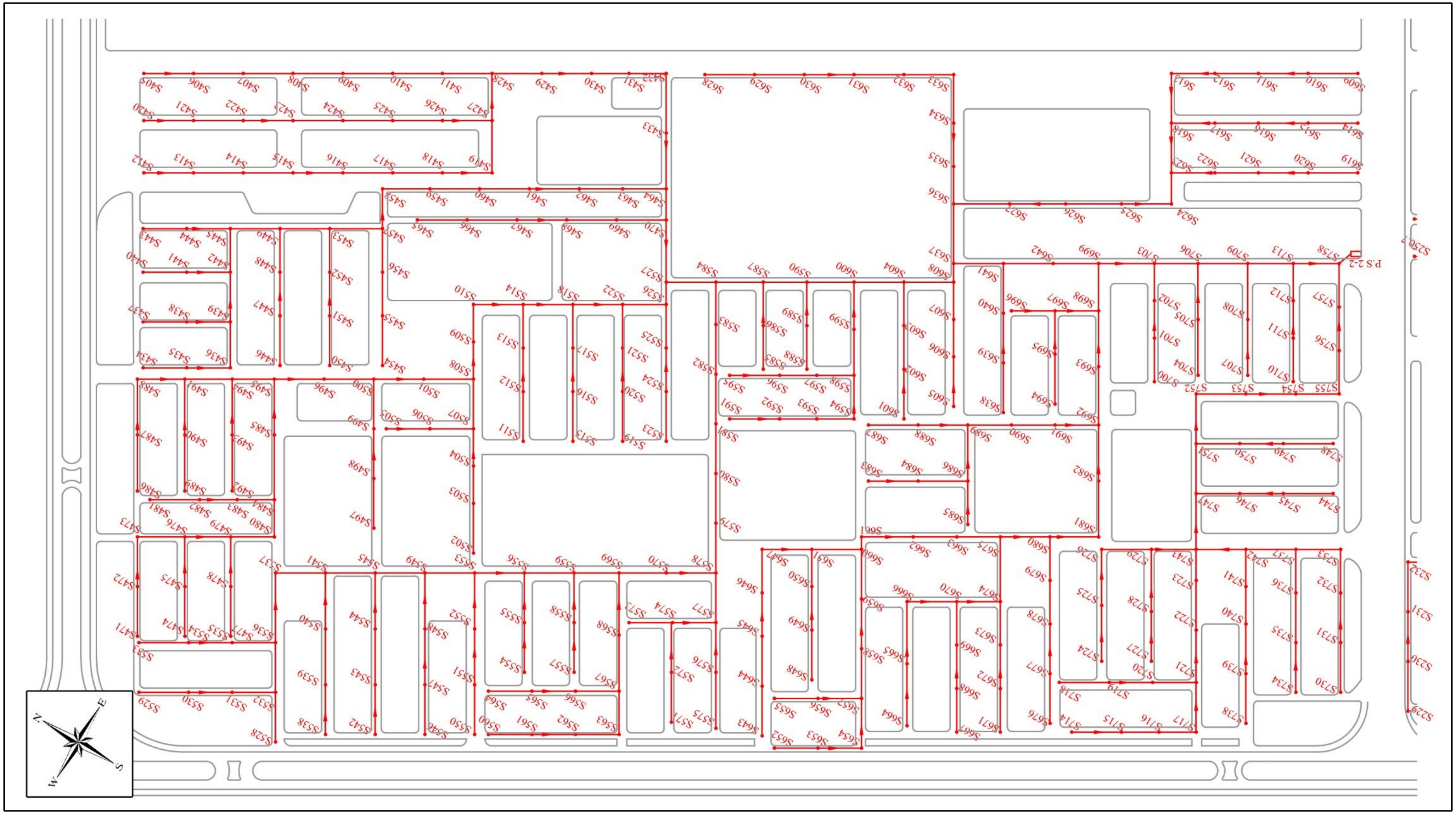


Figure 5-5: Layout of the second case study (third sector from Al-Amil district) (GIS-DKS, 2017).

able 5-7: Characteristics and manual design for the second case study (GIS-DKS, 2017).

Link ID	Ground Elevation (m)		L (m)	Invert Elevation (m)		Dia. (mm)	Slope m/m
	U/S	D/S		U/S	D/S		
405 406	29.56	29.85	40	28.24	28.11	315	0.00317
406 407	29.85	30.20	40	28.11	27.98	315	0.00317
407 408	30.20	30.36	40	27.98	27.86	315	0.00317
408 409	30.36	30.50	40	27.86	27.73	315	0.00317
409 410	30.50	30.79	40	27.73	27.60	315	0.00317
410 411	30.79	30.95	40	27.60	27.47	315	0.00317
411 428	30.95	30.98	40	27.47	27.35	315	0.00317
412 413	29.56	29.90	40	28.24	28.12	315	0.00317
413 414	29.90	30.50	40	28.12	28.00	315	0.00317
414 415	30.50	30.90	40	28.00	27.88	315	0.00317
415 416	30.90	30.90	40	27.88	27.76	315	0.00317
416 417	30.90	30.70	40	27.76	27.64	315	0.00317
417 418	30.70	30.83	40	27.64	27.52	315	0.00317
418 419	30.83	30.70	40	27.52	27.40	315	0.00317
419 427	30.70	30.65	40	27.40	27.28	315	0.00317
420 421	29.65	30.00	40	28.33	28.21	315	0.00317
421 422	30.00	30.30	40	28.21	28.09	315	0.00317
422 423	30.30	30.61	40	28.09	27.97	315	0.00317
423 424	30.61	60.80	40	27.97	27.85	315	0.00317
424 425	60.80	31.00	40	27.85	27.73	315	0.00317
425 426	31.00	31.00	40	27.73	27.61	315	0.00317
426 427	31.00	30.65	40	27.61	27.49	315	0.00317
427 428	30.65	30.98	40	27.28	27.16	315	0.00317
428 429	30.98	30.75	40	27.075	26.97	315	0.00317
429 430	30.75	30.65	40	26.97	26.87	315	0.00317
430 431	30.65	30.50	30	26.87	26.80	315	0.00317
431 432	30.50	30.45	30	26.80	26.72	315	0.00317
432 433	30.45	30.48	50	26.72	26.60	400	0.00250
433 464	30.48	30.50	45	26.60	26.48	400	0.00250
434 435	30.20	30.30	35	28.95	28.81	250	0.00400
435 436	30.30	30.53	35	28.81	28.67	250	0.00400
436 439	30.53	30.49	35	28.67	28.53	250	0.00400
437 438	30.15	30.15	35	28.90	28.76	250	0.00400
438 439	30.15	30.49	35	28.76	28.62	250	0.00400
439 442	30.49	30.81	40	28.53	28.37	250	0.00400
440 441	29.93	30.20	35	28.68	28.54	250	0.00400
441 442	30.20	30.81	35	28.54	28.40	250	0.00400
442 445	30.81	30.69	35	28.37	28.23	250	0.00400
443 444	29.76	30.40	35	28.51	28.37	250	0.00400
444 445	30.40	30.69	35	28.37	28.23	250	0.00400
445 449	30.69	31.00	40	28.23	28.07	250	0.00400
446 447	30.86	31.10	40	29.61	29.45	250	0.00400
447 448	31.10	31.10	35	29.45	29.31	250	0.00400
448 449	31.10	31.00	35	29.31	29.17	250	0.00400
449 453	31.00	31.22	40	28.07	27.91	250	0.00400
450 451	30.92	31.00	40	29.67	29.51	250	0.00400

Table 5-7: Continued.

Link ID	Ground Elevation (m)		L (m)	Invert Elevation (m)		Dia. (mm)	Slope m/m
	U/S	D/S		U/S	D/S		
451 452	31.00	31.10	35	29.51	29.37	250	0.00400
452 453	31.10	31.22	35	29.37	29.23	250	0.00400
453 457	31.22	30.72	42	27.91	27.74	250	0.00400
454 455	30.93	31.35	40	29.68	29.52	250	0.00400
455 456	31.35	31.85	35	29.52	29.38	250	0.00400
456 457	31.85	30.72	35	29.38	29.24	250	0.00400
457 458	30.72	30.66	35	27.675	27.56	315	0.00317
458 459	30.66	30.70	40	27.56	27.44	315	0.00317
459 460	30.70	30.70	40	27.44	27.31	315	0.00317
460 461	30.70	30.65	40	27.31	27.18	315	0.00317
461 462	30.65	30.60	40	27.18	27.06	315	0.00317
462 463	30.60	30.55	35	27.06	26.94	315	0.00317
463 464	30.55	30.50	35	26.94	26.83	315	0.00317
464 470	30.50	30.52	25	26.48	26.42	400	0.00250
465 466	30.52	30.58	40	29.27	29.11	250	0.00400
466 467	30.58	30.60	40	29.11	28.95	250	0.00400
467 468	30.60	30.65	40	28.95	28.79	250	0.00400
468 469	30.65	30.68	40	28.79	28.63	250	0.00400
469 470	30.68	30.70	40	28.63	28.47	250	0.00400
470 527	30.70	30.80	50	26.42	26.30	400	0.00250
471 472	31.17	30.85	40	29.57	29.41	250	0.00400
472 473	30.85	30.53	40	29.41	29.25	250	0.00400
473 476	30.53	30.70	40	29.25	29.09	250	0.00400
474 475	31.31	31.20	40	29.77	29.61	250	0.00400
475 476	31.20	30.70	40	29.61	29.45	250	0.00400
476 479	30.70	30.64	35	29.09	28.95	250	0.00400
477 478	31.50	31.10	40	29.71	29.55	250	0.00400
478 479	31.10	30.64	40	29.55	29.39	250	0.00400
479 480	30.64	30.66	35	28.95	28.81	250	0.00400
480 484	30.66	30.53	30	28.81	28.69	250	0.00400
481 482	30.50	30.50	40	29.25	29.09	250	0.00400
482 483	30.50	30.65	30	29.09	28.97	250	0.00400
483 484	30.65	30.53	30	28.97	28.85	250	0.00400
484 485	30.53	30.60	50	28.69	28.49	250	0.00400
485 495	30.60	30.86	45	28.49	28.31	250	0.00400
486 487	30.50	30.35	45	29.25	29.07	250	0.00400
487 488	30.35	30.20	45	29.07	28.89	250	0.00400
488 491	30.20	30.30	40	28.89	28.73	250	0.00400
489 490	30.50	30.85	45	29.25	29.07	250	0.00400
490 491	30.85	30.30	45	29.07	28.89	250	0.00400
491 494	30.30	30.53	38	28.73	28.57	250	0.00400
492 493	30.65	30.60	45	29.40	29.22	250	0.00400
493 494	30.60	30.53	45	29.22	29.04	250	0.00400
494 495	30.53	30.86	35	28.57	28.44	250	0.00400
495 496	30.86	30.92	40	28.31	28.15	250	0.00400
496 500	30.92	30.93	40	28.15	27.99	250	0.00400

Table 5-7: Continued.

Link ID	Ground Elevation (m)		L (m)	Invert Elevation (m)		Dia. (mm)	Slope m/m
	U/S	D/S		U/S	D/S		
497 498	31.21	31.29	40	29.96	29.80	250	0.00400
498 499	31.29	31.11	40	28.66	28.50	250	0.00400
499 500	31.11	30.93	40	28.50	28.34	250	0.00400
500 501	30.93	31.61	40	27.99	27.83	250	0.00400
501 508	31.61	31.56	40	27.83	27.67	250	0.00400
502 503	31.45	31.73	40	30.20	30.04	250	0.00400
503 504	31.73	31.65	30	30.04	29.92	250	0.00400
504 507	31.65	31.70	30	29.92	29.80	250	0.00400
505 506	30.86	31.60	35	29.61	29.47	250	0.00400
506 507	31.60	31.70	35	29.47	29.33	250	0.00400
507 508	31.70	31.56	40	29.00	28.84	315	0.00317
508 509	31.56	31.42	30	27.605	27.51	315	0.00317
509 510	31.42	31.32	30	27.51	27.41	315	0.00317
510 514	31.32	31.67	40	27.41	27.29	315	0.00317
511 512	31.45	31.70	40	30.20	30.04	250	0.00400
512 513	31.70	31.85	35	30.04	29.90	250	0.00400
513 514	31.85	31.67	35	29.70	29.56	250	0.00400
514 518	31.67	31.41	40	27.29	27.16	315	0.00317
515 516	31.35	31.61	40	30.10	29.94	250	0.00400
516 517	31.61	31.60	35	29.94	29.80	250	0.00400
517 518	31.60	31.41	35	29.60	29.46	250	0.00400
518 522	31.41	31.55	40	27.16	27.03	315	0.00317
519 520	31.31	31.65	40	30.06	29.90	250	0.00400
520 521	31.65	31.83	35	29.90	29.76	250	0.00400
521 522	31.83	31.55	35	29.47	29.33	250	0.00400
522 526	31.55	31.50	35	27.03	26.92	315	0.00317
523 524	31.22	31.10	40	29.97	29.81	250	0.00400
524 525	31.10	31.00	35	29.81	29.67	250	0.00400
525 526	31.00	31.50	35	29.67	29.53	250	0.00400
526 527	31.50	30.80	18	26.92	26.86	315	0.00317
527 584	30.80	31.08	40	26.30	26.20	400	0.00250
528 532	32.10	31.72	40	30.63	30.47	250	0.00400
529 530	31.50	31.90	40	30.25	30.09	250	0.00400
530 531	31.90	31.65	35	30.09	29.95	250	0.00400
531 532	31.65	31.72	35	29.95	29.81	250	0.00400
532 536	31.72	31.44	40	29.81	29.65	250	0.00400
533 534	31.17	31.31	40	29.92	29.76	250	0.00400
534 535	31.31	31.50	35	29.76	29.62	250	0.00400
535 536	31.50	31.44	35	29.62	29.48	250	0.00400
536 537	31.44	31.19	55	29.48	29.26	250	0.00400
537 541	31.19	31.14	40	29.00	28.84	250	0.00400
538 539	32.38	32.20	40	30.41	30.25	250	0.00400
539 540	32.20	31.60	45	30.25	30.07	250	0.00400
540 541	31.60	31.14	45	30.07	29.89	250	0.00400
541 545	31.14	31.86	40	28.84	28.68	250	0.00400
542 543	32.68	32.80	40	31.43	31.27	250	0.00400

Table 5-7: Continued.

Link ID	Ground Elevation (m)		L (m)	Invert Elevation (m)		Dia. (mm)	Slope m/m
	U/S	D/S		U/S	D/S		
543 544	32.80	32.20	45	30.97	30.79	250	0.00400
544 545	32.20	31.86	45	30.79	30.61	250	0.00400
545 549	31.86	31.20	40	28.68	28.52	250	0.00400
546 547	32.98	32.80	40	30.47	30.31	250	0.00400
547 548	32.80	32.51	45	30.31	30.13	250	0.00400
548 549	32.51	31.20	45	30.13	29.95	250	0.00400
549 553	31.20	31.45	40	28.52	28.36	250	0.00400
550 551	33.22	33.06	40	31.97	31.81	250	0.00400
551 552	33.06	32.50	45	30.56	30.38	250	0.00400
552 553	32.50	31.45	45	30.38	30.20	250	0.00400
553 556	31.45	32.06	40	28.36	28.20	250	0.00400
554 555	33.00	32.60	40	31.13	30.97	250	0.00400
555 556	32.60	32.06	40	30.97	30.81	250	0.00400
556 559	32.06	32.14	40	28.20	28.04	250	0.00400
557 558	33.06	32.70	40	31.24	31.08	250	0.00400
558 559	32.70	32.17	40	31.08	30.92	250	0.00400
559 569	32.17	32.09	35	28.04	27.90	250	0.00400
560 561	33.22	33.24	35	31.97	31.83	250	0.00400
561 562	33.24	33.40	35	31.83	31.69	250	0.00400
562 563	33.40	33.69	35	31.69	31.55	250	0.00400
563 567	33.69	33.65	35	31.55	31.41	250	0.00400
564 565	33.09	33.07	35	31.84	31.70	250	0.00400
565 566	33.07	33.30	35	31.70	31.56	250	0.00400
566 567	33.30	33.65	35	31.56	31.42	250	0.00400
567 568	33.65	33.40	45	31.41	31.23	250	0.00400
568 569	33.40	32.09	50	31.04	30.84	250	0.00400
569 570	32.09	31.90	40	27.90	27.74	250	0.00400
570 578	31.90	31.60	40	27.74	27.58	250	0.00400
571 572	33.91	32.85	40	31.76	31.60	250	0.00400
572 574	32.85	33.06	40	31.60	31.44	250	0.00400
573 574	32.73	33.06	35	31.26	31.12	250	0.00400
574 577	33.06	32.23	35	31.12	30.98	250	0.00400
575 576	33.85	32.33	45	30.87	30.69	250	0.00400
576 577	32.33	32.23	40	30.69	30.53	250	0.00400
577 578	32.23	31.60	45	30.53	30.35	250	0.00400
578 579	31.60	31.45	40	27.515	27.38	315	0.00317
579 580	31.45	31.30	40	27.38	27.26	315	0.00317
580 581	31.30	31.28	40	27.26	27.13	315	0.00317
581 582	31.28	31.09	40	27.13	27.00	315	0.00317
582 583	31.09	31.08	40	27.00	26.88	315	0.00317
583 584	31.08	31.08	35	26.88	26.77	315	0.00317
584 587	31.08	30.81	40	26.2	26.10	400	0.00250
585 586	31.80	31.15	35	29.84	29.70	250	0.00400
586 587	31.15	30.81	35	29.70	29.56	250	0.00400
587 590	30.81	30.71	35	26.10	26.01	400	0.00250
588 589	31.03	31.08	35	29.74	29.60	250	0.00400

Table 5-7: Continued.

Link ID	Ground Elevation (m)		L (m)	Invert Elevation (m)		Dia. (mm)	Slope m/m
	U/S	D/S		U/S	D/S		
589 590	31.08	30.71	35	29.60	29.46	250	0.00400
590 600	30.71	30.74	35	26.01	25.92	400	0.00250
591 592	31.40	31.15	40	29.95	29.79	250	0.00400
592 593	31.15	31.00	30	29.79	29.67	250	0.00400
593 594	31.00	30.80	30	29.107	29.05	250	0.00400
594 598	30.80	30.79	35	29.05	28.91	250	0.00400
595 596	31.09	31.04	40	29.84	29.68	250	0.00400
596 597	31.04	30.91	30	29.68	29.56	250	0.00400
597 598	30.91	30.79	30	29.56	29.44	250	0.00400
598 599	30.79	30.77	40	28.91	28.75	250	0.00400
599 600	30.77	30.74	40	28.75	28.59	250	0.00400
600 604	30.74	30.75	40	25.92	25.82	400	0.00250
601 602	30.94	30.87	40	29.69	29.53	250	0.00400
602 603	30.87	30.80	35	29.53	29.39	250	0.00400
603 604	30.80	30.75	35	29.39	29.25	250	0.00400
604 608	30.75	30.40	40	25.82	25.725	400	0.00250
605 606	30.86	30.96	40	29.55	29.39	250	0.00400
606 607	30.96	30.65	30	29.39	29.27	250	0.00400
607 608	30.65	30.40	30	29.27	29.15	250	0.00400
608 637	30.40	30.32	13	25.725	25.69	400	0.00250
609 610	31.50	31.50	40	30.25	30.09	250	0.00400
610 611	31.50	31.52	40	30.09	29.93	250	0.00400
611 612	31.52	31.20	35	29.93	29.79	250	0.00400
612 613	31.20	31.10	35	29.61	29.47	250	0.00400
613 618	31.10	30.56	40	29.47	29.31	250	0.00400
614 615	31.60	31.40	40	29.91	29.75	250	0.00400
615 616	31.40	31.10	40	29.75	29.59	250	0.00400
616 617	31.10	30.85	35	29.59	29.45	250	0.00400
617 618	30.85	30.56	35	29.45	29.31	250	0.00400
618 623	30.56	30.40	40	29.31	29.15	250	0.00400
619 620	31.30	31.07	40	29.75	29.59	250	0.00400
620 621	31.07	30.85	40	29.59	29.43	250	0.00400
621 622	30.85	30.62	35	29.43	29.29	250	0.00400
622 623	30.62	30.40	35	29.29	29.15	250	0.00400
623 624	30.40	30.45	25	29.15	29.05	250	0.00400
624 625	30.45	30.42	40	29.05	28.89	250	0.00400
625 626	30.42	30.40	45	28.89	28.71	250	0.00400
626 627	30.40	30.37	45	28.71	28.53	250	0.00400
627 636	30.37	30.35	45	28.53	28.35	250	0.00400
628 629	30.40	30.38	40	29.15	28.99	250	0.00400
629 630	30.38	30.35	40	28.99	28.83	250	0.00400
630 631	30.35	30.30	40	28.83	28.67	250	0.00400
631 632	30.30	30.25	40	28.67	28.51	250	0.00400
632 633	30.25	30.25	40	28.51	28.35	250	0.00400
633 634	30.25	30.25	35	28.35	28.21	250	0.00400
634 635	30.25	30.30	35	28.21	28.07	250	0.00400

Table 5-7: Continued.

Link ID	Ground Elevation (m)		L (m)	Invert Elevation (m)		Dia. (mm)	Slope m/m
	U/S	D/S		U/S	D/S		
635 636	30.30	30.35	30	28.07	27.95	250	0.00400
636 637	30.35	30.32	50	27.95	27.75	250	0.00400
637 641	30.32	30.55	40	25.69	25.59	400	0.00250
638 639	30.93	30.80	40	29.68	29.52	250	0.00400
639 640	30.80	30.75	40	29.52	29.36	250	0.00400
640 641	30.75	30.55	40	29.36	29.20	250	0.00400
641 642	30.55	30.45	40	25.59	25.49	400	0.00250
642 699	30.45	30.50	35	25.49	25.40	400	0.00250
643 644	33.10	32.40	40	31.17	31.01	250	0.00400
644 645	32.40	32.15	40	31.01	30.85	250	0.00400
645 646	32.15	33.48	35	30.85	30.71	250	0.00400
646 647	33.48	31.30	35	30.19	30.05	250	0.00400
647 651	31.30	31.70	40	29.80	29.64	250	0.00400
648 649	32.90	32.58	40	30.87	30.71	250	0.00400
649 650	32.58	31.97	35	30.71	30.57	250	0.00400
650 651	31.97	31.70	30	30.57	30.45	250	0.00400
651 660	31.70	31.70	40	29.64	29.48	250	0.00400
652 653	33.50	33.75	35	32.25	32.11	250	0.00400
653 654	33.75	33.91	35	32.11	31.97	250	0.00400
654 657	33.91	33.90	40	31.97	31.81	250	0.00400
655 656	32.68	32.90	35	31.43	31.29	250	0.00400
656 657	32.90	33.90	35	31.29	31.15	250	0.00400
657 658	33.90	33.25	40	31.15	30.99	250	0.00400
658 659	33.25	32.80	40	30.77	30.61	250	0.00400
659 660	32.80	31.70	40	30.61	30.45	250	0.00400
660 661	31.70	31.75	10	29.48	29.44	250	0.00400
661 662	31.75	31.65	35	29.44	29.30	250	0.00400
662 663	31.65	31.50	35	29.30	29.16	250	0.00400
663 675	31.50	31.85	40	29.16	29.00	250	0.00400
664 665	34.41	33.78	50	32.16	31.96	250	0.00400
665 666	33.78	33.01	50	31.96	31.76	250	0.00400
666 670	33.01	32.94	40	31.76	31.60	250	0.00400
667 668	34.33	34.39	35	33.08	32.94	250	0.00400
668 669	34.39	33.65	35	31.97	31.83	250	0.00400
669 670	33.65	32.94	35	31.83	31.69	250	0.00400
670 674	32.94	33.00	35	31.60	31.46	250	0.00400
671 672	34.09	34.15	35	32.17	32.03	250	0.00400
672 673	34.15	33.50	35	32.03	31.89	250	0.00400
673 674	33.50	33.00	35	29.64	29.50	250	0.00400
674 675	33.00	31.85	50	29.50	29.30	250	0.00400
675 680	31.85	32.00	40	29.00	28.84	250	0.00400
676 677	34.15	34.15	40	32.90	32.74	250	0.00400
677 678	34.15	33.60	40	31.198	31.04	250	0.00400
678 679	33.60	33.30	35	30.03	29.89	250	0.00400
679 680	33.30	32.00	37	29.89	29.742	250	0.00400
680 681	32.00	31.76	40	28.84	28.68	250	0.00400

Table 5-7: Continued.

Link ID	Ground Elevation (m)		L (m)	Invert Elevation (m)		Dia. (mm)	Slope m/m
	U/S	D/S		U/S	D/S		
681 682	31.76	31.40	45	28.68	28.50	250	0.00400
682 692	31.40	30.76	45	28.50	28.32	250	0.00400
683 684	31.21	31.45	40	29.96	29.80	250	0.00400
684 686	31.45	31.49	40	29.80	29.64	250	0.00400
685 686	31.50	31.49	35	30.25	30.11	250	0.00400
686 689	31.49	30.85	45	29.64	29.46	250	0.00400
687 688	30.80	30.94	40	29.55	29.39	250	0.00400
688 689	30.94	30.85	40	29.39	29.23	250	0.00400
689 690	30.85	31.20	35	29.23	29.09	250	0.00400
690 691	31.20	31.13	35	29.09	28.95	250	0.00400
691 692	31.13	30.76	35	28.95	28.81	250	0.00400
692 693	30.76	30.87	45	28.255	28.075	315	0.00317
693 698	30.87	30.49	45	28.075	27.895	315	0.00317
694 695	30.39	30.80	40	29.59	29.43	250	0.00400
695 697	30.80	30.54	35	29.43	29.29	250	0.00400
696 697	30.75	30.54	35	29.43	29.29	250	0.00400
697 698	30.54	30.49	35	29.29	29.15	250	0.00400
698 699	30.49	30.40	40	27.895	27.735	315	0.00317
699 703	30.40	30.50	45	25.40	25.29	400	0.00250
700 701	30.95	30.83	35	29.70	29.56	250	0.00400
701 702	30.83	30.56	30	29.37	29.25	250	0.00400
702 703	30.56	30.50	30	27.12	27.00	250	0.00400
703 706	30.50	30.60	35	25.29	25.20	400	0.00250
704 705	30.90	30.67	45	29.53	29.35	250	0.00400
705 706	30.67	30.60	45	28.58	28.40	250	0.00400
706 709	30.60	30.90	40	25.20	25.10	400	0.00250
707 708	31.80	31.45	45	30.01	29.83	250	0.00400
708 709	31.45	30.90	45	29.83	29.65	250	0.00400
709 713	30.90	31.07	35	25.10	25.01	400	0.00250
710 711	31.86	31.87	35	30.61	30.47	250	0.00400
711 712	31.87	31.87	30	30.06	29.94	250	0.00400
712 713	31.87	31.07	30	29.94	29.82	250	0.00400
713 758	31.07	31.55	37	25.01	24.92	400	0.00250
714 715	32.50	33.05	40	31.25	31.09	250	0.00400
715 716	33.05	33.20	30	31.09	30.97	250	0.00400
716 717	33.20	33.70	30	30.97	30.85	250	0.00400
717 721	33.70	33.63	40	30.85	30.69	250	0.00400
718 719	34.00	33.30	40	32.21	32.05	250	0.00400
719 720	33.30	33.56	35	32.05	31.91	250	0.00400
720 721	33.56	33.63	35	31.91	31.77	250	0.00400
721 722	33.63	33.12	40	30.69	30.53	250	0.00400
722 723	33.12	32.50	40	30.53	30.37	250	0.00400
723 743	32.50	32.15	27	30.37	30.26	250	0.00400
724 725	32.15	32.35	45	30.90	30.72	250	0.00400
725 726	32.35	31.79	45	30.72	30.54	250	0.00400
726 729	31.79	32.33	40	30.04	29.88	250	0.00400

Table 5-7: Continued.

Link ID	Ground Elevation (m)		L (m)	Invert Elevation (m)		Dia. (mm)	Slope m/m
	U/S	D/S		U/S	D/S		
727 728	33.38	32.90	45	31.44	31.26	250	0.00400
728 729	32.90	32.33	45	31.26	31.08	250	0.00400
729 743	32.33	32.15	35	29.88	29.74	250	0.00400
730 731	33.24	33.00	40	31.75	31.59	250	0.00400
731 732	33.00	32.80	40	31.59	31.43	250	0.00400
732 733	32.80	32.60	35	31.43	31.29	250	0.00400
733 737	32.60	32.40	35	31.29	31.15	250	0.00400
734 735	33.35	33.12	40	31.61	31.45	250	0.00400
735 736	33.12	32.74	40	31.45	31.29	250	0.00400
736 737	32.74	32.40	35	31.29	31.15	250	0.00400
737 742	32.40	32.36	40	31.15	30.99	250	0.00400
738 739	33.70	33.10	40	31.69	31.53	250	0.00400
739 740	33.10	32.86	40	31.53	31.37	250	0.00400
740 741	32.86	32.62	35	31.37	31.23	250	0.00400
741 742	32.62	32.36	30	31.23	30.99	250	0.00400
742 743	32.36	32.15	40	30.99	30.83	250	0.00400
743 747	32.15	31.79	54	29.74	29.56	250	0.00400
744 745	32.31	32.02	40	30.93	30.77	250	0.00400
745 746	32.02	31.90	35	30.77	30.63	250	0.00400
746 747	31.90	31.79	35	30.63	30.49	250	0.00400
747 751	31.79	31.39	40	29.56	29.40	250	0.00400
748 749	32.24	31.98	40	30.58	30.42	250	0.00400
749 750	31.98	31.81	35	30.42	30.28	250	0.00400
750 751	31.81	31.39	35	30.28	30.14	250	0.00400
751 752	31.39	31.50	40	29.40	29.24	250	0.00400
752 753	31.50	31.50	40	29.24	29.08	250	0.00400
753 754	31.50	31.86	40	29.08	28.92	250	0.00400
754 755	31.86	32.50	35	28.92	28.78	250	0.00400
755 756	32.50	32.20	35	28.78	28.64	250	0.00400
756 757	32.20	32.15	35	28.64	28.50	250	0.00400
757 758	32.15	31.55	35	28.50	28.36	250	0.00400
758 900	31.55	31.25	10	24.92	24.90	400	0.00250

CHAPTER SIX

Chapter Six

Results and Discussion

This chapter deals with the applying side to use a GA-HP model, comprises presentation of the results gained and discussion of the operator methods for genetic algorithm employed to improve the workability of the optimization model to achieve optimum results.

6.1. Application of a GA-HP model for the first benchmark problem

The performance of the proposed GA-HP model is discussed into three stages such as follows:

1. Evaluate selection methods: discuss the performance of the proposed GA-HP model with different selection methods.
2. Evaluate crossover methods: discuss the performance of the proposed GA-HP model with different crossover methods.
3. Evaluate population size: discuss the performance of the proposed GA-HP model with different population size.

6.1.1. Evaluate Selection method

In this section, a GA-HP model is tested to find the optimal design of sewer network for first benchmark problem with different selection methods for Genetic Algorithm (GA). The results are obtained with a 1-point crossover, the probability of crossover (Pc*)* = 1, and a one-gene mutation per chromosome, the probability of mutation (Pm*)* = 0.5.

Figure (6-1) shows the typical convergence curves for the best solution cost, over a number of generations during the evolution process, with Roulette Wheel Selection (RWS) method for the first sewer network problem. The figure shows the existence of more than one optimal solution for the problem with the little disparity between it, but the total cost for the optimal design was obtained after 497 generations.

Figure (6-2) shows the typical convergence curves for the best solution cost, over a number of generations during the evolution process, with Rank Roulette Wheel Selection (RRWS) method for the first sewer network problem. This method uses the same procedure the RWS method, but use the rank of the fitness function in probability of selection instead of the fitness function. It is clear that the number of generations required for the final solution improved with the RRWS method, also this method obtained the optimal solution faster from the RWS method in which the total cost for the optimal design was obtained after 61 generations.

Figure (6-3) shows the typical convergence curves for the best solution cost, over a number of generations during the evolution process, with Linear Ranking Selection (LRS) method for the first sewer network problem. This method uses the scaled the fitness function between known intervals depended on the rank of fitness function as mentioned previously in chapter three. The total cost for the optimal design was obtained after 241 generations.

Figure (6-4) shows the typical convergence curves for the best solution cost, over a number of generations during the evolution process, with Exponential Ranking Selection (ERS) method for the first sewer network problem. When the Exponential selection method started running, there was a huge disparity in costs, leading to the optimal cost occurring at 556 generations.

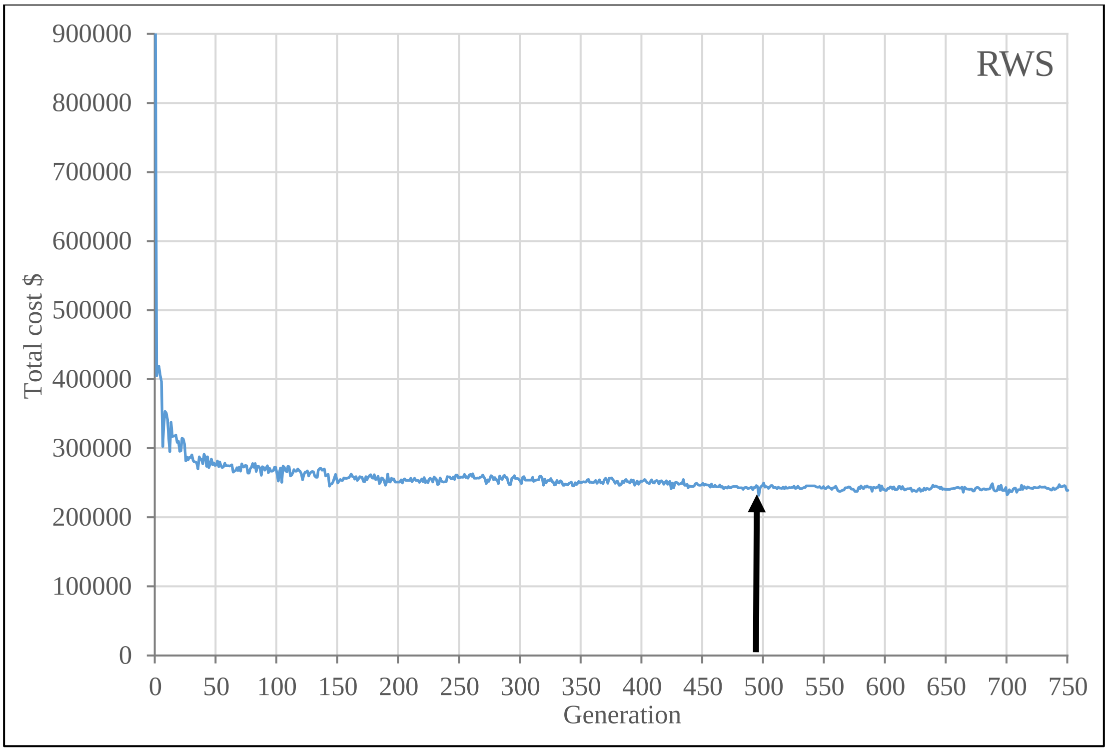


Figure 6-1: The optimum cost solution of iterations for (RWS) method by the proposed GA-HP model for first problem.

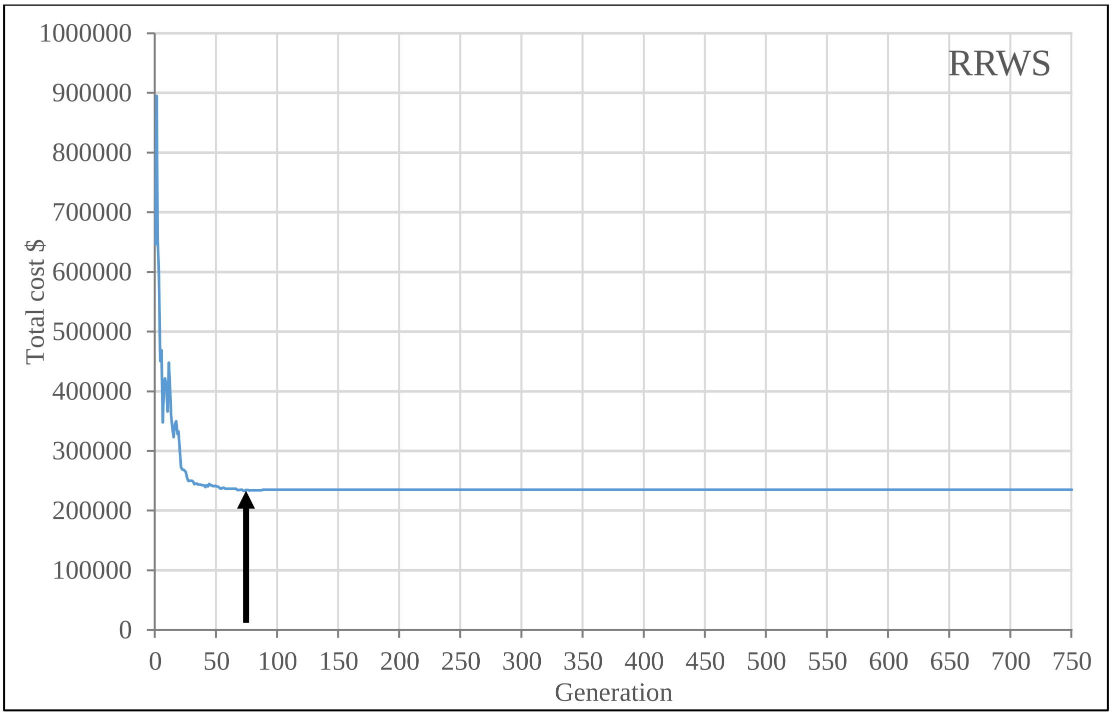


Figure 6-2: The optimum cost solution of iterations for (RRWS) method by the proposed GA-HP model for first problem.

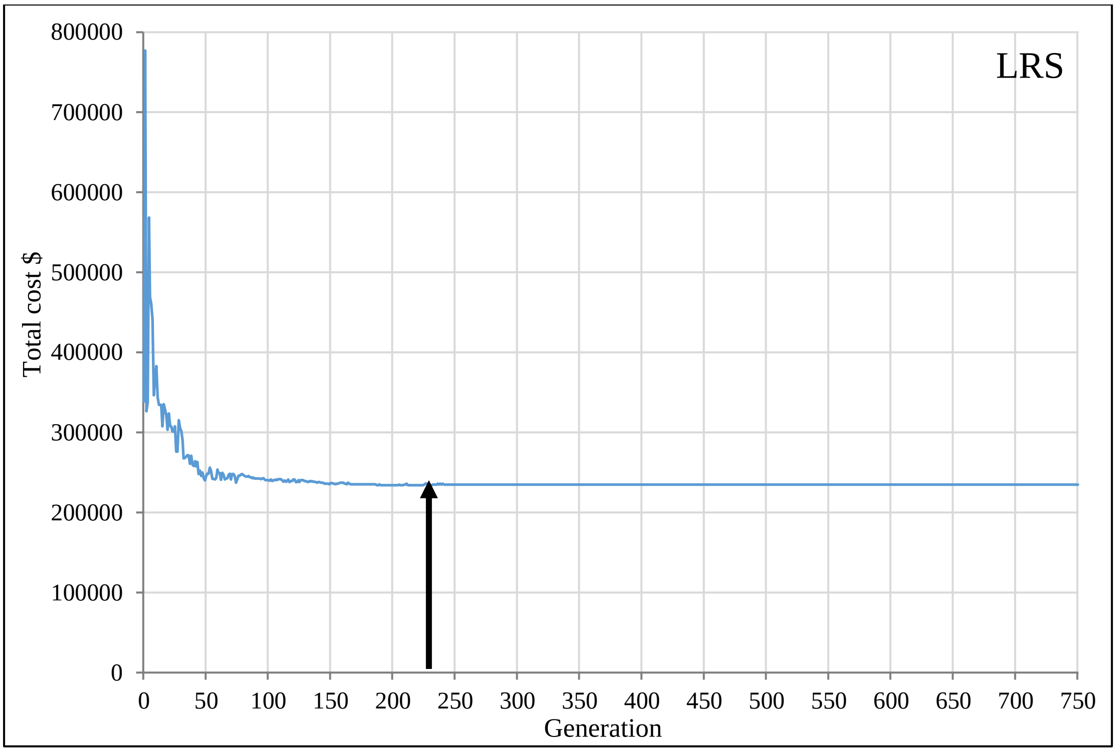


Figure 6-3: The optimum cost solution of iterations for (LRS) method by the proposed GA-HP model for first problem.

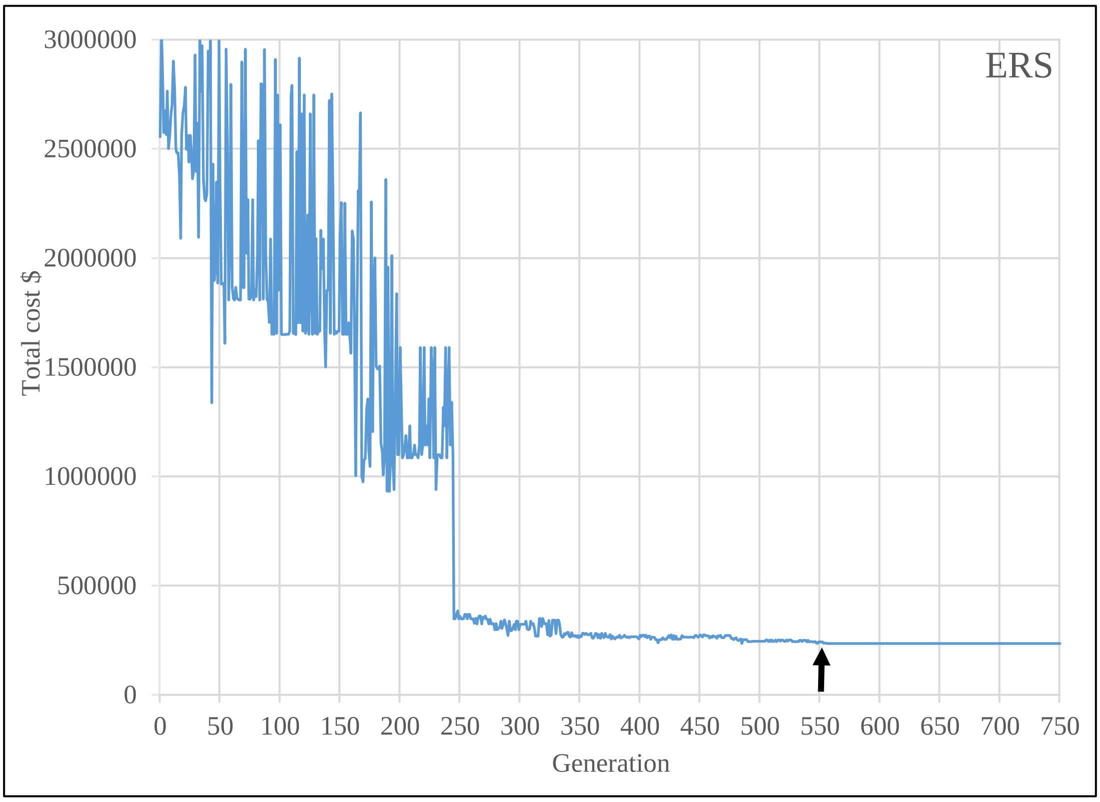


Figure 6-4: The optimum cost solution of iterations for (ERS) method by the proposed GA-HP model for first problem.

Figure (6-5) shows the typical convergence curves for the best solution cost, over a number of generations during the evolution process, with Truncation Selection (TRS) method for the first sewer network problem. Through the chart shown this method improve the GA-HP model to find the optimal solution faster from the previous methods in which obtained the total cost for the optimal design after 55 generations.

Figure (6-6) shows the typical convergence curves for the best solution cost, over a number of generations during the evolution process, with Stochastic Universal Sampling (SUS) method for the first sewer network problem. The chart shows the existence of more than one optimal solution for the problem with the little disparity between it, but the total cost for the optimal design was obtained after 447 generations. The results proved this method better than the roulette wheel selection method and Exponential Ranking selection method.

Figure (6-7) shows the typical convergence curves for the best solution cost, over a number of generations during the evolution process, with Tournament Selection (TOS) method for the first sewer network problem. Through the results, this method proved powerful and effective to find the optimal solution in which the total cost for the optimal design was obtained after 39 generations.

Figure (6-8) shows the best solution cost, over a number of generations during the evolution process, with Random Selection (RMS) method for the first sewer network problem. The figure shows the data irregular which indicates that the random selection method don’t work with GA-HP model, the total cost for the minimum solution was (342,341 units) obtained after 482 generations.

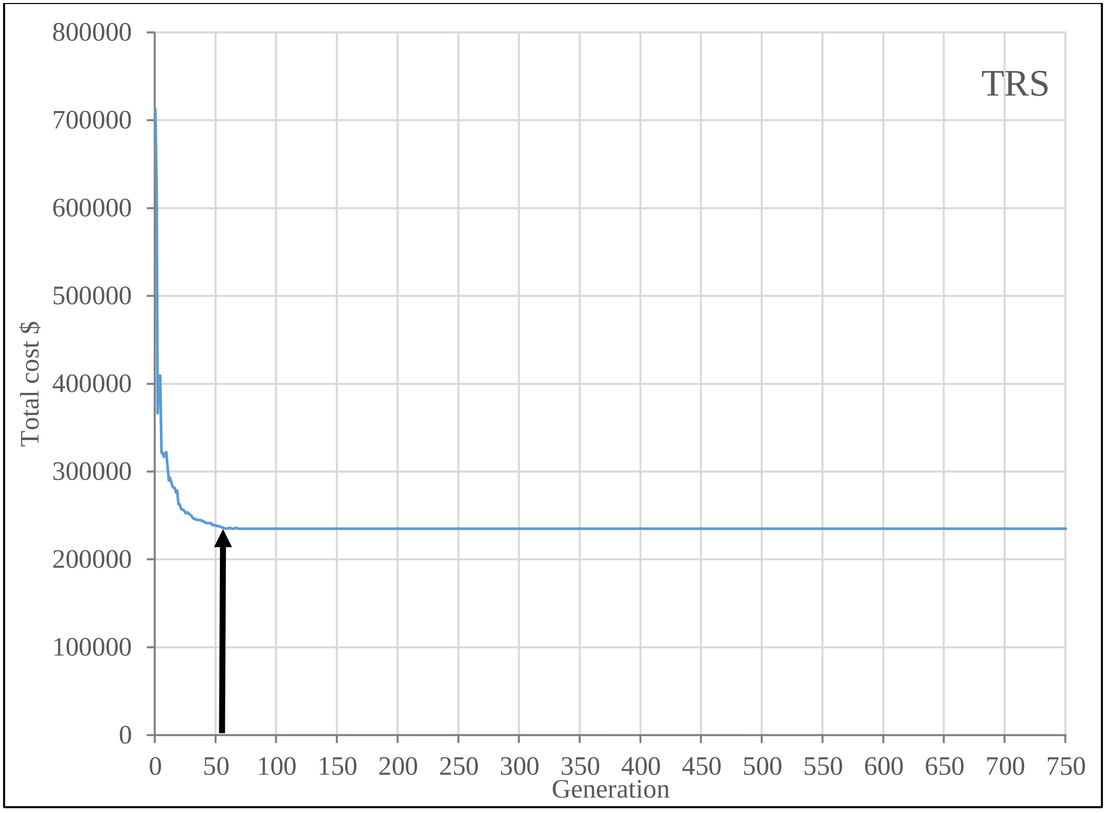


Figure 6-5: The optimum cost solution of iterations for (TRS) method by the proposed GA-HP model for first problem.

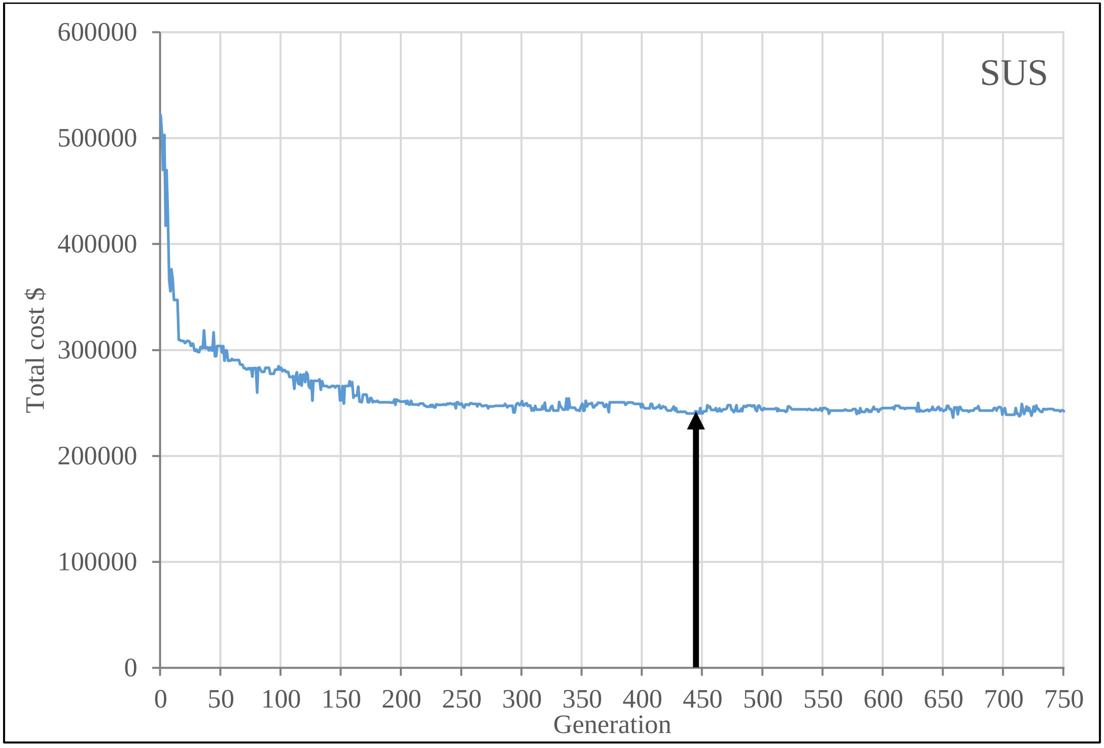


Figure 6-6: The optimum cost solution of iterations for (SUS) method by the proposed GA-HP model for first problem.

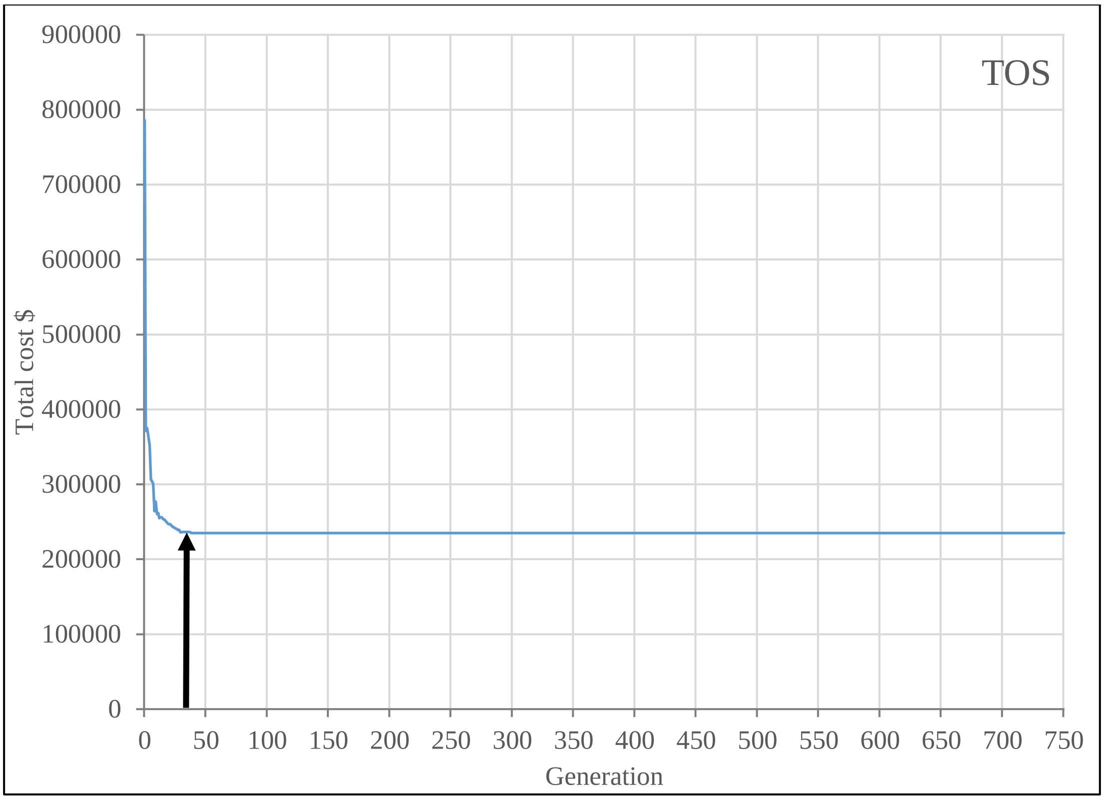


Figure 6-7: The optimum cost solution of iterations for (TOS) method by the proposed GA-HP model for first problem.

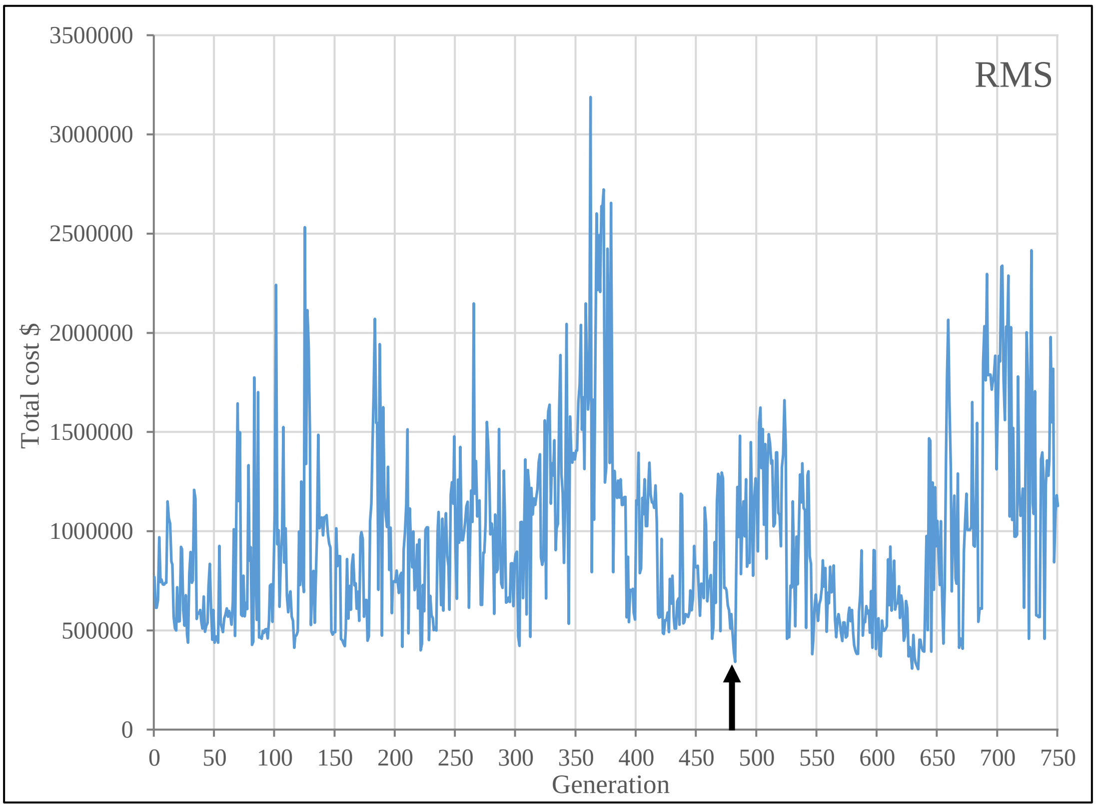


Figure 6-8: The optimum cost solution of iterations for (RMS) method by the proposed GA-HP model for first problem.

It is clear that as expected, the number of generations required for the final solution improves with different selection methods. The total cost for the optimal design was obtained after 556, 497, 446, 241, 61, 55 and 39 generations, for the ERS, RWS, SUS, LRS, RRWS, TRS and TOS selection methods, respectively. The RRWS, TRS and TOS selection methods exhibited much faster characteristics, yielding an RWS, SUS and LRS selection methods result within 497, 446 and 241 generations, respectively. When the Exponential selection method started running, there was a huge disparity in costs, leading to the optimal cost occurring at 556 generations. In the other hand, the Random selection method don’t work with GA-HP model. The optimum objective function of solution (235,000 units) was obtained with the Tournament selection (TOS) method, within 39 generations and with a depth of flow = 0.9; this is the best and fastest selection method for the GA-HP model.

6.1.2. Evaluate crossover methods

Figure (6-9) shows the typical convergence curves for the best solution cost over a number of generations during the evolution process, with different N-points crossover method for the first sewer network problem. These results were obtained using TOS, $Pc = 1$, and a one-gene mutation per chromosome, $Pm = 0.5$. As expected, the number of generations required for the final solution improves with increase points of crossover, but increase points crossover that required more processing leading to slow the model and because the improvement by increasing points is relatively small, this indicates that one-point crossover method is the best method. The total cost for an optimal design was obtained after 39, 38, 35 and 31 generations for 1-point, 2-points, 3-points and 4-points crossover methods, respectively. The best crossover method in this model is the 4-point crossover because it found the optimal solution within 31 generations, but requires high processing processes and don’t give the big difference in generations. Finally, the 1-point crossover method is the best because requires low processing and give the optimal design at 39 generation.

Figure (6-10) shows the typical convergence curves for the best solution cost over a number of generations during the evolution process, with different crossover methods for the first sewer network problem. These results were obtained using TOS, Pc = 1, and a one-gene mutation per chromosome, Pm = 0.5. As expected, the number of generations required for the final solution improves with different crossover methods. The total cost for an optimal design was obtained after 87, 72, 47, 40 and 39 generations for Uniform, Arithmetic, Intermediate, Shuffle and 1-point crossover methods, respectively. The best crossover method in this model is the one-point crossover because it found the optimal solution within 39 generations.

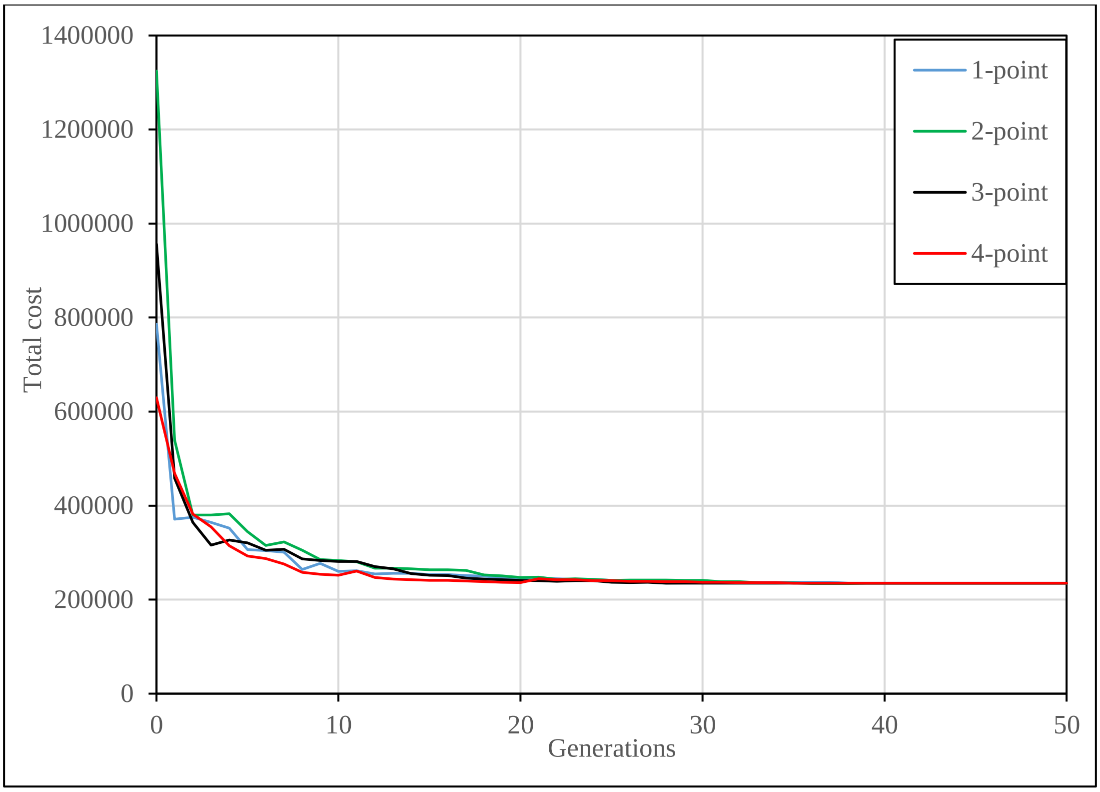


Figure 6-9: The optimum cost solution of iterations for different points crossover methods for TOS selection by the GA-HP model.

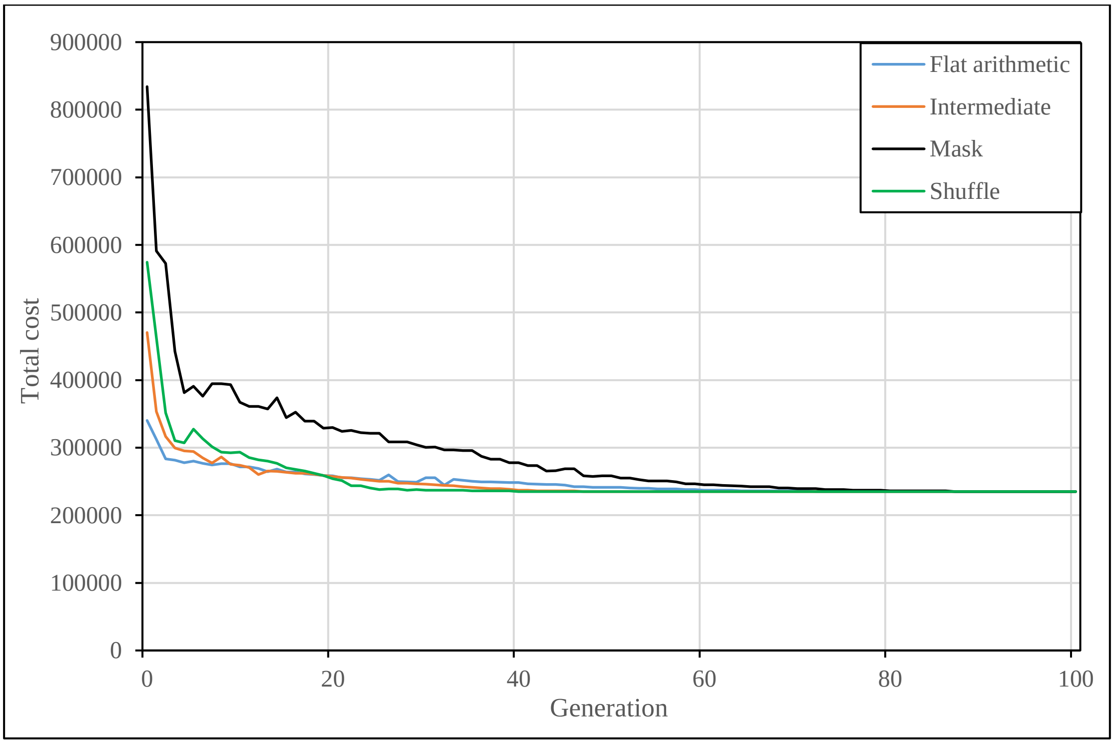


Figure 6-10: The optimum cost solution of iterations for different crossover methods for TOS selection by the GA-HP model.

6.1.3. Evaluate population size

Figure (6-11) shows the effects of population size on the performance of the GA-HP model during the evolution process, for the first sewer network example. These results were obtained with a Tournament selection method, single-point crossover, the probability of crossover (*Pc*) = 1, and one-gene mutation per chromosome, the probability of mutation (*Pm*) = 0.5. As expected, the quality of the final solution improves with an increase in population size. The total cost for the optimal design was obtained after 63, 47, 38, 31 and 28 generations, for population sizes of 50, 100, 200, 300 and 400, respectively. While the expectation is for a better solution with a higher population size at the expense of increased computational effort and storage requirements, a higher population size may reduce the probability of selecting the best individual for crossover. Especially at the large networks as in real networks.

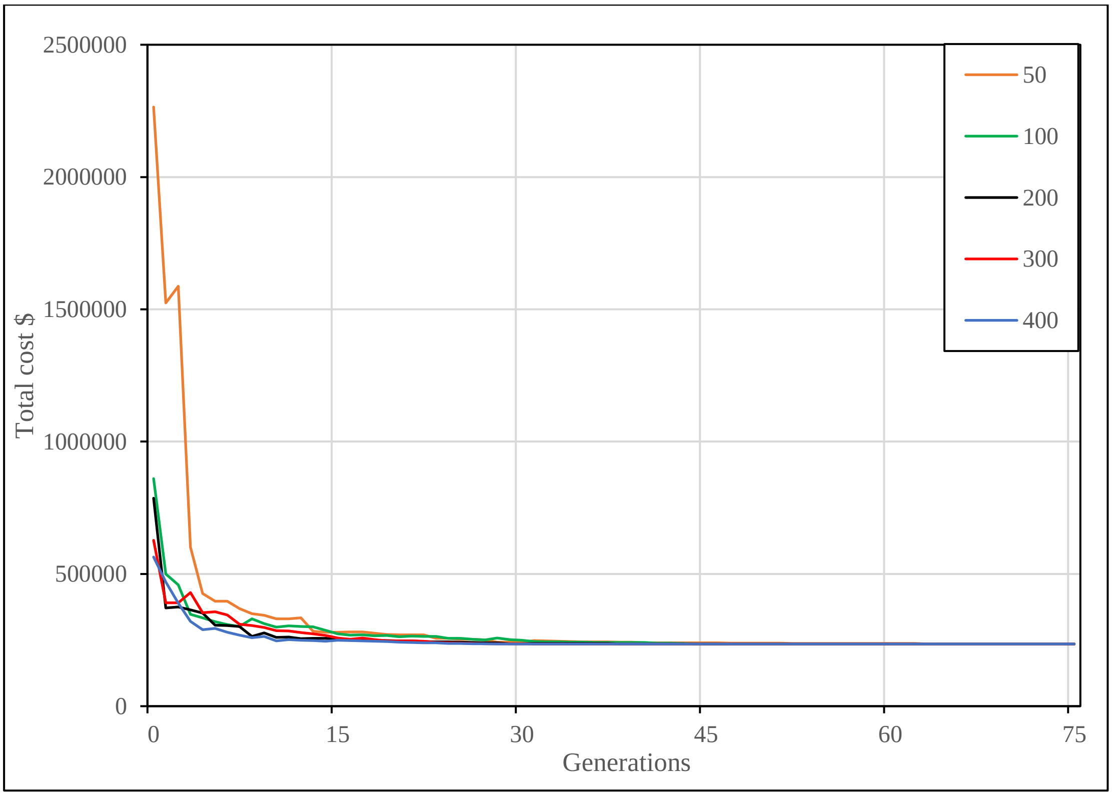


Figure 6-11: The optimum cost solution of iterations for different population sizes for TOS selection by proposed (GA-HP) model.

This problem is a storm sewer network, originally designed by (Mays and Yen, 1975), and solved by many researchers. Mays and Yen (1975) & (1976) used this problem to test the proposed Discrete Differential Dynamic Programming (DDDP) model, an iterative technique by which the recursive DP equation is used to search for an improved path through the discrete state in the neighbourhood of a trial solution.

The problem was later solved by Robinson and Labadie (1981) with a different version of the Dynamic Programming model, Miles and Heaney (1988) using a spreadsheet template, (Afshar et al., 2006) applying Genetic Algorithm (GA), (Afshar, 2006) employing Ant Colony Optimization (ACO), and (Yeh et al., 2013) using Tabu Search (TS) and Simulated Annealing (SA). The many researchers also solved this problem with different optimization methods.

Table (6-1) compares the optimal network costs obtained, optimisation methods and number of evaluations by different researchers, with those of the proposed GA-HP model. It can be seen that the GA-HP model has the lowest cost and number of evaluations or the optimal design in comparison to all the other methods. Moreover, the number of evaluations was very small compared with the other methods. The characteristics of the best solution obtained in this experiment, with depth of flow 0.82 and 0.9, are shown in tables (6-2) and (6-3), respectively.

Table 6-1: Optimal sewer networks cost and optimization methods for first problem.

Model		Method	Cost (units)	No. of Evaluation
(Mays and Yen, 1975)		DDDP	265,775	-
(Robinson and Labadie, 1981)		Version of DP	275,218	-
(Miles and Heaney, 1988)		Spreadsheet	245,874	-
(Afshar, 2006)		ACOA	241,496	29,900
(Afshar, 2010a) & β_{max} = 0.82		UCACOA	242,121	14,925
(Afshar et al., 2011) & β_{max} = 0.90		CA	253,483	50
(Afshar, 2012) & β_{max} = 0.82		Rebirthing GA	241,988	58,454
(Yeh et al., 2013) & β_{max} = 0.82		TS	244,571	1,034,809
		SA	241,770	15,932,235
(Zaheri and Afshar, 2016)		Two phase CA	240,084	515
(Afshar et al., 2016) & β_{max} = 0.82		Adaptive CA	239,757	192
Present model	β_{max} = 0.82	GA-HP	239,672	38
	β_{max} = 0.90	GA-HP	235,000	39

Table 6-2: Characteristics of optimal design for first example with β=0.82 using the GA-HP model.

Link ID	Crown Elevation (m)		D (mm)	V (m/s)	Depth of flow (%)
	Upstream	Downstream			
01 02	150. 0000	148. 4760	304. 8	1. 877	0. 76
02 03	148. 4760	146. 0876	381. 0	2. 475	0. 66
03 06	146. 0876	143. 9040	381. 0	2. 614	0. 79
04 05	146. 9520	145. 4280	304. 8	1. 762	0. 82
05 06	145. 4280	143. 9040	457. 2	2. 114	0. 62
06 10	143. 9040	140. 6743	533. 4	3. 176	0. 82
07 08	146. 9520	144. 6898	381. 0	2. 263	0. 82
08 09	144. 6898	142. 3800	457. 2	2. 649	0. 72
09 10	142. 3800	140. 8560	533. 4	2. 687	0. 70
10 14	140. 6743	138. 9218	762. 0	3. 113	0. 82
11 12	145. 4280	142. 3800	381. 0	2. 586	0. 80
12 13	142. 3800	140. 8560	533. 4	2. 687	0. 70
13 14	140. 8560	139. 1576	533. 4	2. 887	0. 82
14 18	138. 3247	136. 2480	914. 4	3. 597	0. 79
15 16	140. 2464	138. 7124	304. 8	1. 768	0. 82
16 17	138. 7124	137. 8080	381. 0	1. 812	0. 76
17 18	137. 8080	136. 2480	457. 2	2. 385	0. 62
18 19	136. 2480	135. 0648	1066. 8	3. 537	0. 72
19 20	135. 0648	133. 8731	1066. 8	3. 212	0. 82
20 21	133. 8731	132. 2459	1066. 8	3. 393	0. 82

Table 6-3: Characteristics of optimal design for first example with β =0.9 using the GA-HP model.

Link ID	Crown Elevation (m)		D (mm)	V (m/s)	Depth of flow (%)
	Upstream	Downstream			
01 02	150. 0000	148. 4760	304. 8	1. 88	0. 76
02 03	148. 4760	146. 0876	381. 0	2. 48	0. 66
03 06	146. 0876	143. 9040	381. 0	2. 61	0. 79
04 05	146. 9520	145. 4280	304. 8	1. 76	0. 82
05 06	145. 4280	143. 9040	457. 2	2. 11	0. 62
06 10	143. 9040	140. 8560	533. 4	3. 08	0. 84
07 08	146. 9520	145. 4280	457. 2	2. 02	0. 64
08 09	145. 4280	142. 3800	457. 2	2. 97	0. 65
09 10	142. 3800	140. 8560	533. 4	2. 69	0. 70
10 14	140. 8560	139. 3320	762. 0	2. 87	0. 90
11 12	145. 4280	142. 3800	381. 0	2. 59	0. 80
12 13	142. 3800	140. 8560	533. 4	2. 69	0. 70
13 14	140. 8560	139. 3320	533. 4	2. 72	0. 87
14 18	138. 3829	136. 2480	914. 4	3. 64	0. 78
15 16	140. 2464	138. 8949	304. 8	1. 64	0. 90
16 17	138. 8949	137. 8080	381. 0	1. 96	0. 71
17 18	137. 8080	136. 2480	457. 2	2. 39	0. 62
18 19	136. 2480	135. 0648	1,066. 8	3. 54	0. 72
19 20	135. 0648	134. 0148	1,066. 8	2. 97	0. 90
20 21	134. 0148	132. 5812	1,066. 8	3. 14	0. 90

6.2. Application of a GA-HP model for the second benchmark problem

Figure (6-12) shows the typical convergence curves for the best solution cost, over a number of generations during the evolution process, with different selection methods for the second benchmark sewer network problem. These results were obtained with a 1-point crossover, Pc = 1, and a one-gene mutation per chromosome, Pm=0.5. It is clear that as expected, the number of generations required for the final solution improves with different selection methods. The total cost for the optimal design was obtained after 579, 563, 444, 407, 143, 58 and 37 generations, for the SUS, ERS, RWS, LRS, RRWS, TRS and TOS selection methods, respectively. The TOS selection method exhibited much faster characteristics.

Figure (6-13) shows the typical convergence curves for the best solution cost over a number of generations during the evolution process, with different crossover methods for the first sewer network example. These results were obtained using TOS, Pc = 1, and a one-gene mutation per chromosome, Pm=0.5. As expected, the number of generations required for the final solution improves with different crossover methods. The total cost for an optimal design was obtained after 98, 80, 61, 44, 37 and 35 generations for Arithmetic, mask, intermediate, shuffle, 1-point and 2-point crossover methods, respectively. The best crossover method in this model is the 2-point crossover because it found the optimal solution within 35 generations, but requires high processing processes and don't give the big difference in generations. Finally, the 1-point crossover method is the best because requires low processing and give the optimal design at 37 generation.

Also, the TOS selection method, one-point crossover method were the best method worked with GA-HP model for second benchmark problem.

The second problem is part of the Kerman sewerage system in Iran. Mansouri and Khanjani (1999) were the first to design this network using mathematical programming and GA. Afshar et al. (2011) used the one-stage CA method, while Afshar and Rohani (2012) applied a two-stage HCA method to design the network. In a recent study, Zaheri and Afshar (2016) applied a Two-Phase Simulation-Optimisation CA.

Table (6-4) shows the optimal cost of the network and the number of function evaluations needed by different methods with a minimum cover of 2.45m. Details of the optimal design attained by the proposed model are presented in table (6-5). The results show that the proposed GA-HP process lowers the cost (81,265 unit) and number of evaluations (37) in the optimal design compared to all other methods.

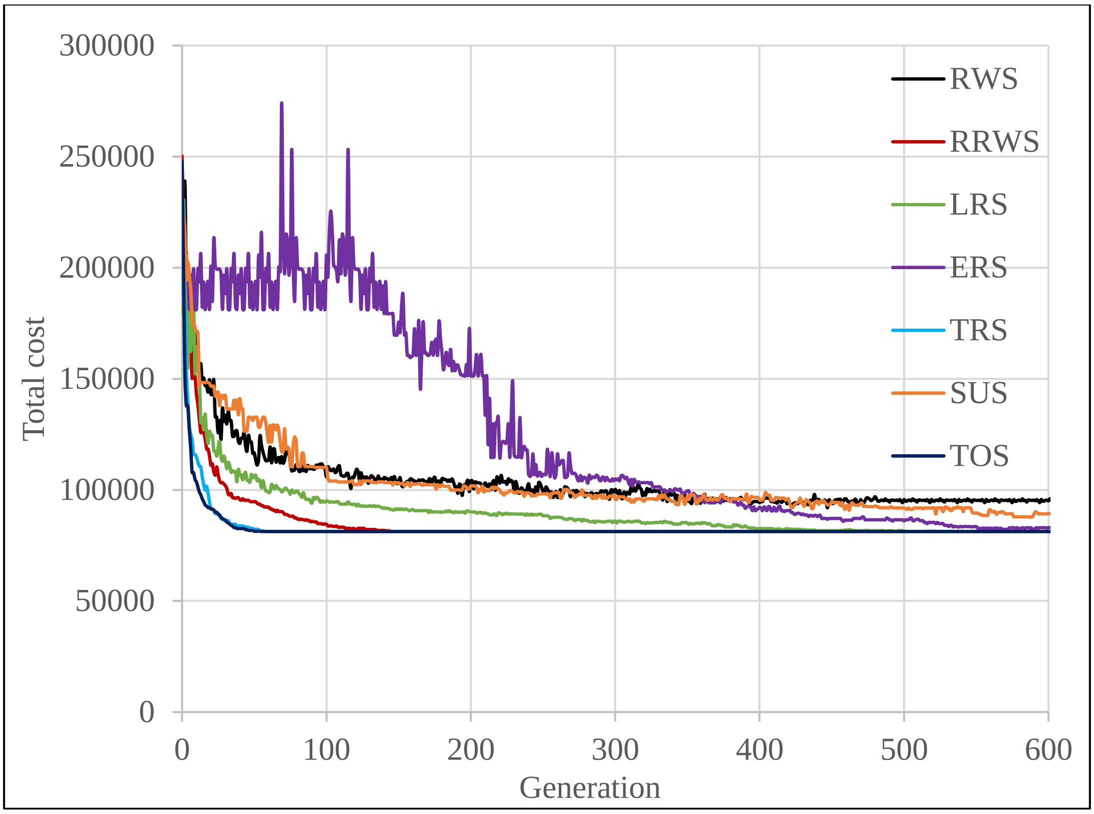


Figure 6-12: The optimum cost solution of iterations for different selection methods by proposed (GA-HP) model for second problem.

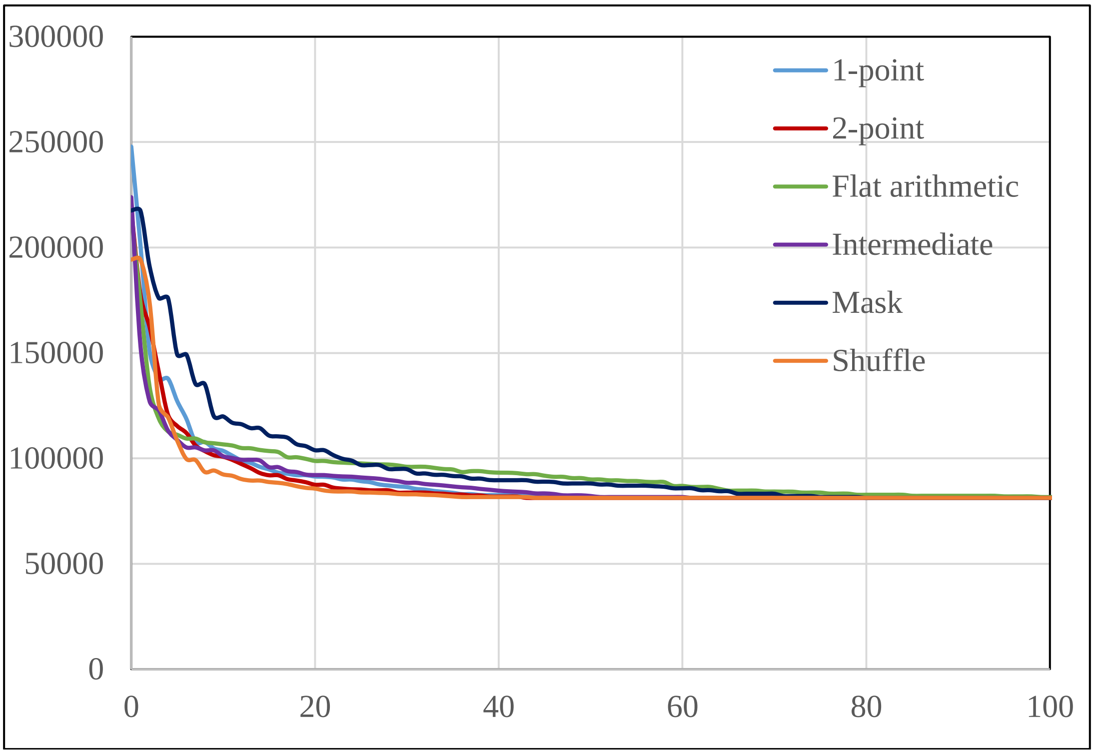


Figure 6-133: The optimum cost solution of iterations for different crossover methods by proposed (GA-HP) model for second problem.

Table 6-4: Optimal sewer networks cost and optimization methods for second example with min. cover = 2.45 m.

Model	Method	Cost (units)	No. of Evaluation
(Mansouri and Khanjani, 1999)	NLP	83,116	-
(Setoodeh, 2004)	BFGS	82,732	-
	Fletcher-reeves	81,553	-
Present model	GA-HP	81,265	37

Table 6-5: Characteristics of optimal design for second example with min. cover = 2.45 m.

Link ID	Crown Elevation (m)		D	V	Depth of
	Upstream	Downstream	(mm)	(m/s)	flow (%)
01 02	72. 1400	71. 2100	250	0. 80	0. 66
02 03	71. 2100	69. 6500	250	0. 79	0. 72
03 04	69. 6500	68. 7400	250	0. 81	0. 75
04 05	68. 7400	67. 4000	250	0. 91	0. 71
05 06	67. 4000	65. 6967	250	0. 85	0. 82
06 11	65. 6967	64. 8300	300	0. 72	0. 71
07 08	68. 2500	67. 2838	300	0. 89	0. 82
08 09	67. 2838	66. 8500	350	0. 69	0. 78
09 10	66. 8500	65. 9500	350	0. 89	0. 64
10 11	65. 9500	64. 8300	350	0. 85	0. 68
11 12	64. 8300	63. 7700	400	0. 90	0. 79
12 13	63. 7700	63. 3294	450	0. 73	0. 82
13 20	63. 3294	62. 8712	450	0. 75	0. 82
14 15	70. 5500	68. 8958	200	0. 77	0. 82
15 16	68. 8958	67. 6500	250	0. 75	0. 67
16 17	67. 6500	66. 1500	250	0. 83	0. 69
17 18	66. 1500	64. 3500	250	0. 82	0. 73
18 19	64. 3500	63. 6500	300	0. 65	0. 81
19 20	63. 6500	62. 9700	350	0. 58	0. 74
20 21	62. 8712	61. 7885	450	1. 19	0. 82

Some researchers ((Afshar and Sotoodeh, 2003); Afshar et al., 2011; Afshar and Rohani, 2012; Zaheri and Afshar, 2016;and Afshar et al., 2016) found the optimal design for a second example, using the minimum cover as the minimum excavation (minimum invert elevation). In this part of the current study, the second example was designed under the same condition, using the minimum cover as the minimum excavation, the optimal network costs obtained by different models, compared to those of the proposed GA-HP model, shown in table (6-6). The cost of the GA-HP model is the lowest compared to the optimal solutions obtained by the other methods, requiring much less computational effort than the other methods. Details of the optimal design obtained by the proposed model are presented in table (6-7).

Table 6-6: Optimal sewer networks cost and optimization methods for second example with min. invert = 2.45 m.

Model		Method	Cost (units)	No. of Evaluation
(Afshar and Sotoodeh, 2003)		GA	77,736	100,000
(Afshar et al., 2011)		CA	80,879	23
(Afshar and Rohani, 2012)	Discrete	Hybrid CA	77,327	45
	Continuous	Hybrid CA	77,433	38
(Zaheri and Afshar, 2016)		Two-Phase CA	76,750	1184
(Afshar et al., 2016)		Adaptive CA	77,285	196
Present model		GA-HP	75,253	53

Table 6-7: Characteristics of optimal design for second example with min. invert = 2.45 m.

Link ID	Crown Elevation (m)		D (mm)	V (m/s)	Depth of flow (%)
	Upstream	Downstream			
01 02	72. 3900	70. 9600	250	0. 80	0. 66
02 03	71. 4600	69. 4000	250	0. 79	0. 72
03 04	69. 9000	68. 4900	250	0. 81	0. 75
04 05	68. 9900	67. 1500	250	0. 91	0. 71
05 06	67. 6500	65. 4467	250	0. 85	0. 82
06 11	65. 9967	64. 5300	300	0. 72	0. 71
07 08	68. 5500	66. 9838	300	0. 89	0. 82
08 09	67. 6338	66. 5000	350	0. 69	0. 78
09 10	67. 2000	65. 6000	350	0. 89	0. 64
10 11	66. 3000	64. 4800	350	0. 85	0. 68
11 12	65. 2300	63. 3700	400	0. 90	0. 79
12 13	64. 2200	62. 8794	450	0. 73	0. 82
13 20	63. 7794	62. 4212	450	0. 75	0. 82
14 15	70. 7500	68. 6958	200	0. 77	0. 82
15 16	69. 1458	67. 4000	250	0. 75	0. 67
16 17	67. 9000	65. 9000	250	0. 83	0. 69
17 18	66. 4000	64. 1000	250	0. 82	0. 73
18 19	64. 6500	63. 3500	300	0. 65	0. 81
19 20	64. 0000	62. 6200	350	0. 58	0. 74
20 21	63. 3212	61. 3385	450	1. 19	0. 82

6.3. Application of a GA-HP model for the case studies

The performance of the proposed GA-HP model previously with two benchmarks problems found the Tournament selection method (TOS) and the One-point crossover method proved to be the most efficient in relation to the optimal design.

In this section, the performance of the proposed GA-HP model will test for relatively small and large real networks with a flat slope to find the optimal design of sewer networks and compare it with the manual design (as build) in terms of total cost.

A previously designed sewer network of cases study for some of the residential quarters of Karbala city as shown in figures (5-4) and (5-5) which described in chapter five, was designed optimally using the same criteria and constraints used in the manual design. The same cost functions were used in both design and the final cost compared.

The cases study networks were designed using the minimum diameter equal to 200 mm because most of the international specifications used this diameter, as well as there are some Iraqi research published in Iraq, the researchers used a minimum diameter equal to 200 mm such as: (Omran, 1986), (Jurji, 1988) and (Zainal and Abbas, 2015). On the other hands, the reason using the minimum diameter equal to 250 mm because the manual design using it, to prove the proposed GA-HP model work with this case conditions.

Figures (6-13) and (6-14), shows the typical convergence curves for the best solution cost over a number of generations during the evolution process for the first sewer network of case study with minimum diameter equal to 200 and 250 mm, respectively. These designs were obtained with a Tournament selection method, One-point crossover, the probability of crossover (Pc) = 1, one-gene mutation per chromosome, the probability of mutation (Pm) = 0.5, and population size equal to 200 chromosomes.

The first case study was relatively small network includes 91 manholes and 90 pipes, the total length of a network (3,605 m). The total cost of the network was lowered from (529.7 million ID manual design (as build)) to (380.8 million ID optimum design with minimum diameter = 200 mm) resulting in a reduction of about (28.1%) as show in table (6-8). The comparison includes excavations, pipes and manholes costs. The manual design is shown on table (5-6) and the optimum design presented on Table (A-1) with minimum diameter = 200 mm.

The second case study was large network includes 355 manholes and 354 pipes, the total length of a network (13,506 m). The total cost of the network was lowered from (2,190.6 million ID manual design (as build)) to (1,567.43 million ID optimum design with minimum diameter = 200 mm) and (2,032.9 million ID optimum design with minimum diameter = 250 mm), resulting in a reduction of about (28.45%) and (7.2%), respectively as show in table (6-8). The comparison includes excavations, pipes and manholes costs. The manual design is shown on table (5-7) and the optimum design presented on table (A-2) with minimum diameter = 200 mm, tables (B-1) minimum diameter = 250 mm.

Table (6-8) shows the saving percentages for case studies with different minimum diameter. After viewing the table shows the GA-HP model was able to provide an 7.2% reduction for the medium network despite using a minimum diameter equal to 250 mm this indicate the proposed GA-HP model effect with large real network. The proposed GA-HP model is expected to provide a high saving percentage if used to design of the main trunk lines because it is very expensive, contained high discharges and Extended for long distances.

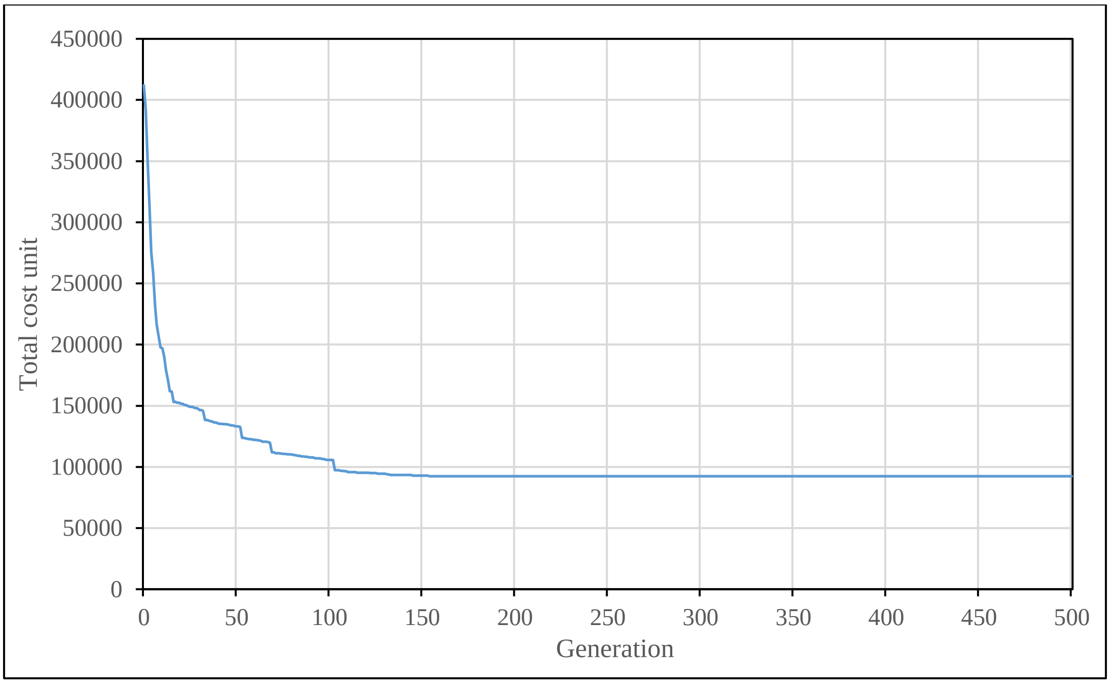


Figure 6-14: The optimum cost solution of iterations by the proposed GA-HP model for first case study with min. diameter = 200 mm.

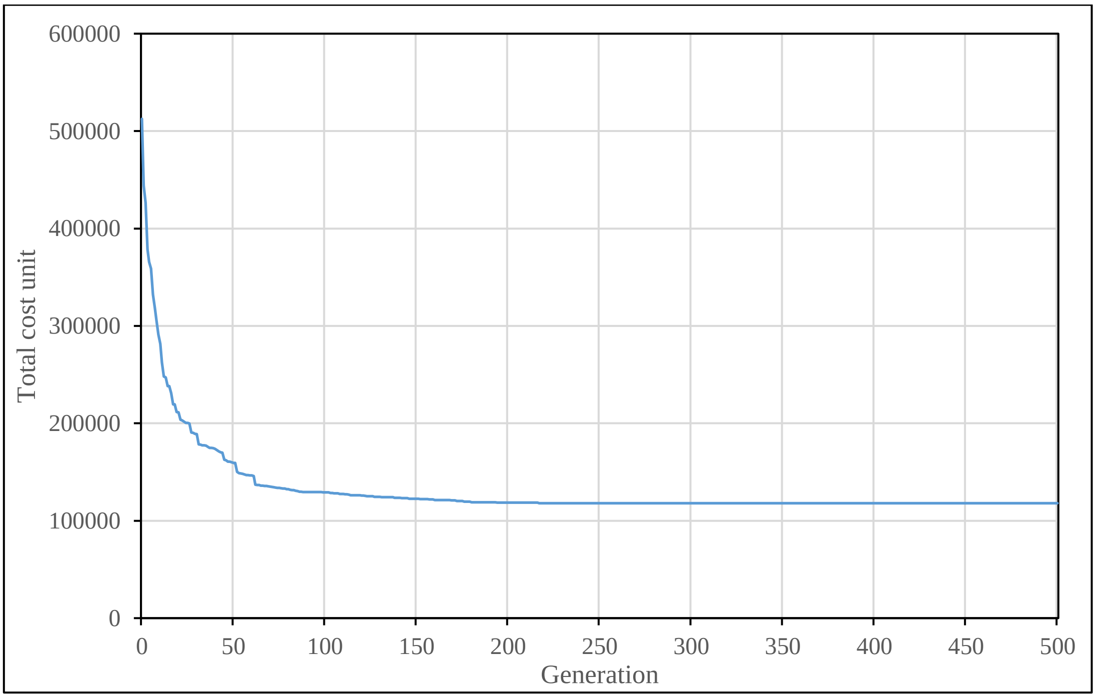


Figure 6-15: The optimum cost solution of iterations by the proposed GA-HP model for first case study with min. diameter = 250 mm.

Table 6-8: The saving percentage for case studies.

Case study	Type of design	Cost (million ID)	Saving percentage
First case study	Manual design	529.7	-
	min. D = 200	380.8	28.1 %
Second case study	Manual design	2,190.67	-
	min. D = 200	1,567.43	28.45%
	min. D = 250	2,032.90	7.2%

CHAPTER SEVEN

Chapter Seven

Conclusions and Recommendations

7.1. Conclusions

A hybrid Genetic Algorithm with Heuristic Programming (GA-HP) model is proposed for the optimal design of sewer networks. The performance of said GA-HP model was tested on two sewer networks' optimization benchmark problems and two real cases study. A number of conclusions were reached by studying and analysing the results as follows:

1. The Tournament Selection method (TOS), the One-point crossover method proved to be the most efficient in relation to the optimal design and the best population size equal to 200 individuals.
2. These results indicate that GA-HP gives a better objective function value than DDDP, VDP, Spreadsheet, ACO, CACO, CA, RGA, TS, SA, Two-phase CA and Adaptive CA.
3. The GA-HP required less iterations (generation) than that required by ACO, CACO, CA, RGA, TS, SA, Two-phase CA and Adaptive CA.
4. All the hydraulic parameters calculated were in agreement with the given discharge design. This result shows that the penalty approach used in the GA-HP model guarantees satisfaction within a given set of constraints.
5. The cost of construction is the most important performance measure when assessing optimisation methods. That said, the number of generations needed to determine the best design is also considered an important performance measure. The proposed GA-HP model led to minimum costs (optimum) for designs and a minimum number of generations, compared to the previous designs applied to the

benchmark problems. that lead to a conclusion that "the GA-HP model is most efficient for designing large networks”.

6. In case studies, the savings percentage obtained through the optimal design by using the proposed GA-HP model indicate that the model is well performing.
7. In order to ensure the efficiency of the proposed GA-HP model for the design of large networks, it was examined with two case studies located in Karbala Holy city, then compared the cost of the manual designs with the designs obtained from this model for networks. The saving percentage was (28.1%) and (28.45%) for relatively small and large networks, respectively.

7.2. Recommendations

1. Developing the Proposed GA-HP model to be a visual program (package program) user-friendly to use for design of real networks in the future.
2. Developing the proposed GA-HP model to design of sewer networks with pump station.
3. Design of sewer network by combine optimization techniques with Heuristic Programming (HP).
4. Using new optimization techniques to find optimal layout for sewer networks.
5. Using new optimization techniques to design water distribution networks.

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APPENDICES

Appendix A: Design with min. dia. = 200mm.

Table A-1: Characteristics of optimal design for first case study with min. diameter=200 mm.

Link ID	Ground Elevation (m)		L. (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
01 02	36. 55	36. 25	25	35.375	35.250	0.200	0.005000
02 03	36. 25	36. 50	40	35.250	35.050	0.200	0.005000
03 04	36. 50	36. 67	40	35.050	34.850	0.200	0.005000
04 05	36. 67	37. 21	40	34.850	34.650	0.200	0.005000
05 06	37. 21	37. 40	40	34.650	34.450	0.200	0.005000
06 12	37. 40	37. 54	50	34.450	34.200	0.200	0.005000
07 08	36. 45	36. 58	25	35.450	35.325	0.200	0.005000
08 09	36. 58	36. 81	40	35.325	35.125	0.200	0.005000
09 10	36. 81	37. 14	40	35.125	34.925	0.200	0.005000
10 11	37. 14	37. 52	40	34.925	34.725	0.200	0.005000
11 12	37. 52	37. 54	40	34.725	34.525	0.200	0.005000
12 16	37. 54	37. 24	50	34.200	33.950	0.200	0.005000
13 14	36. 69	36. 85	40	35.690	35.490	0.200	0.005000
14 15	36. 85	37. 08	40	35.490	35.290	0.200	0.005000
15 16	37. 08	37. 24	40	35.290	35.090	0.200	0.005000
16 17	37. 24	37. 04	40	33.950	33.818	0.200	0.003303
17 18	37. 04	36. 67	40	33.818	33.686	0.200	0.003303
18 19	36. 67	36. 55	40	33.686	33.554	0.200	0.003303
19 43	36. 55	36. 27	40	33.554	33.422	0.200	0.003303
20 21	36. 68	36. 51	40	35.680	35.480	0.200	0.005000
21 22	36. 51	36. 50	40	35.480	35.280	0.200	0.005000
22 23	36. 50	36. 27	40	35.280	35.080	0.200	0.005000
23 24	36. 27	36. 27	40	35.080	34.880	0.200	0.005000
24 25	36. 27	35. 75	40	34.880	34.680	0.200	0.005000
25 31	35. 75	36. 52	45	34.680	34.455	0.200	0.005000
26 27	36. 55	36. 98	40	35.550	35.350	0.200	0.005000
27 28	36. 98	37. 12	40	35.350	35.150	0.200	0.005000
28 29	37. 12	37. 00	40	35.150	34.950	0.200	0.005000
29 30	37. 00	36. 78	40	34.950	34.750	0.200	0.005000
30 31	36. 78	36. 52	40	34.750	34.550	0.200	0.005000
31 37	36. 52	36. 80	50	34.455	34.205	0.200	0.005000
32 33	36. 30	37. 20	40	35.300	35.100	0.200	0.005000
33 34	37. 20	37. 05	40	35.100	34.900	0.200	0.005000
34 35	37. 05	37. 00	40	34.900	34.700	0.200	0.005000
35 36	37. 00	36. 87	40	34.700	34.500	0.200	0.005000
36 37	36. 87	36. 80	40	34.500	34.300	0.200	0.005000
37 40	36. 80	36. 66	50	34.205	33.955	0.200	0.005000
38 39	36. 48	35. 71	40	35.480	34.710	0.200	0.019250
39 40	35. 71	36. 66	40	34.710	34.510	0.200	0.005000
40 41	36. 66	36. 51	40	33.955	33.823	0.200	0.003303
41 42	36. 51	36. 50	40	33.823	33.691	0.200	0.003303

Table A-1: Continued.

Link ID	Ground Elevation (m)		L. (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
42 43	36. 50	36. 27	40	33.691	33.559	0.200	0.003303
43 48	36. 27	36. 21	50	33.422	33.178	0.200	0.004878
44 45	36. 27	35. 75	20	35.270	34.750	0.200	0.026000
45 46	35. 75	36. 98	40	34.750	34.550	0.200	0.005000
46 47	36. 98	37. 12	40	34.550	34.350	0.200	0.005000
47 48	37. 12	36. 21	50	34.350	34.100	0.200	0.005000
48 49	36. 21	36. 05	45	33.178	32.912	0.200	0.005900
49 60	36. 05	35. 98	45	32.912	32.635	0.200	0.006150
57 58	36. 42	36. 32	30	35.420	35.270	0.200	0.005000
54 55	36. 70	36. 69	30	34.750	34.600	0.200	0.005000
55 56	36. 69	36. 63	35	34.600	34.425	0.200	0.005000
56 58	36. 63	36. 32	40	34.425	34.225	0.200	0.005000
58 59	36. 32	36. 21	50	34.225	33.975	0.200	0.005000
50 51	36. 68	36. 68	30	35.680	35.530	0.200	0.005000
51 52	36. 68	36. 63	40	35.530	35.330	0.200	0.005000
52 53	36. 63	36. 27	40	35.330	35.130	0.200	0.005000
53 59	36. 27	36. 21	30	35.130	34.980	0.200	0.005000
59 60	36. 21	35. 98	50	33.975	33.725	0.200	0.005000
60 65	35. 98	35. 80	50	32.635	32.190	0.200	0.008898
61 62	36. 44	36. 34	50	35.440	35.190	0.200	0.005000
62 63	36. 34	36. 24	45	35.190	34.965	0.200	0.005000
63 64	36. 24	36. 04	45	34.965	34.740	0.200	0.005000
64 65	36. 04	35. 80	50	34.740	34.490	0.200	0.005000
65 91	35. 80	35. 42	50	32.190	31.661	0.200	0.010591
73 74	34. 80	34. 55	35	33.800	33.550	0.200	0.007143
74 75	34. 55	34. 34	40	33.550	33.340	0.200	0.005250
75 76	34. 34	34. 62	40	33.340	33.140	0.200	0.005000
76 84	34. 62	34. 89	40	33.140	32.940	0.200	0.005000
77 78	35. 26	35. 10	35	34.260	34.085	0.200	0.005000
78 79	35. 10	35. 13	35	34.085	33.910	0.200	0.005000
79 80	35. 13	35. 28	40	33.910	33.710	0.200	0.005000
80 81	35. 28	35. 22	40	33.710	33.510	0.200	0.005000
81 82	35. 22	35. 09	40	33.510	33.310	0.200	0.005000
82 83	35. 09	34. 85	30	33.310	33.160	0.200	0.005000
83 84	34. 85	34. 89	30	33.160	33.010	0.200	0.005000
84 85	34. 89	35. 58	50	32.940	32.690	0.200	0.005000
66 67	35. 66	35. 78	35	34.660	34.485	0.200	0.005000
67 68	35. 78	35. 92	35	34.485	34.310	0.200	0.005000
68 69	35. 92	35. 97	40	34.310	34.110	0.200	0.005000
69 70	35. 97	35. 94	40	34.110	33.910	0.200	0.005000
70 71	35. 94	35. 77	40	33.910	33.710	0.200	0.005000
71 72	35. 77	35. 61	30	33.710	33.560	0.200	0.005000
72 85	35. 61	35. 58	30	33.560	33.410	0.200	0.005000
85 91	35. 58	35. 42	45	32.690	32.541	0.200	0.003303
86 87	34. 35	34. 54	35	33.350	33.175	0.200	0.005000

Table A-1: Continued.

Link ID	Ground Elevation (m)		L. (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
87 88	34. 54	34. 75	40	33.175	32.975	0.200	0.005000
88 89	34. 75	35. 00	40	32.975	32.775	0.200	0.005000
89 90	35. 00	35. 14	40	32.775	32.575	0.200	0.005000
90 91	35. 14	35. 42	50	31.661	31.053	0.200	0.012153

Table A-2: Characteristics of optimal design for second case study with min. diameter=200 mm.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
405 406	29.56	29.85	40	28.560	28.433	0.315	0.00317
406 407	29.85	30.20	40	28.433	28.306	0.315	0.00317
407 408	30.20	30.36	40	28.306	28.179	0.315	0.00317
408 409	30.36	30.50	40	28.179	28.052	0.315	0.00317
409 410	30.50	30.79	40	28.052	27.925	0.315	0.00317
410 411	30.79	30.95	40	27.925	27.798	0.315	0.00317
411 428	30.95	30.98	40	27.798	27.671	0.315	0.00317
412 413	29.56	29.90	40	28.560	28.433	0.315	0.00317
413 414	29.90	30.50	40	28.433	28.306	0.315	0.00317
414 415	30.50	30.90	40	28.306	28.179	0.315	0.00317
415 416	30.90	30.90	40	28.179	28.052	0.315	0.00317
416 417	30.90	30.70	40	28.052	27.925	0.315	0.00317
417 418	30.70	30.83	40	27.925	27.798	0.315	0.00317
418 419	30.83	30.70	40	27.798	27.671	0.315	0.00317
419 427	30.70	30.65	40	27.671	27.544	0.315	0.00317
420 421	29.65	30.00	40	28.650	28.523	0.315	0.00317
421 422	30.00	30.30	40	28.523	28.396	0.315	0.00317
422 423	30.30	30.61	40	28.396	28.269	0.315	0.00317
423 424	30.61	60.80	40	28.269	28.142	0.315	0.00317
424 425	60.80	31.00	40	28.142	28.015	0.315	0.00317
425 426	31.00	31.00	40	28.015	27.888	0.315	0.00317
426 427	31.00	30.65	40	27.888	27.761	0.315	0.00317
427 428	30.65	30.98	40	27.544	27.417	0.315	0.00317
428 429	30.98	30.75	40	27.417	27.290	0.315	0.00317
429 430	30.75	30.65	40	27.290	27.130	0.250	0.00400
430 431	30.65	30.50	30	27.130	27.010	0.250	0.00400
431 432	30.50	30.45	30	27.010	26.890	0.250	0.00400
432 433	30.45	30.48	50	26.890	26.690	0.250	0.00400
433 464	30.48	30.50	45	26.690	26.510	0.250	0.00400
434 435	30.20	30.30	35	29.200	29.025	0.200	0.00500
435 436	30.30	30.53	35	29.025	28.850	0.200	0.00500
436 439	30.53	30.49	35	28.850	28.675	0.200	0.00500
437 438	30.15	30.15	35	29.150	28.975	0.200	0.00500
438 439	30.15	30.49	35	28.975	28.800	0.200	0.00500
439 442	30.49	30.81	40	28.675	28.475	0.200	0.00500
440 441	29.93	30.20	35	28.930	28.755	0.200	0.00500
441 442	30.20	30.81	35	28.755	28.580	0.200	0.00500
442 445	30.81	30.69	35	28.475	28.300	0.200	0.00500
443 444	29.76	30.40	35	28.760	28.585	0.200	0.00500
444 445	30.40	30.69	35	28.585	28.410	0.200	0.00500
445 449	30.69	31.00	40	28.300	28.100	0.200	0.00500
446 447	30.86	31.10	40	29.860	29.660	0.200	0.00500
447 448	31.10	31.10	35	29.660	29.485	0.200	0.00500
448 449	31.10	31.00	35	29.485	29.310	0.200	0.00500

Table A-2: Continued.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
449 453	31.00	31.22	40	28.100	27.900	0.200	0.00500
450 451	30.92	31.00	40	29.920	29.720	0.200	0.00500
451 452	31.00	31.10	35	29.720	29.545	0.200	0.00500
452 453	31.10	31.22	35	29.545	29.370	0.200	0.00500
453 457	31.22	30.72	42	27.900	27.690	0.200	0.00500
454 455	30.93	31.35	40	29.930	29.730	0.200	0.00500
455 456	31.35	31.85	35	29.730	29.555	0.200	0.00500
456 457	31.85	30.72	35	29.555	29.380	0.200	0.00500
457 458	30.72	30.66	35	27.690	27.515	0.200	0.00500
458 459	30.66	30.70	40	27.515	27.315	0.200	0.00500
459 460	30.70	30.70	40	27.315	27.115	0.200	0.00500
460 461	30.70	30.65	40	27.115	26.915	0.200	0.00500
461 462	30.65	30.60	40	26.915	26.715	0.200	0.00500
462 463	30.60	30.55	35	26.715	26.540	0.200	0.00500
463 464	30.55	30.50	35	26.540	26.424	0.200	0.00330
464 470	30.50	30.52	25	26.424	26.363	0.250	0.00245
465 466	30.52	30.58	40	29.520	29.320	0.200	0.00500
466 467	30.58	30.60	40	29.320	29.120	0.200	0.00500
467 468	30.60	30.65	40	29.120	28.920	0.200	0.00500
468 469	30.65	30.68	40	28.920	28.720	0.200	0.00500
469 470	30.68	30.70	40	28.720	28.520	0.200	0.00500
470 527	30.70	30.80	50	26.363	26.240	0.250	0.00245
471 472	31.17	30.85	40	30.170	29.850	0.200	0.00800
472 473	30.85	30.53	40	29.850	29.530	0.200	0.00800
473 476	30.53	30.70	40	29.530	29.330	0.200	0.00500
474 475	31.31	31.20	40	30.310	30.110	0.200	0.00500
475 476	31.20	30.70	40	30.110	29.700	0.200	0.01025
476 479	30.70	30.64	35	29.330	29.155	0.200	0.00500
477 478	31.50	31.10	40	30.500	30.100	0.200	0.01000
478 479	31.10	30.64	40	30.100	29.640	0.200	0.01150
479 480	30.64	30.66	35	29.155	28.980	0.200	0.00500
480 484	30.66	30.53	30	28.980	28.830	0.200	0.00500
481 482	30.50	30.50	40	29.500	29.300	0.200	0.00500
482 483	30.50	30.65	30	29.300	29.150	0.200	0.00500
483 484	30.65	30.53	30	29.150	29.000	0.200	0.00500
484 485	30.53	30.60	50	28.830	28.580	0.200	0.00500
485 495	30.60	30.86	45	28.580	28.355	0.200	0.00500
486 487	30.50	30.35	45	29.500	29.275	0.200	0.00500
487 488	30.35	30.20	45	29.275	29.050	0.200	0.00500
488 491	30.20	30.30	40	29.050	28.850	0.200	0.00500
489 490	30.50	30.85	45	29.500	29.275	0.200	0.00500
490 491	30.85	30.30	45	29.275	29.050	0.200	0.00500
491 494	30.30	30.53	38	28.850	28.660	0.200	0.00500
492 493	30.65	30.60	45	29.650	29.425	0.200	0.00500
493 494	30.60	30.53	45	29.425	29.200	0.200	0.00500
494 495	30.53	30.86	35	28.660	28.485	0.200	0.00500

Table A-2: Continued.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
495 496	30.86	30.92	40	28.355	28.155	0.200	0.00500
496 500	30.92	30.93	40	28.155	27.955	0.200	0.00500
497 498	31.21	31.29	40	30.210	30.010	0.200	0.00500
498 499	31.29	31.11	40	30.010	29.810	0.200	0.00500
499 500	31.11	30.93	40	29.810	29.610	0.200	0.00500
500 501	30.93	31.61	40	27.955	27.823	0.200	0.00330
501 508	31.61	31.56	40	27.823	27.691	0.200	0.00330
502 503	31.45	31.73	40	30.450	30.250	0.200	0.00500
503 504	31.73	31.65	30	30.250	30.100	0.200	0.00500
504 507	31.65	31.70	30	30.100	29.950	0.200	0.00500
505 506	30.86	31.60	35	29.860	29.685	0.200	0.00500
506 507	31.60	31.70	35	29.685	29.510	0.200	0.00500
507 508	31.70	31.56	40	29.510	29.310	0.200	0.00500
508 509	31.56	31.42	30	27.691	27.592	0.200	0.00330
509 510	31.42	31.32	30	27.592	27.493	0.200	0.00330
510 514	31.32	31.67	40	27.493	27.360	0.200	0.00330
511 512	31.45	31.70	40	30.450	30.250	0.200	0.00500
512 513	31.70	31.85	35	30.250	30.075	0.200	0.00500
513 514	31.85	31.67	35	30.075	29.900	0.200	0.00500
514 518	31.67	31.41	40	27.360	27.228	0.200	0.00330
515 516	31.35	31.61	40	30.350	30.150	0.200	0.00500
516 517	31.61	31.60	35	30.150	29.975	0.200	0.00500
517 518	31.60	31.41	35	29.975	29.800	0.200	0.00500
518 522	31.41	31.55	40	27.228	27.088	0.200	0.00351
519 520	31.31	31.65	40	30.310	30.110	0.200	0.00500
520 521	31.65	31.83	35	30.110	29.935	0.200	0.00500
521 522	31.83	31.55	35	29.935	29.760	0.200	0.00500
522 526	31.55	31.50	35	27.088	26.949	0.200	0.00397
523 524	31.22	31.10	40	30.220	30.020	0.200	0.00500
524 525	31.10	31.00	35	30.020	29.845	0.200	0.00500
525 526	31.00	31.50	35	29.845	29.670	0.200	0.00500
526 527	31.50	30.80	18	26.949	26.905	0.250	0.00245
527 584	30.80	31.08	40	26.905	26.807	0.250	0.00245
528 532	32.10	31.72	40	31.100	30.720	0.200	0.00950
529 530	31.50	31.90	40	30.500	30.300	0.200	0.00500
530 531	31.90	31.65	35	30.300	30.125	0.200	0.00500
531 532	31.65	31.72	35	30.125	29.950	0.200	0.00500
532 536	31.72	31.44	40	29.950	29.750	0.200	0.00500
533 534	31.17	31.31	40	30.170	29.970	0.200	0.00500
534 535	31.31	31.50	35	29.970	29.795	0.200	0.00500
535 536	31.50	31.44	35	29.795	29.620	0.200	0.00500
536 537	31.44	31.19	55	29.620	29.345	0.200	0.00500
537 541	31.19	31.14	40	29.345	29.145	0.200	0.00500
538 539	32.38	32.20	40	31.380	31.180	0.200	0.00500
539 540	32.20	31.60	45	31.180	30.600	0.200	0.01289
540 541	31.60	31.14	45	30.600	30.140	0.200	0.01022

Table A-2: Continued.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
541 545	31.14	31.86	40	29.145	28.945	0.200	0.00500
542 543	32.68	32.80	40	31.680	31.480	0.200	0.00500
543 544	32.80	32.20	45	31.480	31.200	0.200	0.00622
544 545	32.20	31.86	45	31.200	30.860	0.200	0.00756
545 549	31.86	31.20	40	28.945	28.745	0.200	0.00500
546 547	32.98	32.80	40	31.980	31.780	0.200	0.00500
547 548	32.80	32.51	45	31.780	31.510	0.200	0.00600
548 549	32.51	31.20	45	31.510	30.200	0.200	0.02911
549 553	31.20	31.45	40	28.745	28.545	0.200	0.00500
550 551	33.22	33.06	40	32.220	32.020	0.200	0.00500
551 552	33.06	32.50	45	32.020	31.500	0.200	0.01156
552 553	32.50	31.45	45	31.500	30.450	0.200	0.02333
553 556	31.45	32.06	40	28.545	28.345	0.200	0.00500
554 555	33.00	32.60	40	32.000	31.600	0.200	0.01000
555 556	32.60	32.06	40	31.600	31.060	0.200	0.01350
556 559	32.06	32.14	40	28.345	28.213	0.200	0.00330
557 558	33.06	32.70	40	32.060	31.700	0.200	0.00900
558 559	32.70	32.17	40	31.700	31.170	0.200	0.01325
559 569	32.17	32.09	35	28.213	28.097	0.200	0.00330
560 561	33.22	33.24	35	32.220	32.045	0.200	0.00500
561 562	33.24	33.40	35	32.045	31.870	0.200	0.00500
562 563	33.40	33.69	35	31.870	31.695	0.200	0.00500
563 567	33.69	33.65	35	31.695	31.520	0.200	0.00500
564 565	33.09	33.07	35	32.090	31.915	0.200	0.00500
565 566	33.07	33.30	35	31.915	31.740	0.200	0.00500
566 567	33.30	33.65	35	31.740	31.565	0.200	0.00500
567 568	33.65	33.40	45	31.520	31.295	0.200	0.00500
568 569	33.40	32.09	50	31.295	31.045	0.200	0.00500
569 570	32.09	31.90	40	28.097	27.965	0.200	0.00330
570 578	31.90	31.60	40	27.965	27.833	0.200	0.00330
571 572	33.91	32.85	40	32.910	31.850	0.200	0.02650
572 574	32.85	33.06	40	31.850	31.650	0.200	0.00500
573 574	32.73	33.06	35	31.730	31.555	0.200	0.00500
574 577	33.06	32.23	35	31.555	31.230	0.200	0.00929
575 576	33.85	32.33	45	32.850	31.330	0.200	0.03378
576 577	32.33	32.23	40	31.330	31.130	0.200	0.00500
577 578	32.23	31.60	45	31.130	30.600	0.200	0.01178
578 579	31.60	31.45	40	27.833	27.701	0.200	0.00330
579 580	31.45	31.30	40	27.701	27.569	0.200	0.00330
580 581	31.30	31.28	40	27.569	27.437	0.200	0.00330
581 582	31.28	31.09	40	27.437	27.305	0.200	0.00330
582 583	31.09	31.08	40	27.305	27.172	0.200	0.00330
583 584	31.08	31.08	35	27.172	27.054	0.200	0.00338
584 587	31.08	30.81	40	26.807	26.735	0.315	0.00180
585 586	31.80	31.15	35	30.800	30.150	0.200	0.01857
586 587	31.15	30.81	35	30.150	29.810	0.200	0.00971

Table A-2: Continued.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
587 590	30.81	30.71	35	26.735	26.672	0.315	0.00180
588 589	31.03	31.08	35	30.030	29.855	0.200	0.00500
589 590	31.08	30.71	35	29.855	29.680	0.200	0.00500
590 600	30.71	30.74	35	26.672	26.608	0.315	0.00180
591 592	31.40	31.15	40	30.400	30.150	0.200	0.00625
592 593	31.15	31.00	30	30.150	30.000	0.200	0.00500
593 594	31.00	30.80	30	30.000	29.800	0.200	0.00667
594 598	30.80	30.79	35	29.800	29.625	0.200	0.00500
595 596	31.09	31.04	40	30.090	29.890	0.200	0.00500
596 597	31.04	30.91	30	29.890	29.740	0.200	0.00500
597 598	30.91	30.79	30	29.740	29.590	0.200	0.00500
598 599	30.79	30.77	40	29.590	29.390	0.200	0.00500
599 600	30.77	30.74	40	29.390	29.190	0.200	0.00500
600 604	30.74	30.75	40	26.608	26.531	0.315	0.00193
601 602	30.94	30.87	40	29.940	29.740	0.200	0.00500
602 603	30.87	30.80	35	29.740	29.565	0.200	0.00500
603 604	30.80	30.75	35	29.565	29.390	0.200	0.00500
604 608	30.75	30.40	40	26.531	26.450	0.315	0.00203
605 606	30.86	30.96	40	29.860	29.660	0.200	0.00500
606 607	30.96	30.65	30	29.660	29.510	0.200	0.00500
607 608	30.65	30.40	30	29.510	29.360	0.200	0.00500
608 637	30.40	30.32	13	26.450	26.423	0.315	0.00211
609 610	31.50	31.50	40	30.500	30.300	0.200	0.00500
610 611	31.50	31.52	40	30.300	30.100	0.200	0.00500
611 612	31.52	31.20	35	30.100	29.925	0.200	0.00500
612 613	31.20	31.10	35	29.925	29.750	0.200	0.00500
613 618	31.10	30.56	40	29.750	29.550	0.200	0.00500
614 615	31.60	31.40	40	30.600	30.400	0.200	0.00500
615 616	31.40	31.10	40	30.400	30.100	0.200	0.00750
616 617	31.10	30.85	35	30.100	29.850	0.200	0.00714
617 618	30.85	30.56	35	29.850	29.560	0.200	0.00829
618 623	30.56	30.40	40	29.550	29.350	0.200	0.00500
619 620	31.30	31.07	40	30.300	30.070	0.200	0.00575
620 621	31.07	30.85	40	30.070	29.850	0.200	0.00550
621 622	30.85	30.62	35	29.850	29.620	0.200	0.00657
622 623	30.62	30.40	35	29.620	29.400	0.200	0.00629
623 624	30.40	30.45	25	29.350	29.225	0.200	0.00500
624 625	30.45	30.42	40	29.225	29.025	0.200	0.00500
625 626	30.42	30.40	45	29.025	28.800	0.200	0.00500
626 627	30.40	30.37	45	28.800	28.575	0.200	0.00500
627 636	30.37	30.35	45	28.575	28.350	0.200	0.00500
628 629	30.40	30.38	40	29.400	29.200	0.200	0.00500
629 630	30.38	30.35	40	29.200	29.000	0.200	0.00500
630 631	30.35	30.30	40	29.000	28.800	0.200	0.00500
631 632	30.30	30.25	40	28.800	28.600	0.200	0.00500
632 633	30.25	30.25	40	28.600	28.400	0.200	0.00500

Table A-2: Continued.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
633 634	30.25	30.25	35	28.400	28.225	0.200	0.00500
634 635	30.25	30.30	35	28.225	28.050	0.200	0.00500
635 636	30.30	30.35	30	28.050	27.900	0.200	0.00500
636 637	30.35	30.32	50	27.900	27.735	0.200	0.00330
637 641	30.32	30.55	40	26.423	26.296	0.315	0.00318
638 639	30.93	30.80	40	26.296	26.167	0.315	0.00321
639 640	30.80	30.75	40	26.167	26.037	0.315	0.00325
640 641	30.75	30.55	40	26.037	25.906	0.315	0.00328
641 642	30.55	30.45	40	25.906	25.773	0.315	0.00332
642 699	30.45	30.50	35	25.773	25.656	0.315	0.00335
643 644	33.10	32.40	40	32.100	31.400	0.200	0.01750
644 645	32.40	32.15	40	31.400	31.150	0.200	0.00625
645 646	32.15	33.48	35	31.150	30.975	0.200	0.00500
646 647	33.48	31.30	35	30.975	30.300	0.200	0.01929
647 651	31.30	31.70	40	30.300	30.100	0.200	0.00500
648 649	32.90	32.58	40	31.900	31.580	0.200	0.00800
649 650	32.58	31.97	35	31.580	30.970	0.200	0.01743
650 651	31.97	31.70	30	30.970	30.700	0.200	0.00900
651 660	31.70	31.70	40	30.100	29.900	0.200	0.00500
652 653	33.50	33.75	35	32.500	32.325	0.200	0.00500
653 654	33.75	33.91	35	32.325	32.150	0.200	0.00500
654 657	33.91	33.90	40	32.150	31.950	0.200	0.00500
655 656	32.68	32.90	35	31.680	31.505	0.200	0.00500
656 657	32.90	33.90	35	31.505	31.330	0.200	0.00500
657 658	33.90	33.25	40	31.330	31.130	0.200	0.00500
658 659	33.25	32.80	40	31.130	30.930	0.200	0.00500
659 660	32.80	31.70	40	30.930	30.700	0.200	0.00575
660 661	31.70	31.75	10	29.900	29.850	0.200	0.00500
661 662	31.75	31.65	35	29.850	29.675	0.200	0.00500
662 663	31.65	31.50	35	29.675	29.500	0.200	0.00500
663 675	31.50	31.85	40	29.500	29.300	0.200	0.00500
664 665	34.41	33.78	50	33.410	32.780	0.200	0.01260
665 666	33.78	33.01	50	32.780	32.010	0.200	0.01540
666 670	33.01	32.94	40	32.010	31.810	0.200	0.00500
667 668	34.33	34.39	35	33.330	33.155	0.200	0.00500
668 669	34.39	33.65	35	33.155	32.650	0.200	0.01443
669 670	33.65	32.94	35	32.650	31.940	0.200	0.02029
670 674	32.94	33.00	35	31.810	31.635	0.200	0.00500
671 672	34.09	34.15	35	33.090	32.915	0.200	0.00500
672 673	34.15	33.50	35	32.915	32.500	0.200	0.01186
673 674	33.50	33.00	35	32.500	32.000	0.200	0.01429
674 675	33.00	31.85	50	31.635	30.850	0.200	0.01570
675 680	31.85	32.00	40	29.300	29.168	0.200	0.00330
676 677	34.15	34.15	40	33.150	32.950	0.200	0.00500
677 678	34.15	33.60	40	32.950	32.600	0.200	0.00875
678 679	33.60	33.30	35	32.600	32.300	0.200	0.00857

Table A-2: Continued.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
679 680	33.30	32.00	37	32.300	31.000	0.200	0.03514
680 681	32.00	31.76	40	29.168	29.036	0.200	0.00330
681 682	31.76	31.40	45	29.036	28.887	0.200	0.00330
682 692	31.40	30.76	45	28.887	28.738	0.200	0.00330
683 684	31.21	31.45	40	30.210	30.010	0.200	0.00500
684 686	31.45	31.49	40	30.010	29.810	0.200	0.00500
685 686	31.50	31.49	35	30.500	30.325	0.200	0.00500
686 689	31.49	30.85	45	29.810	29.585	0.200	0.00500
687 688	30.80	30.94	40	29.800	29.600	0.200	0.00500
688 689	30.94	30.85	40	29.600	29.400	0.200	0.00500
689 690	30.85	31.20	35	29.400	29.225	0.200	0.00500
690 691	31.20	31.13	35	29.225	29.050	0.200	0.00500
691 692	31.13	30.76	35	29.050	28.875	0.200	0.00500
692 693	30.76	30.87	45	28.738	28.590	0.200	0.00330
693 698	30.87	30.49	45	28.590	28.441	0.200	0.00330
694 695	30.39	30.80	40	29.390	29.190	0.200	0.00500
695 697	30.80	30.54	35	29.190	29.015	0.200	0.00500
696 697	30.75	30.54	35	29.750	29.540	0.200	0.00600
697 698	30.54	30.49	35	29.015	28.840	0.200	0.00500
698 699	30.49	30.40	40	28.441	28.291	0.200	0.00375
699 703	30.40	30.50	45	25.656	25.393	0.315	0.00584
700 701	30.95	30.83	35	29.950	29.775	0.200	0.00500
701 702	30.83	30.56	30	29.775	29.560	0.200	0.00717
702 703	30.56	30.50	30	29.560	29.410	0.200	0.00500
703 706	30.50	30.60	35	25.393	25.184	0.315	0.00599
704 705	30.90	30.67	45	29.900	29.670	0.200	0.00511
705 706	30.67	30.60	45	29.670	29.445	0.200	0.00500
706 709	30.60	30.90	40	25.184	24.938	0.315	0.00615
707 708	31.80	31.45	45	30.800	30.450	0.200	0.00778
708 709	31.45	30.90	45	30.450	29.900	0.200	0.01222
709 713	30.90	31.07	35	24.938	24.717	0.315	0.00630
710 711	31.86	31.87	35	30.860	30.685	0.200	0.00500
711 712	31.87	31.87	30	30.685	30.535	0.200	0.00500
712 713	31.87	31.07	30	30.535	30.070	0.200	0.01550
713 758	31.07	31.55	37	24.717	24.478	0.315	0.00646
714 715	32.50	33.05	40	31.500	31.300	0.200	0.00500
715 716	33.05	33.20	30	31.300	31.150	0.200	0.00500
716 717	33.20	33.70	30	31.150	31.000	0.200	0.00500
717 721	33.70	33.63	40	31.000	30.800	0.200	0.00500
718 719	34.00	33.30	40	33.000	32.300	0.200	0.01750
719 720	33.30	33.56	35	32.300	32.125	0.200	0.00500
720 721	33.56	33.63	35	32.125	31.950	0.200	0.00500
721 722	33.63	33.12	40	30.800	30.600	0.200	0.00500
722 723	33.12	32.50	40	30.600	30.400	0.200	0.00500
723 743	32.50	32.15	27	30.400	30.265	0.200	0.00500
724 725	32.15	32.35	45	31.150	30.925	0.200	0.00500

Table A-2: Continued.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
725 726	32.35	31.79	45	30.925	30.700	0.200	0.00500
726 729	31.79	32.33	40	30.700	30.500	0.200	0.00500
727 728	33.38	32.90	45	32.380	31.900	0.200	0.01067
728 729	32.90	32.33	45	31.900	31.330	0.200	0.01267
729 743	32.33	32.15	35	30.500	30.325	0.200	0.00500
730 731	33.24	33.00	40	32.240	32.000	0.200	0.00600
731 732	33.00	32.80	40	32.000	31.800	0.200	0.00500
732 733	32.80	32.60	35	31.800	31.600	0.200	0.00571
733 737	32.60	32.40	35	31.600	31.400	0.200	0.00571
734 735	33.35	33.12	40	32.350	32.120	0.200	0.00575
735 736	33.12	32.74	40	32.120	31.740	0.200	0.00950
736 737	32.74	32.40	35	31.740	31.400	0.200	0.00971
737 742	32.40	32.36	40	31.400	31.200	0.200	0.00500
738 739	33.70	33.10	40	32.700	32.100	0.200	0.01500
739 740	33.10	32.86	40	32.100	31.860	0.200	0.00600
740 741	32.86	32.62	35	31.860	31.620	0.200	0.00686
741 742	32.62	32.36	30	31.620	31.360	0.200	0.00867
742 743	32.36	32.15	40	31.200	31.000	0.200	0.00500
743 747	32.15	31.79	54	30.265	30.087	0.200	0.00330
744 745	32.31	32.02	40	31.310	31.020	0.200	0.00725
745 746	32.02	31.90	35	31.020	30.845	0.200	0.00500
746 747	31.90	31.79	35	30.845	30.670	0.200	0.00500
747 751	31.79	31.39	40	30.087	29.955	0.200	0.00330
748 749	32.24	31.98	40	31.240	30.980	0.200	0.00650
749 750	31.98	31.81	35	30.980	30.805	0.200	0.00500
750 751	31.81	31.39	35	30.805	30.390	0.200	0.01186
751 752	31.39	31.50	40	29.955	29.822	0.200	0.00330
752 753	31.50	31.50	40	29.822	29.690	0.200	0.00330
753 754	31.50	31.86	40	29.690	29.558	0.200	0.00330
754 755	31.86	32.50	35	29.558	29.443	0.200	0.00330
755 756	32.50	32.20	35	29.443	29.327	0.200	0.00330
756 757	32.20	32.15	35	29.327	29.211	0.200	0.00330
757 758	32.15	31.55	35	29.211	29.096	0.200	0.00330
758 900	31.55	31.25	10	24.478	24.391	0.315	0.00869

Appendix B: Design with min. dia. = 250mm.

Table B- 1: Characteristics of optimal design for second case study with min. diameter=250 mm.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
405 406	29.56	29.85	40	28.560	28.433	0.315	0.00317
406 407	29.85	30.20	40	28.433	28.306	0.315	0.00317
407 408	30.20	30.36	40	28.306	28.179	0.315	0.00317
408 409	30.36	30.50	40	28.179	28.052	0.315	0.00317
409 410	30.50	30.79	40	28.052	27.925	0.315	0.00317
410 411	30.79	30.95	40	27.925	27.798	0.315	0.00317
411 428	30.95	30.98	40	27.798	27.671	0.315	0.00317
412 413	29.56	29.90	40	28.560	28.433	0.315	0.00317
413 414	29.90	30.50	40	28.433	28.306	0.315	0.00317
414 415	30.50	30.90	40	28.306	28.179	0.315	0.00317
415 416	30.90	30.90	40	28.179	28.052	0.315	0.00317
416 417	30.90	30.70	40	28.052	27.925	0.315	0.00317
417 418	30.70	30.83	40	27.925	27.798	0.315	0.00317
418 419	30.83	30.70	40	27.798	27.671	0.315	0.00317
419 427	30.70	30.65	40	27.671	27.544	0.315	0.00317
420 421	29.65	30.00	40	28.650	28.523	0.315	0.00317
421 422	30.00	30.30	40	28.523	28.396	0.315	0.00317
422 423	30.30	30.61	40	28.396	28.269	0.315	0.00317
423 424	30.61	60.80	40	28.269	28.142	0.315	0.00317
424 425	60.80	31.00	40	28.142	28.015	0.315	0.00317
425 426	31.00	31.00	40	28.015	27.888	0.315	0.00317
426 427	31.00	30.65	40	27.888	27.761	0.315	0.00317
427 428	30.65	30.98	40	27.544	27.417	0.315	0.00317
428 429	30.98	30.75	40	27.417	27.290	0.315	0.00317
429 430	30.75	30.65	40	27.290	27.163	0.315	0.00317
430 431	30.65	30.50	30	27.163	27.068	0.315	0.00317
431 432	30.50	30.45	30	27.068	26.973	0.315	0.00317
432 433	30.45	30.48	50	26.973	26.814	0.315	0.00317
433 464	30.48	30.50	45	26.814	26.671	0.315	0.00317
434 435	30.20	30.30	35	29.200	29.060	0.250	0.00400
435 436	30.30	30.53	35	29.060	28.920	0.250	0.00400
436 439	30.53	30.49	35	28.920	28.780	0.250	0.00400
437 438	30.15	30.15	35	29.150	29.010	0.250	0.00400
438 439	30.15	30.49	35	29.010	28.870	0.250	0.00400
439 442	30.49	30.81	40	28.780	28.620	0.250	0.00400
440 441	29.93	30.20	35	28.930	28.790	0.250	0.00400
441 442	30.20	30.81	35	28.790	28.650	0.250	0.00400
442 445	30.81	30.69	35	28.620	28.480	0.250	0.00400
443 444	29.76	30.40	35	28.760	28.620	0.250	0.00400
444 445	30.40	30.69	35	28.620	28.480	0.250	0.00400
445 449	30.69	31.00	40	28.480	28.320	0.250	0.00400
446 447	30.86	31.10	40	29.860	29.700	0.250	0.00400

Table B-1: Continued.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
447 448	31.10	31.10	35	29.700	29.560	0.250	0.00400
448 449	31.10	31.00	35	29.560	29.420	0.250	0.00400
449 453	31.00	31.22	40	28.320	28.160	0.250	0.00400
450 451	30.92	31.00	40	29.920	29.760	0.250	0.00400
451 452	31.00	31.10	35	29.760	29.620	0.250	0.00400
452 453	31.10	31.22	35	29.620	29.480	0.250	0.00400
453 457	31.22	30.72	42	28.160	27.992	0.250	0.00400
454 455	30.93	31.35	40	29.930	29.770	0.250	0.00400
455 456	31.35	31.85	35	29.770	29.630	0.250	0.00400
456 457	31.85	30.72	35	29.630	29.490	0.250	0.00400
457 458	30.72	30.66	35	27.992	27.852	0.250	0.00400
458 459	30.66	30.70	40	27.852	27.692	0.250	0.00400
459 460	30.70	30.70	40	27.692	27.532	0.250	0.00400
460 461	30.70	30.65	40	27.532	27.372	0.250	0.00400
461 462	30.65	30.60	40	27.372	27.212	0.250	0.00400
462 463	30.60	30.55	35	27.212	27.072	0.250	0.00400
463 464	30.55	30.50	35	27.072	26.932	0.250	0.00400
464 470	30.50	30.52	25	26.671	26.592	0.315	0.00317
465 466	30.52	30.58	40	29.520	29.360	0.250	0.00400
466 467	30.58	30.60	40	29.360	29.200	0.250	0.00400
467 468	30.60	30.65	40	29.200	29.040	0.250	0.00400
468 469	30.65	30.68	40	29.040	28.880	0.250	0.00400
469 470	30.68	30.70	40	28.880	28.720	0.250	0.00400
470 527	30.70	30.80	50	26.592	26.502	0.315	0.00180
471 472	31.17	30.85	40	30.170	29.850	0.250	0.00800
472 473	30.85	30.53	40	29.850	29.530	0.250	0.00800
473 476	30.53	30.70	40	29.530	29.403	0.315	0.00317
474 475	31.31	31.20	40	30.310	30.150	0.250	0.00400
475 476	31.20	30.70	40	30.150	29.700	0.250	0.01125
476 479	30.70	30.64	35	29.403	29.292	0.315	0.00317
477 478	31.50	31.10	40	30.500	30.100	0.250	0.01000
478 479	31.10	30.64	40	30.100	29.640	0.250	0.01150
479 480	30.64	30.66	35	29.292	29.181	0.315	0.00317
480 484	30.66	30.53	30	29.181	29.086	0.315	0.00317
481 482	30.50	30.50	40	29.500	29.340	0.250	0.00400
482 483	30.50	30.65	30	29.340	29.220	0.250	0.00400
483 484	30.65	30.53	30	29.220	29.100	0.250	0.00400
484 485	30.53	30.60	50	29.086	28.927	0.315	0.00317
485 495	30.60	30.86	45	28.927	28.784	0.315	0.00317
486 487	30.50	30.35	45	29.500	29.320	0.250	0.00400
487 488	30.35	30.20	45	29.320	29.140	0.250	0.00400
488 491	30.20	30.30	40	29.140	29.013	0.315	0.00317
489 490	30.50	30.85	45	29.500	29.320	0.250	0.00400
490 491	30.85	30.30	45	29.320	29.140	0.250	0.00400
491 494	30.30	30.53	38	29.013	28.892	0.315	0.00317
492 493	30.65	30.60	45	29.650	29.470	0.250	0.00400

Table B-1: Continued.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
493 494	30.60	30.53	45	29.470	29.290	0.250	0.00400
494 495	30.53	30.86	35	28.892	28.781	0.315	0.00317
495 496	30.86	30.92	40	28.781	28.654	0.315	0.00317
496 500	30.92	30.93	40	28.654	28.527	0.315	0.00317
497 498	31.21	31.29	40	30.210	30.050	0.250	0.00400
498 499	31.29	31.11	40	30.050	29.890	0.250	0.00400
499 500	31.11	30.93	40	29.890	29.730	0.250	0.00400
500 501	30.93	31.61	40	28.527	28.400	0.315	0.00317
501 508	31.61	31.56	40	28.400	28.273	0.315	0.00317
502 503	31.45	31.73	40	30.450	30.290	0.250	0.00400
503 504	31.73	31.65	30	30.290	30.170	0.250	0.00400
504 507	31.65	31.70	30	30.170	30.050	0.250	0.00400
505 506	30.86	31.60	35	29.860	29.720	0.250	0.00400
506 507	31.60	31.70	35	29.720	29.580	0.250	0.00400
507 508	31.70	31.56	40	29.580	29.420	0.250	0.00400
508 509	31.56	31.42	30	28.273	28.178	0.315	0.00317
509 510	31.42	31.32	30	28.178	28.083	0.315	0.00317
510 514	31.32	31.67	40	28.083	27.956	0.315	0.00317
511 512	31.45	31.70	40	30.450	30.290	0.250	0.00400
512 513	31.70	31.85	35	30.290	30.150	0.250	0.00400
513 514	31.85	31.67	35	30.150	30.010	0.250	0.00400
514 518	31.67	31.41	40	27.956	27.829	0.315	0.00317
515 516	31.35	31.61	40	30.350	30.190	0.250	0.00400
516 517	31.61	31.60	35	30.190	30.050	0.250	0.00400
517 518	31.60	31.41	35	30.050	29.910	0.250	0.00400
518 522	31.41	31.55	40	27.829	27.702	0.315	0.00317
519 520	31.31	31.65	40	30.310	30.150	0.250	0.00400
520 521	31.65	31.83	35	30.150	30.010	0.250	0.00400
521 522	31.83	31.55	35	30.010	29.870	0.250	0.00400
522 526	31.55	31.50	35	27.702	27.591	0.315	0.00317
523 524	31.22	31.10	40	30.220	30.060	0.250	0.00400
524 525	31.10	31.00	35	30.060	29.920	0.250	0.00400
525 526	31.00	31.50	35	29.920	29.780	0.250	0.00400
526 527	31.50	30.80	18	27.591	27.534	0.315	0.00317
527 584	30.80	31.08	40	27.534	27.407	0.315	0.00317
528 532	32.10	31.72	40	31.100	30.720	0.250	0.00950
529 530	31.50	31.90	40	30.500	30.340	0.250	0.00400
530 531	31.90	31.65	35	30.340	30.200	0.250	0.00400
531 532	31.65	31.72	35	30.200	30.060	0.250	0.00400
532 536	31.72	31.44	40	30.060	29.900	0.250	0.00400
533 534	31.17	31.31	40	30.170	30.010	0.250	0.00400
534 535	31.31	31.50	35	30.010	29.870	0.250	0.00400
535 536	31.50	31.44	35	29.870	29.730	0.250	0.00400
536 537	31.44	31.19	55	29.730	29.510	0.250	0.00400
537 541	31.19	31.14	40	29.510	29.350	0.250	0.00400
538 539	32.38	32.20	40	31.380	31.200	0.250	0.00450

Table B-1: Continued.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
539 540	32.20	31.60	45	31.200	30.600	0.250	0.01333
540 541	31.60	31.14	45	30.600	30.140	0.250	0.01022
541 545	31.14	31.86	40	29.350	29.190	0.250	0.00400
542 543	32.68	32.80	40	31.680	31.520	0.250	0.00400
543 544	32.80	32.20	45	31.520	31.200	0.250	0.00711
544 545	32.20	31.86	45	31.200	30.860	0.250	0.00756
545 549	31.86	31.20	40	29.190	29.030	0.250	0.00400
546 547	32.98	32.80	40	31.980	31.800	0.250	0.00450
547 548	32.80	32.51	45	31.800	31.510	0.250	0.00644
548 549	32.51	31.20	45	31.510	30.200	0.250	0.02911
549 553	31.20	31.45	40	29.030	28.870	0.250	0.00400
550 551	33.22	33.06	40	32.220	32.060	0.250	0.00400
551 552	33.06	32.50	45	32.060	31.500	0.250	0.01244
552 553	32.50	31.45	45	31.500	30.450	0.250	0.02333
553 556	31.45	32.06	40	28.870	28.710	0.250	0.00400
554 555	33.00	32.60	40	32.000	31.600	0.250	0.01000
555 556	32.60	32.06	40	31.600	31.060	0.250	0.01350
556 559	32.06	32.14	40	28.710	28.550	0.250	0.00400
557 558	33.06	32.70	40	32.060	31.700	0.250	0.00900
558 559	32.70	32.17	40	31.700	31.170	0.250	0.01325
559 569	32.17	32.09	35	28.550	28.410	0.250	0.00400
560 561	33.22	33.24	35	32.220	32.080	0.250	0.00400
561 562	33.24	33.40	35	32.080	31.940	0.250	0.00400
562 563	33.40	33.69	35	31.940	31.800	0.250	0.00400
563 567	33.69	33.65	35	31.800	31.660	0.250	0.00400
564 565	33.09	33.07	35	32.090	31.950	0.250	0.00400
565 566	33.07	33.30	35	31.950	31.810	0.250	0.00400
566 567	33.30	33.65	35	31.810	31.670	0.250	0.00400
567 568	33.65	33.40	45	31.660	31.480	0.250	0.00400
568 569	33.40	32.09	50	31.480	31.090	0.250	0.00780
569 570	32.09	31.90	40	28.410	28.250	0.250	0.00400
570 578	31.90	31.60	40	28.250	28.152	0.250	0.00245
571 572	33.91	32.85	40	32.910	31.850	0.250	0.02650
572 574	32.85	33.06	40	31.850	31.690	0.250	0.00400
573 574	32.73	33.06	35	31.730	31.590	0.250	0.00400
574 577	33.06	32.23	35	31.590	31.230	0.250	0.01029
575 576	33.85	32.33	45	32.850	31.330	0.250	0.03378
576 577	32.33	32.23	40	31.330	31.170	0.250	0.00400
577 578	32.23	31.60	45	31.170	30.600	0.250	0.01267
578 579	31.60	31.45	40	28.152	28.054	0.250	0.00245
579 580	31.45	31.30	40	28.054	27.956	0.250	0.00245
580 581	31.30	31.28	40	27.956	27.858	0.250	0.00245
581 582	31.28	31.09	40	27.858	27.759	0.250	0.00245
582 583	31.09	31.08	40	27.759	27.661	0.250	0.00245
583 584	31.08	31.08	35	27.661	27.575	0.250	0.00245
584 587	31.08	30.81	40	27.407	27.335	0.315	0.00180

Table B-1: Continued.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
585 586	31.80	31.15	35	30.800	30.150	0.250	0.01857
586 587	31.15	30.81	35	30.150	29.810	0.250	0.00971
587 590	30.81	30.71	35	27.335	27.272	0.315	0.00180
588 589	31.03	31.08	35	30.030	29.890	0.250	0.00400
589 590	31.08	30.71	35	29.890	29.710	0.250	0.00514
590 600	30.71	30.74	35	27.271	27.208	0.315	0.00180
591 592	31.40	31.15	40	30.400	30.150	0.250	0.00625
592 593	31.15	31.00	30	30.150	30.000	0.250	0.00500
593 594	31.00	30.80	30	30.000	29.800	0.250	0.00667
594 598	30.80	30.79	35	29.800	29.660	0.250	0.00400
595 596	31.09	31.04	40	30.090	29.930	0.250	0.00400
596 597	31.04	30.91	30	29.930	29.810	0.250	0.00400
597 598	30.91	30.79	30	29.810	29.690	0.250	0.00400
598 599	30.79	30.77	40	29.660	29.500	0.250	0.00400
599 600	30.77	30.74	40	29.500	29.340	0.250	0.00400
600 604	30.74	30.75	40	27.208	27.131	0.315	0.00193
601 602	30.94	30.87	40	29.940	29.780	0.250	0.00400
602 603	30.87	30.80	35	29.780	29.640	0.250	0.00400
603 604	30.80	30.75	35	29.640	29.500	0.250	0.00400
604 608	30.75	30.40	40	27.131	27.050	0.315	0.00203
605 606	30.86	30.96	40	29.860	29.700	0.250	0.00400
606 607	30.96	30.65	30	29.700	29.580	0.250	0.00400
607 608	30.65	30.40	30	29.580	29.400	0.250	0.00600
608 637	30.40	30.32	13	27.050	27.023	0.315	0.00211
609 610	31.50	31.50	40	30.500	30.340	0.250	0.00400
610 611	31.50	31.52	40	30.340	30.180	0.250	0.00400
611 612	31.52	31.20	35	30.180	30.040	0.250	0.00400
612 613	31.20	31.10	35	30.040	29.900	0.250	0.00400
613 618	31.10	30.56	40	29.900	29.560	0.250	0.00850
614 615	31.60	31.40	40	30.600	30.400	0.250	0.00500
615 616	31.40	31.10	40	30.400	30.100	0.250	0.00750
616 617	31.10	30.85	35	30.100	29.850	0.250	0.00714
617 618	30.85	30.56	35	29.850	29.560	0.250	0.00829
618 623	30.56	30.40	40	29.560	29.400	0.250	0.00400
619 620	31.30	31.07	40	30.300	30.070	0.250	0.00575
620 621	31.07	30.85	40	30.070	29.850	0.250	0.00550
621 622	30.85	30.62	35	29.850	29.620	0.250	0.00657
622 623	30.62	30.40	35	29.620	29.400	0.250	0.00629
623 624	30.40	30.45	25	29.400	29.300	0.250	0.00400
624 625	30.45	30.42	40	29.300	29.140	0.250	0.00400
625 626	30.42	30.40	45	29.140	28.960	0.250	0.00400
626 627	30.40	30.37	45	28.960	28.780	0.250	0.00400
627 636	30.37	30.35	45	28.780	28.600	0.250	0.00400
628 629	30.40	30.38	40	29.400	29.240	0.250	0.00400
629 630	30.38	30.35	40	29.240	29.080	0.250	0.00400
630 631	30.35	30.30	40	29.080	28.920	0.250	0.00400

Table B-1: Continued.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
631 632	30.30	30.25	40	28.920	28.760	0.250	0.00400
632 633	30.25	30.25	40	28.760	28.600	0.250	0.00400
633 634	30.25	30.25	35	28.600	28.460	0.250	0.00400
634 635	30.25	30.30	35	28.460	28.320	0.250	0.00400
635 636	30.30	30.35	30	28.320	28.200	0.250	0.00400
636 637	30.35	30.32	50	28.200	28.000	0.250	0.00400
637 641	30.32	30.55	40	27.023	26.896	0.315	0.00318
638 639	30.93	30.80	40	26.896	26.767	0.315	0.00321
639 640	30.80	30.75	40	26.767	26.637	0.315	0.00325
640 641	30.75	30.55	40	26.637	26.506	0.315	0.00328
641 642	30.55	30.45	40	26.506	26.373	0.315	0.00332
642 699	30.45	30.50	35	26.373	26.256	0.315	0.00335
643 644	33.10	32.40	40	32.100	31.400	0.250	0.01750
644 645	32.40	32.15	40	31.400	31.150	0.250	0.00625
645 646	32.15	33.48	35	31.150	31.010	0.250	0.00400
646 647	33.48	31.30	35	31.010	30.300	0.250	0.02029
647 651	31.30	31.70	40	30.300	30.140	0.250	0.00400
648 649	32.90	32.58	40	31.900	31.580	0.250	0.00800
649 650	32.58	31.97	35	31.580	30.970	0.250	0.01743
650 651	31.97	31.70	30	30.970	30.700	0.250	0.00900
651 660	31.70	31.70	40	30.140	29.980	0.250	0.00400
652 653	33.50	33.75	35	32.500	32.360	0.250	0.00400
653 654	33.75	33.91	35	32.360	32.220	0.250	0.00400
654 657	33.91	33.90	40	32.220	32.060	0.250	0.00400
655 656	32.68	32.90	35	31.680	31.540	0.250	0.00400
656 657	32.90	33.90	35	31.540	31.400	0.250	0.00400
657 658	33.90	33.25	40	31.400	31.240	0.250	0.00400
658 659	33.25	32.80	40	31.240	31.080	0.250	0.00400
659 660	32.80	31.70	40	31.080	30.700	0.250	0.00950
660 661	31.70	31.75	10	29.980	29.940	0.250	0.00400
661 662	31.75	31.65	35	29.940	29.800	0.250	0.00400
662 663	31.65	31.50	35	29.800	29.660	0.250	0.00400
663 675	31.50	31.85	40	29.660	29.500	0.250	0.00400
664 665	34.41	33.78	50	33.410	32.780	0.250	0.01260
665 666	33.78	33.01	50	32.780	32.010	0.250	0.01540
666 670	33.01	32.94	40	32.010	31.850	0.250	0.00400
667 668	34.33	34.39	35	33.330	33.190	0.250	0.00400
668 669	34.39	33.65	35	33.190	32.650	0.250	0.01543
669 670	33.65	32.94	35	32.650	31.940	0.250	0.02029
670 674	32.94	33.00	35	31.850	31.710	0.250	0.00400
671 672	34.09	34.15	35	33.090	32.950	0.250	0.00400
672 673	34.15	33.50	35	32.950	32.500	0.250	0.01286
673 674	33.50	33.00	35	32.500	32.000	0.250	0.01429
674 675	33.00	31.85	50	31.710	30.850	0.250	0.01720
675 680	31.85	32.00	40	29.500	29.340	0.250	0.00400
676 677	34.15	34.15	40	33.150	32.990	0.250	0.00400

Table B-1: Continued.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
677 678	34.15	33.60	40	32.990	32.600	0.250	0.00975
678 679	33.60	33.30	35	32.600	32.300	0.250	0.00857
679 680	33.30	32.00	37	32.300	31.000	0.250	0.03514
680 681	32.00	31.76	40	29.340	29.180	0.250	0.00400
681 682	31.76	31.40	45	29.180	29.000	0.250	0.00400
682 692	31.40	30.76	45	29.000	28.820	0.250	0.00400
683 684	31.21	31.45	40	30.210	30.050	0.250	0.00400
684 686	31.45	31.49	40	30.050	29.890	0.250	0.00400
685 686	31.50	31.49	35	30.500	30.360	0.250	0.00400
686 689	31.49	30.85	45	29.890	29.710	0.250	0.00400
687 688	30.80	30.94	40	29.800	29.640	0.250	0.00400
688 689	30.94	30.85	40	29.640	29.480	0.250	0.00400
689 690	30.85	31.20	35	29.480	29.340	0.250	0.00400
690 691	31.20	31.13	35	29.340	29.200	0.250	0.00400
691 692	31.13	30.76	35	29.200	29.060	0.250	0.00400
692 693	30.76	30.87	45	28.820	28.710	0.250	0.00245
693 698	30.87	30.49	45	28.710	28.599	0.250	0.00245
694 695	30.39	30.80	40	29.390	29.230	0.250	0.00400
695 697	30.80	30.54	35	29.230	29.090	0.250	0.00400
696 697	30.75	30.54	35	29.750	29.540	0.250	0.00600
697 698	30.54	30.49	35	29.090	28.950	0.250	0.00400
698 699	30.49	30.40	40	28.599	28.501	0.250	0.00245
699 703	30.40	30.50	45	26.256	25.993	0.315	0.00584
700 701	30.95	30.83	35	29.950	29.810	0.250	0.00400
701 702	30.83	30.56	30	29.810	29.560	0.250	0.00833
702 703	30.56	30.50	30	29.560	29.440	0.250	0.00400
703 706	30.50	30.60	35	25.993	25.784	0.315	0.00599
704 705	30.90	30.67	45	29.900	29.670	0.250	0.00511
705 706	30.67	30.60	45	29.670	29.490	0.250	0.00400
706 709	30.60	30.90	40	25.784	25.538	0.315	0.00615
707 708	31.80	31.45	45	30.800	30.450	0.250	0.00778
708 709	31.45	30.90	45	30.450	29.900	0.250	0.01222
709 713	30.90	31.07	35	25.538	25.317	0.315	0.00630
710 711	31.86	31.87	35	30.860	30.720	0.250	0.00400
711 712	31.87	31.87	30	30.720	30.600	0.250	0.00400
712 713	31.87	31.07	30	30.600	30.070	0.250	0.01767
713 758	31.07	31.55	37	25.317	25.078	0.315	0.00646
714 715	32.50	33.05	40	31.500	31.340	0.250	0.00400
715 716	33.05	33.20	30	31.340	31.220	0.250	0.00400
716 717	33.20	33.70	30	31.220	31.100	0.250	0.00400
717 721	33.70	33.63	40	31.100	30.940	0.250	0.00400
718 719	34.00	33.30	40	33.000	32.300	0.250	0.01750
719 720	33.30	33.56	35	32.300	32.160	0.250	0.00400
720 721	33.56	33.63	35	32.160	32.020	0.250	0.00400
721 722	33.63	33.12	40	30.940	30.780	0.250	0.00400
722 723	33.12	32.50	40	30.780	30.620	0.250	0.00400

Table B-1: Continued.

Link ID	Ground Elevation (m)		L (m)	Crown Elevation (m)		Dia. (m)	Slope m/m
	U/S	D/S		U/S	D/S		
723 743	32.50	32.15	27	30.620	30.512	0.250	0.00400
724 725	32.15	32.35	45	31.150	30.970	0.250	0.00400
725 726	32.35	31.79	45	30.970	30.790	0.250	0.00400
726 729	31.79	32.33	40	30.790	30.630	0.250	0.00400
727 728	33.38	32.90	45	32.380	31.900	0.250	0.01067
728 729	32.90	32.33	45	31.900	31.330	0.250	0.01267
729 743	32.33	32.15	35	30.630	30.490	0.250	0.00400
730 731	33.24	33.00	40	32.240	32.000	0.250	0.00600
731 732	33.00	32.80	40	32.000	31.800	0.250	0.00500
732 733	32.80	32.60	35	31.800	31.600	0.250	0.00571
733 737	32.60	32.40	35	31.600	31.400	0.250	0.00571
734 735	33.35	33.12	40	32.350	32.120	0.250	0.00575
735 736	33.12	32.74	40	32.120	31.740	0.250	0.00950
736 737	32.74	32.40	35	31.740	31.400	0.250	0.00971
737 742	32.40	32.36	40	31.400	31.240	0.250	0.00400
738 739	33.70	33.10	40	32.700	32.100	0.250	0.01500
739 740	33.10	32.86	40	32.100	31.860	0.250	0.00600
740 741	32.86	32.62	35	31.860	31.620	0.250	0.00686
741 742	32.62	32.36	30	31.620	31.360	0.250	0.00867
742 743	32.36	32.15	40	31.240	31.080	0.250	0.00400
743 747	32.15	31.79	54	30.490	30.274	0.250	0.00400
744 745	32.31	32.02	40	31.310	31.020	0.250	0.00725
745 746	32.02	31.90	35	31.020	30.880	0.250	0.00400
746 747	31.90	31.79	35	30.880	30.740	0.250	0.00400
747 751	31.79	31.39	40	30.274	30.114	0.250	0.00400
748 749	32.24	31.98	40	31.240	30.980	0.250	0.00650
749 750	31.98	31.81	35	30.980	30.810	0.250	0.00486
750 751	31.81	31.39	35	30.810	30.390	0.250	0.01200
751 752	31.39	31.50	40	30.114	29.954	0.250	0.00400
752 753	31.50	31.50	40	29.954	29.794	0.250	0.00400
753 754	31.50	31.86	40	29.794	29.634	0.250	0.00400
754 755	31.86	32.50	35	29.634	29.494	0.250	0.00400
755 756	32.50	32.20	35	29.494	29.354	0.250	0.00400
756 757	32.20	32.15	35	29.354	29.214	0.250	0.00400
757 758	32.15	31.55	35	29.214	29.074	0.250	0.00400
758 900	31.55	31.25	10	25.078	24.991	0.315	0.00869

Appendix C: Results of some researchers for benchmark problems.

Table C-1: Results obtained by Adaptive CA method for the first example (Afshar et al., 2016).

Link ID	Crown Elevation (m)		D (mm)	V (m/s)	Depth of flow (%)
	Upstream	Downstream			
01 02	147.60	146.10	304.8	1.848	0.77
02 03	146.10	143.70	381	2.46	0.66
03 06	143.70	141.60	381	2.544	0.81
04 05	144.60	143.085	304.8	1.743	0.82
05 06	143.10	141.60	457.2	2.085	0.62
06 10	141.60	138.60	609.6	3.171	0.63
07 08	144.60	143.10	457.2	1.962	0.65
08 09	143.10	140.10	457.2	2.931	0.66
09 10	140.10	138.60	533.4	2.649	0.71
10 14	138.60	136.872	762	3.066	0.82
11 12	143.10	140.10	381	2.544	0.81
12 13	140.10	138.60	533.4	2.649	0.71
13 14	138.60	137.10	609.6	2.826	0.64
14 18	136.218	134.10	914.4	3.6	0.78
15 16	138.00	136.485	304.8	1.743	0.82
16 17	136.56	135.60	381	1.845	0.74
17 18	135.60	134.10	457.2	2.331	0.62
18 19	134.10	132.90	1066.8	3.528	0.72
19 20	132.90	131.724	1066.8	3.168	0.82
20 21	131.724	130.071	1066.8	3.393	0.81

Table C-2: Results obtained by Adaptive CA method for the first example (Afshar et al., 2016).

Link ID	Crown Elevation (m)		D (mm)	V (m/s)	Depth of flow (%)
	Upstream	Downstream			
01 02	72.39	71.46	250	0.80	0.67
02 03	68.60	67.80	350	0.85	0.63
03 04	70.75	69.094	200	0.77	0.82
04 05	71.46	69.90	250	0.80	0.73
05 06	69.90	68.99	250	0.81	0.76
06 11	68.99	67.65	250	0.91	0.71
07 08	67.70	66.09	300	0.87	0.58
08 09	66.09	65.13	300	0.75	0.69
09 10	67.75	66.83	300	0.91	0.82
10 11	66.93	66.35	400	0.76	0.58
11 12	66.30	65.18	350	0.85	0.68
12 13	65.23	64.17	400	0.90	0.81
13 20	64.22	63.775	450	0.73	0.82
14 15	63.825	63.47	500	0.70	0.71
15 16	69.14	67.90	250	0.75	0.67
16 17	67.90	66.40	250	0.83	0.69
17 18	66.40	64.60	250	0.82	0.74
18 19	64.70	64.00	350	0.68	0.59
19 20	64.00	63.32	350	0.58	0.74
20 21	63.37	61.337	400	1.51	0.82

Table C- 3: Results obtained from CA based hybrid method (discrete version) for the first example (Afshar and Rohani, 2012).

Link ID	Crown Elevation (m)		D (mm)	V (m/s)	Depth of flow (%)
	Upstream	Downstream			
01 02	147.90	146.40	304.8	1.683	0.85
02 03	146.48	144.08	381.0	2.166	0.74
03 06	144.08	141.98	381.0	2.346	0.89
04 05	144.90	143.39	304.8	1.614	0.90
05 06	143.54	142.05	457.2	1.818	0.70
06 10	142.20	139.20	609.6	2.778	0.71
07 08	145.05	143.55	457.2	1.728	0.73
08 09	143.55	140.55	457.2	2.58	0.74
09 10	140.63	139.13	533.4	2.358	0.79
10 14	139.35	137.63	762.0	2.838	0.90
11 12	143.48	140.48	381.0	2.346	0.89
12 13	140.63	139.13	533.4	2.358	0.79
13 14	139.13	137.40	533.4	2.661	0.89
14 18	137.78	135.00	914.4	3.6	0.78
15 16	138.38	137.18	381.0	1.446	0.64
16 17	137.18	135.98	381.0	1.794	0.76
17 18	136.05	134.55	533.4	2.04	0.70
18 19	135.15	133.95	1066.8	3.156	0.80
19 20	133.95	132.78	1219.2	2.928	0.90
20 21	132.93	132.14	1066.8	2.37	0.90

Table C-4: Results obtained from CA based hybrid method (discrete version) for the second example (Afshar and Rohani, 2012).

Link ID	Crown Elevation (m)		D (mm)	V (m/s)	Depth of flow (%)
	Upstream	Downstream			
01 02	72.39	71.46	250	0.80	0.67
02 03	68.55	67.58	300	0.89	0.82
03 04	70.80	69.30	250	0.77	0.55
04 05	71.51	69.95	300	0.81	0.52
05 06	69.90	68.99	250	0.81	0.76
06 11	68.99	67.65	250	0.91	0.71
07 08	67.70	66.09	300	0.87	0.58
08 09	66.09	65.13	300	0.75	0.69
09 10	67.68	67.25	400	0.71	0.60
10 11	67.15	66.03	300	0.94	0.82
11 12	66.13	65.23	400	0.79	0.58
12 13	65.23	64.17	400	0.90	0.80
13 20	64.17	63.34	400	0.92	0.82
14 15	63.34	62.48	400	0.95	0.82
15 16	69.30	67.90	250	0.79	0.65
16 17	67.90	66.40	250	0.83	0.69
17 18	66.40	64.60	250	0.82	0.74
18 19	64.65	63.95	300	0.65	0.82
19 20	63.95	62.38	300	0.80	0.74
20 21	62.48	60.45	400	1.50	0.82

الخلاصة

شبكات الصرف الصحي هي احد العناصر الاساسية المهمة للبنى التحتية في المدن الحديثة التي تخدم المساكن المحلية، والمصانع، والمستشفيات والمدارس وغيرها من الأنشطة الحيوية من خلال التخلص من المياه العادمة غير المرغوب فيها ومنع تلوث البيئة المائية. وفي السنوات الأخيرة، ازداد عدد سكان العالم زيادة كبيرة بالتوازي مع الأنشطة التجارية والصناعية. وقد أدى ذلك إلى زيادة استهلاك المياه وما يترتب على ذلك من زيادات في كمية المياه المستعملة المنتجة، مما يعني أن هناك حاجة إلى إنشاء شبكات صرف صحي جديدة في العديد من المناطق.

ويوضح هذا البحث تطبيق الخوارزمية الجينية (Genetic Algorithm) الهجينة مع البرمجة الارشادية (Heuristic Programming)، في التقنية (GA-HP) الجديدة من أجل ايجاد التصميم الأمثل لشبكات المجاري. والهدف من ذلك هو التقليل إلى أدنى حد من وظيفة تكلفة البناء، التي تتمثل في عمق الحفر وقطر الأنابيب. وقد استوفى نموذج (GA-HP) المقترح مهمة التصميم الأمثل في مرحلتين. أولا، تم تطبيق الخوارزمية الجينية (GA) للحصول على الأقطار اللازمة للتصميم الأولي للشبكة. ثانيا، استخدمت التصاميم الأولية للبرمجة الارشادية (Heuristic Programming) للحصول على المنحدر الأمثل لتلك الأقطار وتحديد خصائص أخرى مثل السرعة والعمق النسبي للمياه وأعماق الحفر والتكلفة الإجمالية للشبكة.

تم استخدام كود الماتلاب لتنفيذ نموذج الامثلية (GA-HP). وقد اختبر نموذج (GA-HP) المقترح لتحديد تأثير سلوك التقارب للحل الامثل من خلال أداء ثمانية طرق مختلفة لأختيار الابوين و هي (RWS، RRWS ، LRS، ERS، TRS، SUS، TOS، RMS) ، وسبع طرق مختلفة لتزاوج للكروموسومات (One-point، N-point، Uniform، Flat Arithmetic، Intermediate، Shuffle)، ومختلف حجم السكان (50، 100 ، 200 ، 300 ، 400). وقد أثبتت طريقة اختيار البطولة (Tournament selection) وطريقة التزاوج ذات النقطة الواحدة (One-point crossover) أنها الأكثر فعالية فيما يتعلق بالتصميم الأمثل. يتم اختبار نموذج (GA-HP) المقترح باستخدام بعض الامثلة القياسية لشبكات الصرف الصحي من خلال الدراسات السابقة وحالتين دراسية في مدينة كربلاء المقدسة. وأظهرت النتائج أن نموذج (GA-HP) متفوق على جميع الأساليب السابقة.

من أجل ضمان كفاءة نموذج (GA-HP) المقترح لتصميم الشبكات الكبيرة، تم فحصه مع حالتين دراسية تقعان في مدينة كربلاء المقدسة، ثم قارنت تكلفة التصاميم اليدوية مع التصاميم التي

تم الحصول عليها من هذا النموذج للشبكات. وبلغت نسبة الادخار (28.1٪) و (28.45٪) للشبكات الصغيرة نسبياً والكبيرة، على التوالي.

جمهورية العراق
وزارة التعليم والبحث العلمي
جامعة كربلاء / كلية الهندسة

التصميم الامثل لشبكات الصرف الصحي باستخدام الخوارزمية الجينية

الرسالة مقدمة إلى
قسم الهندسة المدنية / كلية الهندسة في جامعة كربلاء كجزء من متطلبات
نيل درجة الماجستير في علوم الهندسة المدنية (البنى التحتية)

من قبل
صفاء صبري محمد مهدي
(بكلوريوس هندسة مدني 2014)

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1439هـ ربيع الاول

تشرين الاول 2017