UNIVERSITY OF PERADENIYA
PERADENIYA

APPLICATION OF STRUCTURAL OPTIMIZATION FOR BRIDGE DESIGNING

A dissertation submitted in partial fulfillment of the requirements for the degree of
Master of Philosophy Engineering

by

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DECLARATION

I declare that the work presented in this thesis was carried out by me for the partial fulfillment of the degree of Master of Philosophy. This thesis has not been submitted in whole or in part for the candidature of degree/diploma of this or any other university.

S Jothy Kanna

ACKNOWLEDGEMENT

It is great pleasures for me to that I acknowledge my advisor Dr. Ranjith Dissanayaka, for him guidance and continuous encouragement given to me throughout this research. I cannot ever forget him valuable comments on report writing and kind advices which always kept me on the track and facilitated to overcome the difficulties arisen during the study. Meanwhile I wish to express my appreciation and gratitude to Prof. M.P. Ranaweera and Prof. Walgama regarding their comments and valuable advices to make the foundation on this research area.

I would like to thank the staff members of the Structures lab, Civil Department office and Dean's office for their assistance and corporation given to me throughout this study. I also thank Mr.A.G.A. Ariyawansa, Road Development Authority (RDA) for giving their design drawings. Thanks are also extended to my senior brothers Mr. P.A.K. Karunanada and Mr.Siriwardana for their encouragement and help given for report writing, and Mr. S.N.B.Narasinghe and Mr.C.Irrugalrathna for their companionship and encouragement.

I am cordially grateful to my father and my mother for their kind blessings and continuous encouragement given to me throughout the study.

Finally I would like to acknowledge, National Science Foundation of Sri Lanka for the financial support given to me through the research grant number RG/2003/E/001 and NSF/SCH/2005/03.

ABSTRACT

Structural optimization deals with the efficient design of structures. Efficiency implies minimum cost or minimum weight while satisfying a variety of strength and stiffness requirements. In all engineering problems, designers try to find solutions giving good performance, which satisfy several requirements. Using optimization techniques, engineers can obtain the optimum, within the imposed conditions. Structures designed in this way are safer, more reliable and less expensive than the traditional designs.

The application of Structural optimization approach to Bridge system is presented in this thesis. The bridge system consists of deck, beam, abutment, wing wall and pier. The objective function of the optimization problem is the cost (volume) of the every component. Reduced Gradient method is used during the structural optimization process. To design optimized bridge system, software was developed. It will be use with knowledge of bridge designing.

This thesis describes how *MSExcel* is utilized to organize, manage, direct for solving and optimizing bridge components. It is easy to learn and user-friendly software. To evaluate the stress and deflection *SAP2000* was used. Today's engineering structures are often analyzed using the finite element method (*FEM*). Numerical design optimization provides the designer with a computational tool that finds the best design, based on predefined performance requirements. The optimizer automatically makes changes to problem parameters that are allowed to vary, referred to as design variables, perform a new analysis (linear or non-linear) to evaluate the influence of the changes and repeat the process until the design that best satisfies the performance requirement is found. After that

bridge components were modeled using *SAP2000.* Actually, it is used for checking the stress and deflection. Compared the optimized results with manual design results, the optimized results are economical than the manual design results.

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CHAPTER 1: INTRODUCTION

1.1 Background

The optimization theory originated as a branch of study in Mathematics. The Mathematical discipline that deals with parameter optimization is called mathematical programming. Much optimization problem deal with mathematical programming techniques and their application to structural optimization problems defined by discretized models.

Engineering consists of a number of well-established activities including analysis, design, fabrication, sales, research and the development of systems. The subject of this text is the design of systems is a major field of developed and used for centuries, and the existence of fine buildings, bridges, highways, automobiles, airplanes, space vehicles and other complex systems are excellent testimonials. However, evolution of these systems has been slow. The entire process is both time-consuming and costly, requiring substantial human and use a system regardless of whether it was the best one. Improved systems were designed only after a substantial investment had been recovered. The structural optimization is new system performed the same or even more tasks, cost less, and were more efficient.

The several systems can usually accomplish the same task, and that some are better than others. For an example, the purpose of a bridge is to provide continuity in traffic from one side to the other. Several types of bridges can serve this purpose. However, to analyze and possibilities can be a time-consuming and costly affair. Usually one type is selected and designed in detail.

The design of complex systems requires large calculation and data processing. During the large three decades, a revolution in computer technology and numerical computations has taken place. Today's computers can perform complex calculations and process large amount of data efficiently. The engineering design process benefits greatly from this revolution. Better systems can now be designed by analyzing various options in a short time. This is highly desirable because better designed systems cost less, have more capability, and easy to maintain and operate.

Optimal design of structures is always a goal of engineers, whether or not mathematically based approaches are used to drive optimization procedures. In current practice, most building designs are optimized by trial and error combined with the experience of the designer. It is a time taking process but using, optimization algorithms can we make computer programs. In general, optimum design problems seek to minimize a function (usually cost) using a set of design variables subjected to constraints.

The design of systems can be formulated as problems of optimization where a measure of performance is to be optimized while satisfying all the constraints. In recent years, numerical methods of optimization have been developed extensively. Many of the methods have been used to design better systems. This thesis describes optimization methods and their applications to the design of bridge systems.

Any problems in which certain parameters need to be determined to satisfy constraints can be formulated as an optimum design problem. Once this has been done, the concepts and the methods described in this text can be used general, having a wide range of applications is limited only by the imagination or ingenuity of design engineers.

1.2 Problem Statement

Bridge is important structure for the transportation purpose. But the cost for constructing bridge is very high. Therefore the Structural engineers' duty is reducing the total cost while satisfying all the basic requirements. This can be achieved by finding optimum cross sectional dimensions of every components of the bridge system using structural optimization theories. In countries like Sri Lanka, this is more important since study regarding this field has been attempted.

1.3 Objectives of the Study

The main objective of this study is describes how Structural optimization theory is used to organize, manage, direct for solving the design problems of bridge components. For the optimization process I used several soft wares (Genesis, Femap, VisualDoc, MsExcel) which are available in the market. Numerical design optimization provides the designer with a computational tool that finds the best design, based on predefined performance requirements.

1.4 Overview of the Thesis

Chapter 2 includes the details of bridge types used in Sri Lanka and relevant details for optimizing bridge components.

Chapter 3 of this thesis presents a discussion of structural optimization and optimization process in engineering designs.

Chapter 4 of this thesis describes optimization theory and basic concepts of optimization.

Chapter 5 contains about proposed software model and the main modules required in structural optimization problems, such as structural analysis module, optimization module and interface module.

Chapter 6 of this thesis describes the use of this model to optimize reinforced concrete bridge deck by performing a case study. Under the case study simply supported one way concrete deck was considered and optimum depth was found after optimization process.

Chapter 7 contains a case study on pre-stressed beam. Under the case study simply supported pre-stressed concrete beam was considered and optimum cross sectional area of the pre-stressed beam and tendon area were found after optimization process.

Chapter 8 contains a case study for optimum abutment design. Under the case study mass concrete abutment was considered and optimum dimensions of the abutment were found after optimization process.

Chapter 9 contains a case study on wing wall design. Under the case study mass concrete wing wall was considered and optimum dimensions of the wing wall were found after optimization process.

Chapter 10 contains a case study on pier design. Under the case study Hammerhead Circular shaft Pier was considered and optimum diameter of the pier was found after optimization process.

Chapter 11 contains a summary of the present work and a list of the conclusions drawn from this study.

CHAPTER 2: BRIDGES

2.1 Introduction

Bridges are important structures in projects such as highways, elevated expressways, flyovers and water crossings. The effective and efficient design of bridges requires a good understanding of bridge engineering principles and usage of modern computing tools. The purpose of a bridge is to carry a service over an 'obstacle' (which may be another road or railway, a river, a valley ete). The designer has to ensure that bridges are both safe and economic. Safety and aesthetics will continue to play major roles in the selection of structure types. A bridge is consisting of substructure (abutment, piers and foundation) and super structure (beam and road slab). The type of bridge will depend on the length of the longest gap that has to be cleared by a single span, on the type and volume of traffic, on the type of ground, on environmental considerations, on the available budget, and on the relative cost of different designs. There are some types of bridges are available in Sri Lanka, such as

- Steel bridges
- Reinforced cement concrete bridges
- Pre-cast pre-stressed concrete bridges
- Timber bridges
- Arch bridges .

In developing countries like Sri Lanka in case of designing bridges the designers consider the safety, but by using the optimization techniques, can reduce the cost of the bridge. In my research, I concern about Reinforced cement concrete bridges and Pre-cast pre-stressed concrete bridges.

2.1.1 Reinforced cement concrete bridges

In this type of bridge, mainly the deck and the beams are constructed by using reinforced cement concrete. In my research, I have designed an optimum reinforced concrete deck (slab) without a beam arrangement.

In 1980's major bridge projects were constructed by using steel and concrete. The major advantage in the use of concrete for bridges is to have variation of shapes in formwork

From the beginning of RDA history, they have designed reinforced concrete bridge decks. They were used for the entire superstructure as slab spans. Hydraulically, slab spans are better than box culverts. With open railing, slab spans can become a nice solution for low headroom stream crossings where occasional flood inundation is expected. In Sri Lanka large numbers of small streams are crossing across the road, for this case the optimized one way reinforced concrete slab is very important.

2.1.2 Pre-stressed bridges

Pre-stressed concrete combines high-strength concrete with high-strength steel in an "active" manner. This achieved by tensioning the steel and holding it against the concrete, thus putting the concrete into compression. This active combination results in a much better behavior of the two materials. Steel is ductile and now is made to act in high tension by pre-stressing. Concrete is a brittle material with its tensile capacity now improved by being compressed. Thus pre-stressed concrete is an ideal combination of two modern high strength materials.

The historical development of pre-stressed concrete actually started in a different manner when pre-stressing was only intended to create permanent compression in concrete to improve its tensile strength. Later it became clear that the pre-stressing the steel was also essential to the efficient utilization of high-tensile steel.

The basic principle of pre-stressing was applied to construction perhaps centuries ago, when ropes or metal bands were wound around wooden staves to form barrels. However the modern development of pre-stressed concrete is credited to E. Freyssinet of France, who in 1928 started using high-strength steel wires for pre-stressing.

2.1.2.1 Pre-tensioning and post-tensioning.

The term pre-tensioning is used to describe any method of pre-stressing in which the tendons are tensioned before the concrete is placed. Post-tensioning is a method of pre-stressing in which the tendon is tensioned after the concrete has hardened. Thus the pre-stressing is almost always performed against the hardened concrete, and the tendons are anchored against it immediately after pre-stressing. This method can be applied to members either pre-cast or cast in place. In my research I concern about Post- tensioning method.

In this thesis, an optimum design method for pre-stressed concrete beams is studied, in which not only the most economical pre-stressing force, areas of reinforcements and tendon layout but also all the dimensions of I – shape cross section are determined subject to both serviceability and ultimate limit state with respect to all the constraints.

The significance of dealing with the dimensions of I – shape cross section as the design variables and efficiency of the design method are illustrated for single span pre-stressed concrete beam in the chapter 7.

2.2 Components of a Typical Bridge

A bridge consists of Substructure and superstructure. Superstructures are the deck arrangement (slab and beam). Substructures are Abetment, wing wall, pier and foundation.

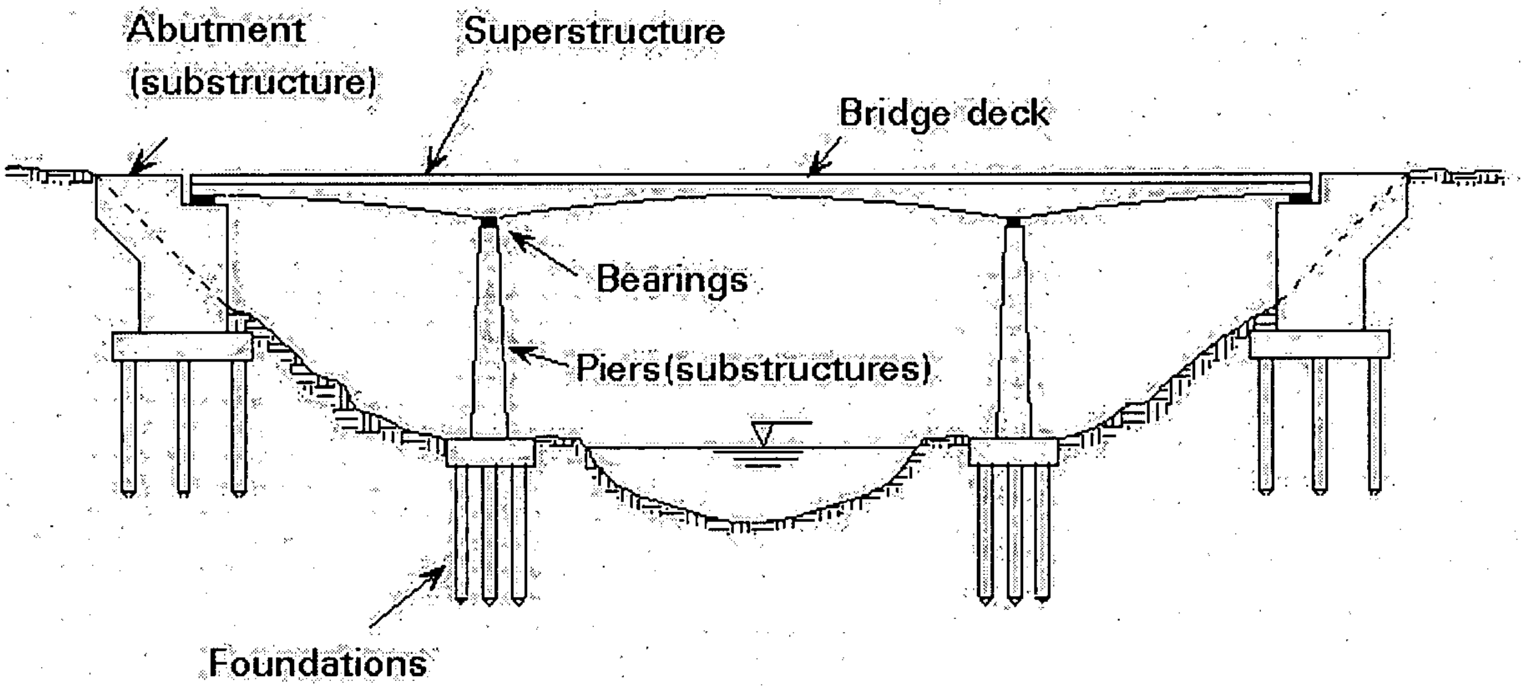

Figure 2.1: Schematic drawing of bridge components

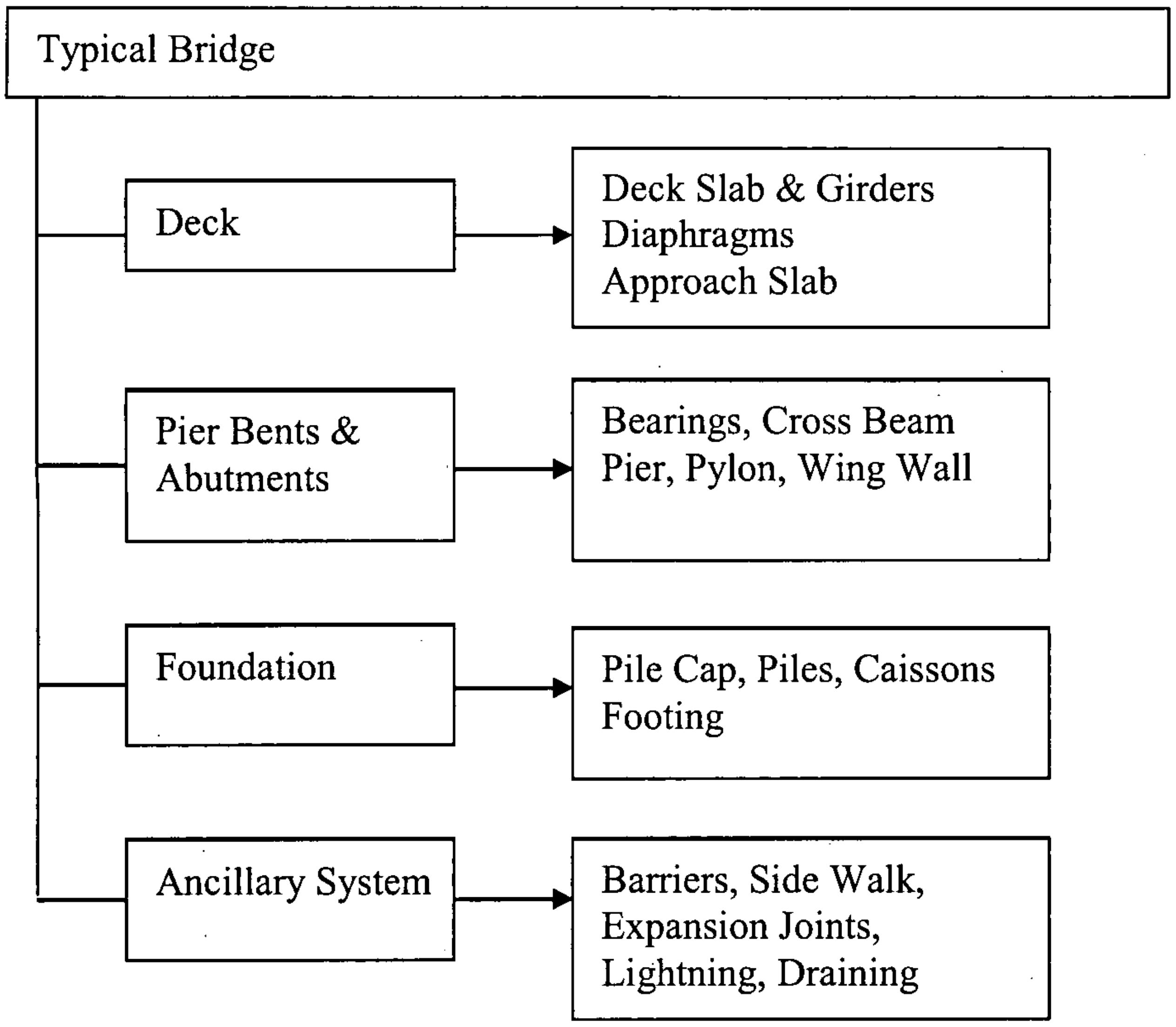

Figure 2.2: Details of bridge components

In my case study, I optimize Simple Reinforced concrete slab deck, Pre-stressed Beam, Abutment (Mass Concrete), Wing Wall and Pier. In the following chapters explains about this case studies.

2.2.1 Superstructures

2.2.1.1 Deck

Whatever the type of bridge, when crossing the bridge, deck is very important. This may not seem very interesting, but aside from the necessity of providing a surface of the required smoothness with high resistance to skidding, there is the problem of what holds that surface up. For a box girder bridge or a suspension bridge with an aerodynamic deck, the answer is straightforward, because the top is flat. The same is true of masonry arches, which are built up to receive the roadway.

2.2.2 Substructures

The substructure is the intermediate portion of a bridge, which bears the load of, and supports, the superstructure. It is a very integral part of the entire bridge, which distributes the weight and the load to the foundations. The basic components of a substructure unit are the abutments and the piers. They transfer the load of the superstructure to the foundations and act as lateral supports to the stability of the entire structure.

2.2.2.1 Abutment and wing wall

An abutment consists of various basic components, but it is a major part of the structural unit. The abutments or end bents are located at the ends of the bridge unit. They serve multiple purposes for the design of the unit. Abutment is used to connect the bridge deck with the road. Wing wall is protecting the river embankment soil. Mass concrete construction is economic for retaining walls of small height, such as where headroom is less than that needed for vehicular traffic.

2.2.2.2 Pier

Piers are vertical structures which hold up everything else. They are often founded under water or deep underground, so that we never see the complete structure. A great many bridges would look very strange if we could see them without the water in which they sit. Piers are not always the most obviously attractive or interesting parts of a bridge, yet their construction can present the most difficult problems and the greatest dangers.

2.2.2.3 Foundations

Foundations are the structures that connect the main structure with the ground. In order to design appropriate foundations, the engineer has to determine the nature and location of the different soil types occurring at the site of the bridge and its approaches, to depths containing strata sufficiently strong to support the bridge and embankments without significant deformation. Forces do not end at the ends of a bridge. They do not even end at the boundaries of the foundations. They spread throughout the earth, getting weaker as the distance increases. Foundations must be made wide enough to reduce the stresses below ground bearing capacity. The size and strength of foundations will depend on the quality of the ground. The foundations may be deep underground, and in some cases under water as well, requiring the use of pneumatic caissons with sharp cutting edges, and pressurised air keep the water out. In my research, I designed Spread footing founded on rock or on suitable soil strata.

2.3 Optimized Bridge Design

In bridge designing, the structural Engineers duty is to design it with optimum solutions with respect to construction cost, maintenance, aesthetics, inconvenience during & after construction, environmental impacts, risk in view of geology & construction, & construction time. In my research, I considered about the construction cost, maximum usage of the materials & aesthetics of the bridge.

To optimize the bridge designs following considerations are very important.

- Utilization & Purpose
- Location, Topography & geology
- Environmental impact of structure & Aesthetics
- Geometry of road in plan & elevation
- Bridge section & profile
- Construction materials
- Cost considerations
- Construction method & time considerations
- Code & regulations (For loading conditions , design & analysis guidelines)

And for any type of a design the following steps will guide the designer to a successful ending.

- Study of feasible designs/ Alternatives

  Utilization, purpose, Topography, Geometry

  Environment, Aesthetics Geology

  Cost, Construction method, Expected life

- Preliminary design of selected solution

  Selection structural system, Material

  Overall dimensions of bridge components

- Final design

  Structural analysis, Design & detailing

  Design of ancillary systems

2.4 Design Data

At the design of optimized bridge following information were considered.

2.4.1 General dimensions

- Number of spans
- Width of the carriage way
- Width of the foot walks
- Maximum thickness of the foot walk
- Clear span of the section
- Maximum clear height of the section
- Thickness of the section
- Thickness of the screed at lower kerb
- Thickness of the wearing surface

2.4.2 Loading (Bs 5400 : Part 2 : 1978)

The load combination considered for the analysis is the dead and live loads acting together, with appropriate load factors. The type of live loads considered were HA only and HA combined with HB 30 as specified in BS 5400 : Part 2 : 1978, Clause 6.1.1.

2.4.2.1 HA loading

Type HA loading represent normal traffic and it consists of uniformly distributed load in combined with a knife-edge load.

i) Uniformly distributed load = 30 kN/m/ Notional lane [Cl. 6.2.1]

ii) Knife edge load = 120 kN/ Notional lane [Cl. 6.2.2]

2.3.2.2 HB loading

Type HB loading represent abnormal vehicle unit loading. The Figure 1 shows the plan and axle arrangement for 30 units (i.e. HB 30) of nominal HB loading. According to the code, the inner axle spacing can be vary from 6 m to 26 m and the shortest inner axle spacing 6 m was selected to get the most severe effect for the design check.

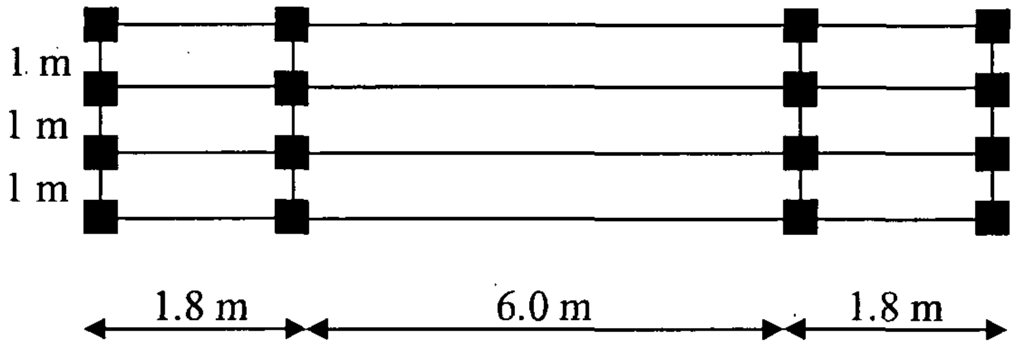

Figure 2.3: HB vehicle with most severe effect

2.4.2.3 Other primary loadings

Traction or breaking force = 8 kN/m for loaded length + 200 kN [Cl. 6.6.1]

Live load surcharge for HA = 10 kN/m^2 [Cl. 5.8.2.1]

2.4.3 Materials

2.4.3.1 Concrete

Pre-stress beam = GR. 50(20)

Concrete deck = GR. 30(20)

Screed = GR. 20(40)

Foot walks = GR. 25(20)

2.4.3.2 Steel

Yield strength of hot rolled mild steel = 250 N/mm^2

Yield strength of high yield deformed bars = 460 N/mm^2

Yield strength Tendons = 1500 N/mm^2

2.4.4 Partial load factors γ_{fl} ULS & SLS for (Bs 5400 : Part 2 : 1978)

Table 2.1: Partial Load Factors γ_{fl} for ULS & SLS

Clause	Load	ULS	SLS
5.1	Dead – concrete	1.15	1.00
5.2	Superimposed dead loads	1.75	1.20
5.8	Earth pressure (retained fill / surcharge)	1.50	1.00
6.6	Longitudinal load HA and associated primary loads	1.25	1.00
6.6	Longitudinal load HB and associated primary loads	1.10	1.00
7.0	Live load in foot walk	1.25	1.00

2.4.5 Other data

Weight of concrete = 24.0 kN/m^3

Weight of wearing surface = 23.0 kN/m^3

Weight of earth = 18.0 kN/m^3

Angle of internal friction = 35°

Friction coefficient between concrete and rock = 0 .4

2.4.6 Load cases under consideration (Bs 5400 : Part 2 :1978, Clause 6.4)

(a) Self weight of the concrete box section.

(b) Self weight of the wearing surface.

(c) HA Uniformly distributed load.

(d) Nominal Knife Edge load at Middle.

(e) Nominal Knife Edge load at Support.

(f) HB Load

(g) Active earth Pressure force.

(h) Surcharge Pressure force.

(i) Tractive force for HA loading.

(j) Tractive force for HB loading.

2.4.7 Load combination under consideration

Table 2.2: Load combinations

LOAD CASES	LOAD COMBINATION	DESCRIPTION
1 (HA load)	COMBINATION - 1	a + b + c + d + g + h
	COMBINATION - 2	a + b + c + e + g + h
	COMBINATION - 3	a + b + c + d + g + h + i
	COMBINATION - 4	a + b + c + e + g + h + i
2 (HB load)	COMBINATION - 5	a + b + f + g + h
	COMBINATION - 6	a + b + f + g + h + j

CHAPTER 3: STRUCTURAL OPTIMIZATION

3.1 Optimum Design

Final task of my research is to design all bridge components with least cost. Then objective function is the Cost. To reduce the cost, designer should be found the optimum design variables with respect to satisfy all the design constraints. In this research, I used Micro level optimization system, which is optimizing every bridge components separately. Another important topic is the appearance of bridges. Engineers must have sense and feeling for the value and essence of beauty. They can select the structural system in the beautiful sites, and then go for the suitable option.

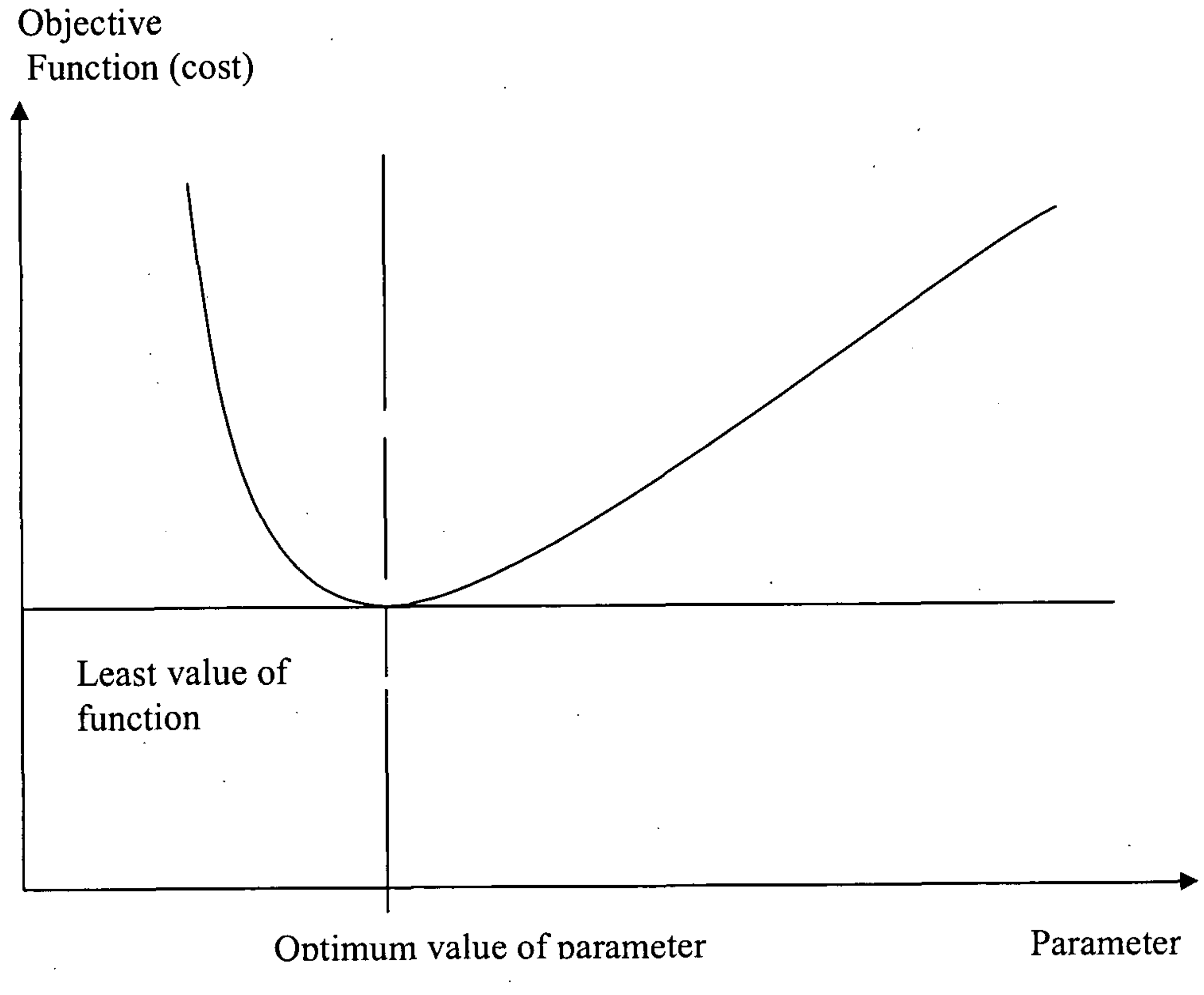

Figure3.1: Objective function vs variable (Showing optimum value of parameter)

3.2 The Design Process

The process of designing systems results in a set of drawings, calculations and reports, and the systems can be fabricated based on these. Design is an iterative process. Iterative implies, analyzing several trial systems in a sequence before an acceptable design is obtained. Engineers strive to design the best systems and depending on the specifications, best can have different connotations for different systems. In general, it implies cost effective, efficient, reliable and durable systems. The process can involve teams of specialists from different disciplines requiring considerable interaction. The basic concepts are described in the thesis to aid the engineer in designing systems at the minimum cost and in the shortest time.

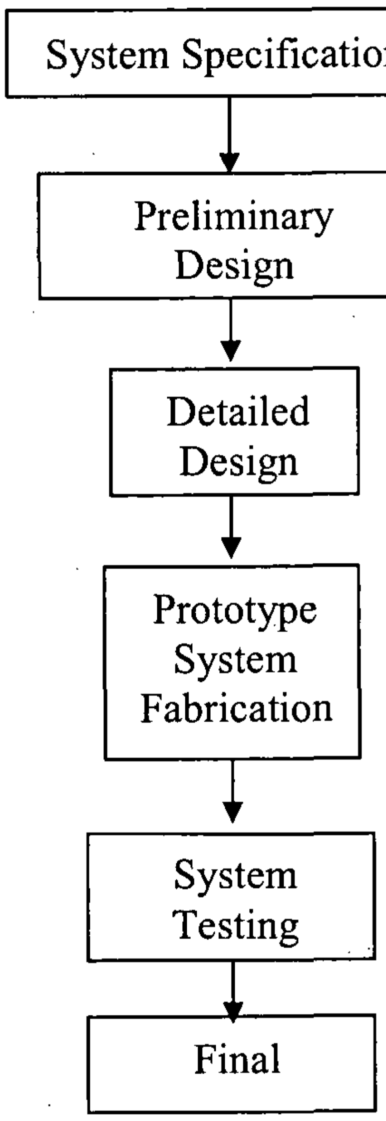

Figure 3.2: Flow chart for optimum design process

The design process should be a well-organized activity. To discuss it, we consider a system evolution model shown in Figure 3.2. The process begins with the identification of a need which may be conceived by engineers or others. The first step in the evolutionary process is to define precisely specifications for the system. Considerable interaction between the engineer and the sponsor is usually necessary to quantify the system specifications. Once these are identified, the designing is starting. The second important step in the process is to come up with a preliminary design of the system. Various concepts for the system are studied. For example traffic condition, site condition, soil conditioned, etc. Various subsystems are identified and their preliminary designs are estimated. Decisions made at this stage generally affect the final appearance and performance of the system. At the end of the preliminary design phase, a few promising concepts need further analysis are identified.

The third step in the process is to carry out a detailed design for all subsystems. To evaluate various possibilities, this must be done for all the promising concepts identified in the previous step. The design parameters for subsystems must be identified. The parameters must be such that once their numerical values are specified, the subsystem can be fabricated. The design parameters must also satisfy technological and system performance requirements. Various subsystems must be designed to minimize a measure of the cost. Systematic optimization methods can aid the description of the system is an available in the form of reports and drawings.

The last two blocks of Figure 3.2 may not be necessary for all systems. These involve a prototype system fabrication and its testing. The steps are necessary when the system has to be mass produced or human lives are involved. These blocks may appear to be the final steps in the design process. However, they are not, because during tests the system may not perform according to specifications. Therefore, specifications may have to be modified necessarily at any step of the design process. This is the reason for giving feedback loops at every stage of the system evolution process as shown in Fig.1.1. The iterative process has to be continued until an acceptable system has found. Depending on the complexity of the system, the process may take anywhere from a few days to several months.

The model described above is a simplified block diagram for system evolution. In actual practice, each block may have to be broken down into several sub-blocks to carry out the studies properly and arrive at rational decisions. The important point is that optimization concepts and methods can help at each stage of the process. The use of such methods along with proper software can be extremely useful in studying various design possibilities in a short time. The techniques can be of aid for preliminary and detailed design as well as for fabrication and testing. In this thesis; I discuss optimization methods and their use in the bridge design process.

3.3 Engineering Design versus Analysis

It is important to realize differences between engineering analysis and design activities .The analysis problem are concerned with determining behavior of an existing system or a trial system begins designed for the given task. Determination of the behavior of the system implies calculation of its response under the specified inputs. Therefore, sizes of various parts and their configurations are given for the analysis problem, i.e. the design of the system is known. On the other hand, the design problem is to calculate sizes and shapes of various components of the system to meet performance requirements. The design of systems is a trial and error procedure. The designer estimate a design of systems is a trial and error procedure. If the trial design does not work, the designer needs to change it to come up with an acceptable system. In both these cases, the designer must be able to analyze design to make further decisions. Thus analysis capability must be available in the design process.

Considerable progress has been made since 1940 in analyzing engineering systems operating in different environments. It is possible to analyze efficiently complex systems under static and dynamic inputs. Linear and nonlinear analyze play a major role in the development of analysis capability. It is now possible to develop similar capabilities for the design of complex systems. Methods of optimization will play a major role in the design process. Therefore, it is important to understand them and the implication of their use in the engineering design process.

3.4 Conventional Versus Optimum Design Process

It is challenger for engineers to design efficient and cost-systems without compromising their integrity. The conventional design process depends on the designer's intuition, experience and skill. This overwhelming presence of a human element can sometimes lead to dangerous and erroneous results in the synthesis of complex systems.

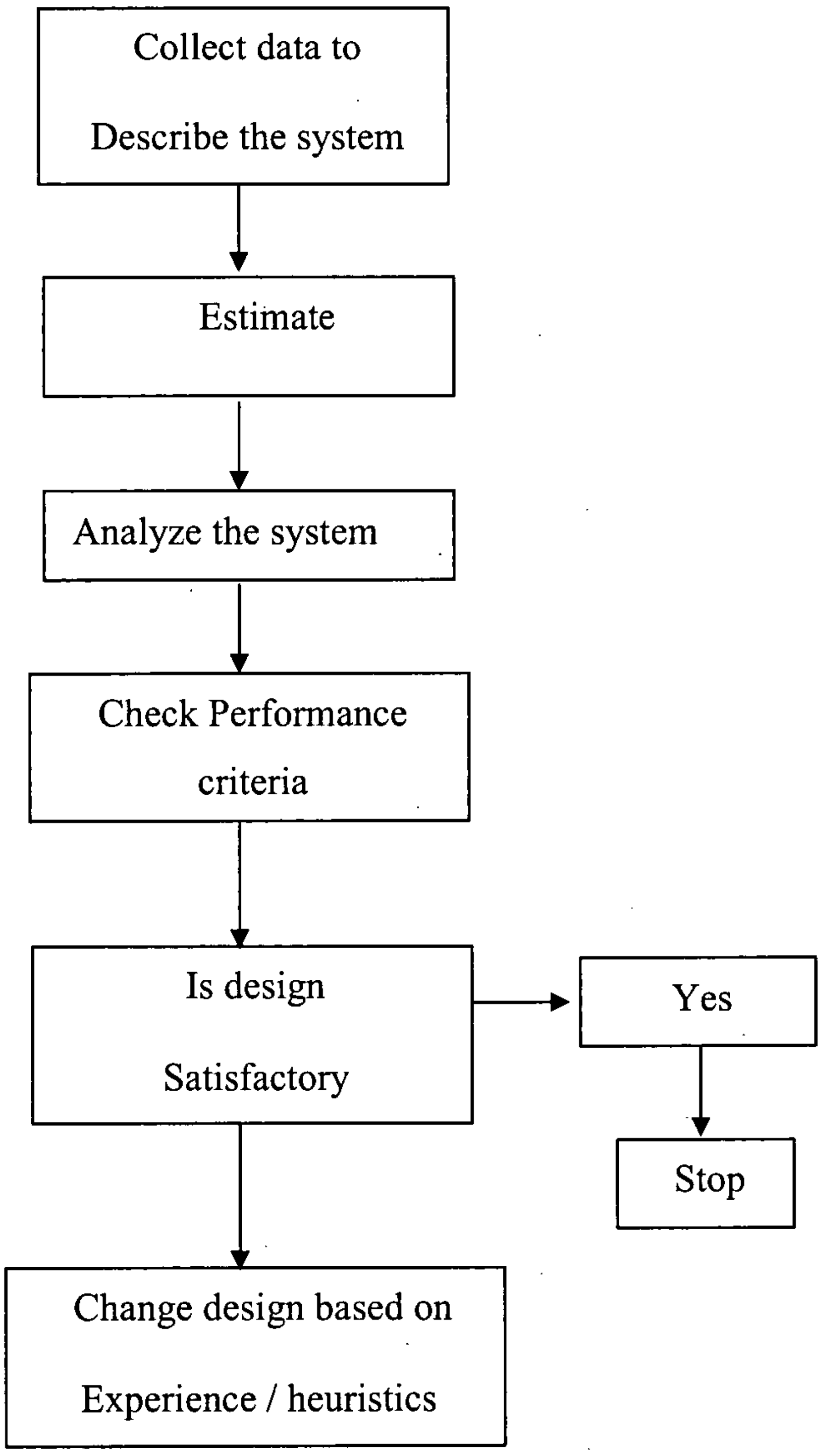

Figure 3.3: shows the self explanatory flow chart for a conventional design process that involves the use of information gathered from one or more trial designs together with the designer's experience and intuition.

Scarcity and need for efficiency in today's competitive word has forced engineers to evince greater interest in economical and better designs. With recent advances in computer technology affecting various disciplines of engineering, the design process can hardly remain untouched. Recently, the term computer-aided design optimization (CADO) has been used for summarizing all computer aids in design. Figure 3.3 shows the optimum design process. Design is not only the more or less intuitively guided creation of new information but is comprised of analysis, presentation of results, simulation and optimization. These are essential constituents of an iterative process leading to a feasible and finally optimum design.

Both the conventional and optimum design processes can be used at different stage of system evolutional. The main advantage in the conventional design process is that the designer's experience and intuition can go into making conceptual changes in the system or to make additional specification in the procedure. For example, the designer can choose either a suspension bridge or an arched bridge, add or deleted design, however, the conventional design process has some disadvantages and difficulties. These difficulties include the treatment of complex constraints (such as limits on vibration frequencies), as well as inputs (for example, when the structure is subjected to a variety of loading conditions). In these cases, the designer would find it difficult to decide whether to increase or decrease the size of a particular structural element to satisfy the constraints. Furthermore, the conventional design process can lead to uneconomical designs and can involve a lot of calendar time. The optimum design process forces the designer to identify explicitly a set of design variables, a cost function to be minimized, and the constraint functions for the system. This accurate formulation of the design problem helps the designer to gain a better understanding of the problem. Proper mathematical formulation of the design problem is a key to good solutions.

The foregoing distinction between the two approaches is that the conventional design process is less formal. An objective function that measures the performance of the system is not identified. Trend information is not calculated to make design decisions for improvement of the system. Most of the decisions are made based on the designer's experience and intuition. Most of the decisions are made based on the designer's experience and intuition. In contrast, the optimization process is more organized using trend information to make decisions. However, the optimization process can benefit substantially from the designer's experience and intuition. Thus, the best approach would be to have an optimum design process that is aided by the designer's interaction.

CHAPTER 4: OPTIMIZATION THEORY

4.1 Introduction

Numerical optimization techniques offer a logical approach to design automation, and many algorithms have been proposed in recent years. Some of these techniques, such as linear, quadratic, dynamic, and geometric programming algorithms, have been developed to deal with specific classes of optimization problems. A more general category of algorithms referred to as nonlinear programming has evolved for the solution of general optimization problems. Methods for numerical optimization are referred to collectively as mathematical programming techniques.

Though the history of mathematical programming is relatively short, roughly 45 years, there has been an almost bewildering number of algorithms published for the solution of numerical optimization problems. The author of each algorithm usually has numerical examples which demonstrate the efficiency and accuracy of the method, and the unsuspecting practitioner will often invest a great deal of time and effort in programming an algorithm, only to find that it will not in fact solve the particular optimization problem being attempted. This often leads to disenchantment with these techniques which can be avoided if the user is knowledgeable in the basic concepts of numerical optimization. There is an obvious need, therefore, for a unified, non-theoretical presentation of optimization concepts.

The purpose here is to attempt to bridge the gap between optimization theory and its practical applications. The remainder of this chapter will be devoted to a discussion of the basic concepts of numerical optimization. I will consider the general statement of the nonlinear constrained optimization problem and some (slightly) theoretical aspects regarding the existence and uniqueness of the solution to the optimization problem. Finally, some practical advantages and limitations to the use of these methods were considered.

4.2 Optimization Concepts

Here I will briefly describe the basic concepts of optimization. Optimization problems are made up of three basic ingredients:

4.2.1 Objective function

In order to find the best feasible design, must have a criterion, such as cost, weight, stiffness, or strength that ranks design. This criterion as a function of design variables is called objective function. If the objective function is better when large (e.g., stiffness), then the optimization problem is a maximization problem. If the objective function is better when small (e.g., weight), then the optimization problem is a minimization problem.

Almost all optimization problems have a single objective function. (When they don't they can often be reformulated so that they do!) The two interesting exceptions are:

- No objective function: In some cases (for example, design of integrated circuit layouts), the goal is to find a set of variables that satisfies the constraints of the model. The user does not particularly want to optimize anything so there is no reason to define an objective function. This type of problems is usually called a feasibility problem.
- Multiple objective functions: Often, the user would actually like to optimize a number of different objectives at once. For instance, in the panel design problem, it would be nice to minimize weight and maximize strength simultaneously. Usually, the different

objectives are not compatible; the variables that optimize one objective may be far from optimal for the others. In practice, problems with multiple objectives are reformulated as single-objective problems by either forming a weighted combination of the different objectives or else replacing some of the objectives by constraints. These approaches are known as multi-objective optimization.

4.2.2 Variables

The design of the structure is often a matter of sizing dimensions. The dimensions and the shape are usually defined in terms of a number of scalar parameters called design variables. Design variables are model parameters that typically influence performance requirements, component & physical limitations and production-based limitations amongst other factors. These are essential. If there are no variables, we cannot define the objective function and the problem constraints.

Design variables are one of four types:

- Constant (variable will not be optimized)
- Continuous
- Discrete Step
- Discrete List of values

4.2.3 Constraints

The design of a structure is normally subject to requirements or limitations. Typical requirements that the structure must be safe, for example, the stresses do not exceed material limits. Stress limits are also specified by standards and design codes.

Manufacturing requirements may also constrain design freedom. In mathematical optimization, equality and inequality constraints introduce these requirements.

Ultimate aim of the design optimization is finding values of the variables that minimize or maximize the objective function while satisfying the constraints.

4.2.4 Optimization Tree

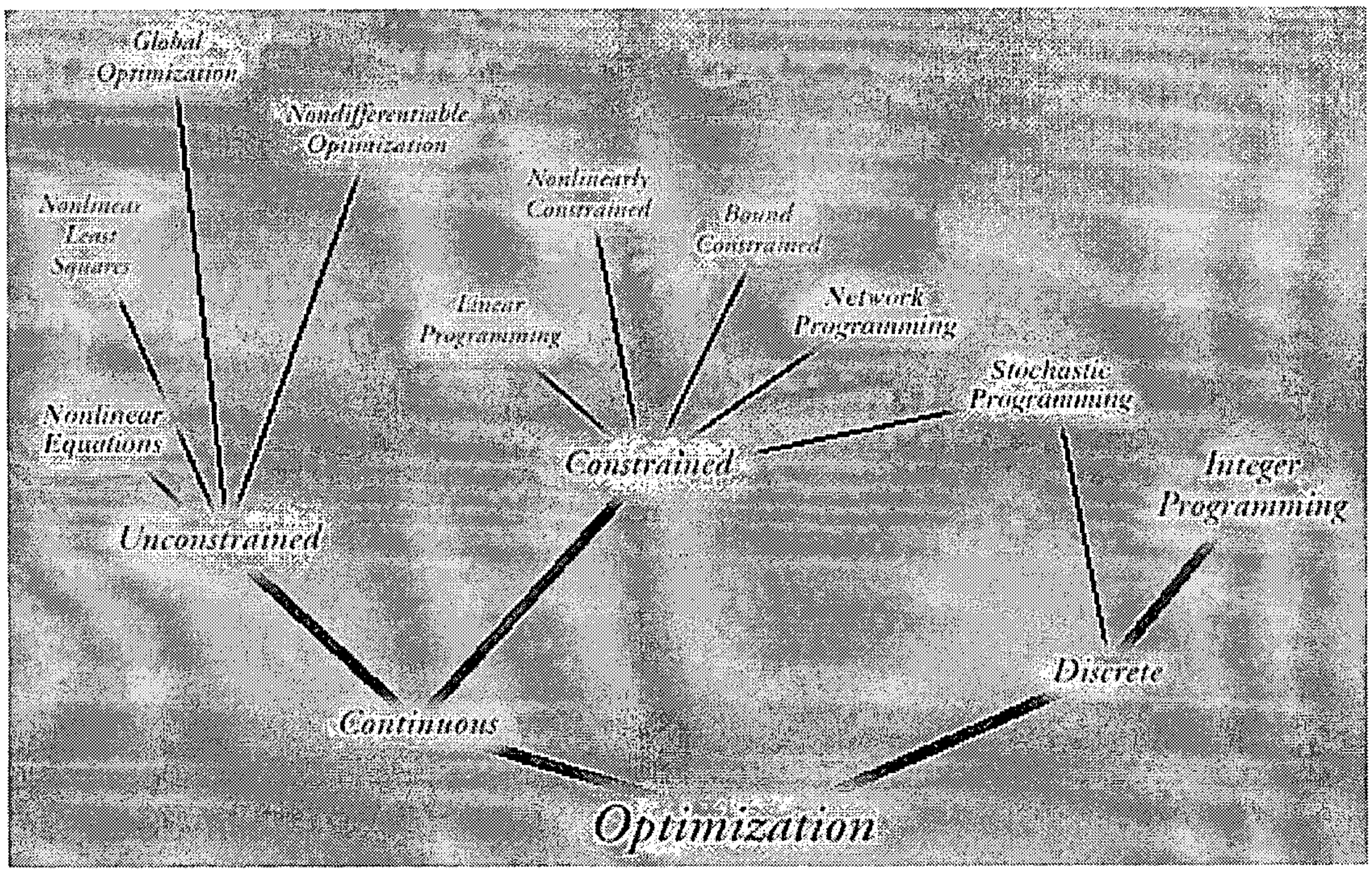

Figure 4.1: Optimization tree

The Optimization Tree is guide to the field of numerical optimization. It introduces the different subfields of optimization and includes outlines of the major algorithms in each area. In the bridge design, most of the optimizations are non-linear constrained problem.

4.3 Non Linear Constrained Optimization

The general constrained optimization problem is to minimize a nonlinear function subject to nonlinear constraints. In constrained optimization, the general aim is to transform the problem into an easier sub problem that can then be solved and used as the basis of an iterative process. A characteristic of a large class of early methods is the translation of the constrained problem to a basic unconstrained problem by using a penalty function for constraints, which are near or beyond the constraint boundary. In this way the constrained problem is solved using a sequence of parameterized unconstrained optimizations, which in the limit (of the sequence) converge to the constrained problem. These methods are now considered relatively inefficient and have been replaced by methods that have focused on the solution of the Kuhn-Tucker (KT) equations. The KT equations are necessary conditions for optimality for a constrained optimization problem. If the problem is a so-called convex programming problem, that is, $F(x)$ and $gi\ (x)$, $i = 1, \ldots\ldots, m$, are convex functions, then the KT equations are both necessary and sufficient for a global solution point.

The Kuhn-Tucker conditions define a stationary point of the Lagrangian

$$L(X,\lambda) = F(X) + \sum_{j=1}^{m} \lambda_j g_j(X) \tag{4-1}$$

All three conditions are listed here for references and state simply that if the vector X^* defines the optimum design, the following conditions must be satisfied:

1. X^* is feasible (4-2)

2. $\lambda_j g_j(X^*) = 0 \qquad j = 1, m \qquad \lambda_j \geq 0$ (4-3)

3. $\nabla F(X^*) + \sum_{j=1}^{m} \lambda_j \nabla g_j(X^*) = 0$ (4-4)

$\lambda_j \geq 0$ (4-5)

Equation (4-2) is a statement of the obvious requirement that the optimum design must satisfy all constraints. Equation (4-3) imposes the requirement that if the constraint $g_j(X)$ is not precisely satisfied [that is, $g_j(X) < 0$] then the corresponding Lagrange multiplier must be zero.

For the gradients to be canceled, Lagrange Multipliers (l*i*, *i* = 1,...........*m)* are necessary to balance the deviations in magnitude of the objective function and constraint gradients. Since only active constraints are included in this canceling operation, constraints that are not active must not be included in this operation and so are given Lagrange multipliers equal to zero. These algorithms attempt to compute directly the Lagrange multipliers. Constrained quasi-Newton methods guarantee super linear convergence by accumulating second order information regarding the KT equations using a quasi-Newton updating procedure.

The main techniques that have been proposed for solving constrained optimization problems are reduced-gradient methods, sequential linear and quadratic programming methods, and methods based on augmented Lagrangians and exact penalty functions. Fundamental to the understanding of these algorithms is the Lagrangian function. In my research I used reduced-gradient methods for optimizing the bridge system.

CHAPTER: 5 PROPOSED SOFTWARE MODEL

5.1 Introduction

To solve the optimization task (minimize the cost of every bridge component), an optimization routine based on "Generalized Reduced Gradient Algorithm" was implemented into a windows-based software. This software is capable of performing optimization within an Excel spreadsheet.

5.2 Basic Module for Structural Optimization

The three main modules required in structural optimization problems are structural analysis module, optimization module and interface module. In the structural analysis module, either analytical or numerical analyses, such as finite element method, are performed to determine the response of the applied loads. The optimization module describes the selected optimization method. The generalized reduced gradient (GRG) method is used as the optimization solver. The interface module describes the way by which the structural analysis module and the optimization modules are coupled. This is an important stage in modern structural optimization process.

5.3 Optimization in MS-Excel (Generalized Reduced Gradient Algorithm)

Microsoft Excel Solver uses the Generalized Reduced Gradient Algorithm for optimizing nonlinear problems. This algorithm was developed by Leon Lasdon, of the University of Texas at Austin, and Allan Waren, of Cleveland State University.

There are several optimization techniques available including: graphical, trial and error, linear and nonlinear programming. The spreadsheet Excel Provides a standard command for optimization (Solver) where the user defines the cells containing the design variables, the objective function, whether maximum or minimum value of the objective function is sought, and constraints.

5.4 Model and Software Development

In order to analyze and design bridge components a spreadsheet was created. This spread sheet provides the basic data needed and sets the design boundaries of the problem for the optimization process to operate within. This analysis process is accomplished through the use of both visual basic programming and spreadsheet.

5.6 GUI (user interface)

A windows user interface was created that allows the user to use the bridge optimization model without prior knowledge in optimization. As can be seen in the **Appendix,** which contains multiple interfaces for basic bridge components. These interfaces allow the user to input the initial design variables and other required parameters.

5.7 Excel Connectivity

Design values are given to Excel and function values and constraint values are read from Excel trough the developed software. This allows for an easy data transfer, which is direct (if does not need text files), immediately. After data transferring, optimization routing was implemented using the Excel solver add-in. After several iteration, it will give optimum design variable with respect to satisfy all the constraints.

CHAPTER 6 : CASE STUDY ON A REINFORCED CONCRETE DECK BRIDGE

6.1 Introduction

The first reinforced concrete bridge was constructed in Lancashire, England in the year 1902, thereafter in Sri Lanka was constructed around 1920 and then it's become very popular bridge type for short and medium span.

Bridge decks are a main structural component designed to carry vehicle traffic and transfer live load to the substructure. Reinforced concrete deck bridges are mainly used for small to medium spans. These are economically feasible and do not involve sophisticated construction technology. Commonly used reinforced concrete deck bridges in Sri Lanka are,

- Single span slab type
- Beam and slab type
- Cellular type
- Composite type

In this case study single span slab type is considered. This type may be employed for spaces with clear openings up to 20 feet. The aim of design is the achievement of an acceptable probability that structures being designed will perform satisfactorily during their intended life. With an appropriate degree of safety, they should sustain all the loads and deformations of normal construction and use and adequate durability and resistance to the effects of misuse and fire.

The purpose of this case study is optimizing construction cost of the concrete bridge deck, while maintaining the safety and other functions. The cost of a reinforced concrete structure is obviously affected by the prices of concrete, steel, formwork and labor cost. Upon the relation between these prices, the economical proportions of the quantities of concrete, reinforcement and formwork depend. Due to the optimization of the effective depth the concrete cost and the formwork cost could be reduced. Also formwork is obviously cheaper if angles are right angles; surfaces are plane and if there is some repetition of use.

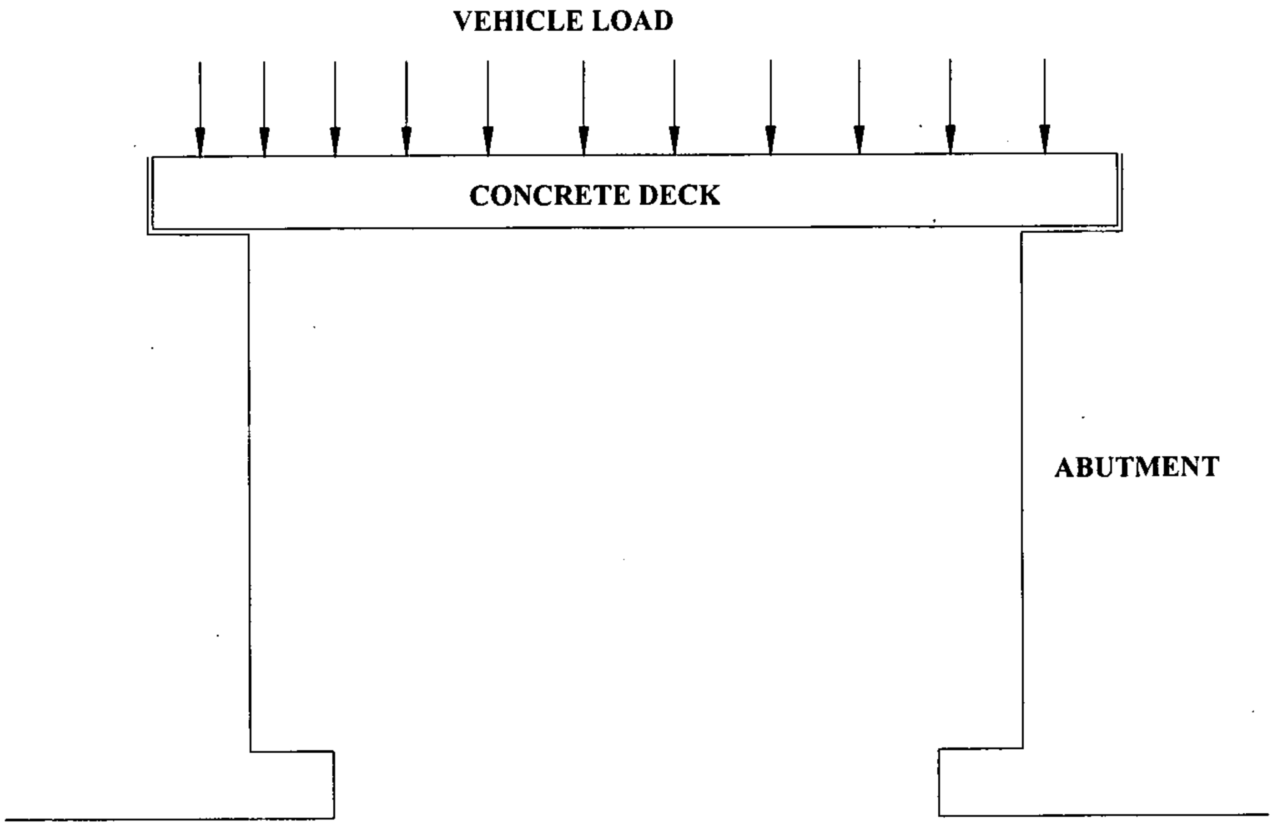

Figure 6.1: Simply supported concrete deck

6.1.1 Design criteria

A reinforced concrete deck in exactly the same manner as reinforced concrete one way slab and it is therefore designed in the same manner. Structural designer will analyze the loadings, bending moment, shear force and reinforcement requirements on a slab strip 1.0 m wide. The correct design of reinforced concrete slab will ensure that it has sufficient strength to resist both bending moment and shear forces, encounter in the outer fibers.

Geometrical detail of the selected bridge detail are given below,

Length of the bridge = 5.4 m

Clear span of the bridge = 4.9 m

Width of the bridge = 6.5 m

Road width = 4.4 m

Slab thickness = 400 mm

6.2 Formulation of Primary Optimal Design Problem for Concrete Deck

6.2.1 Design Variables

In this study, simply supported one way concrete deck was considered. The cross section of one way concrete deck is shown in Figure 6.2. Formulation for this design problem is possible depending on the design variables. Main design variable is thickness (*h)* of the concrete deck.

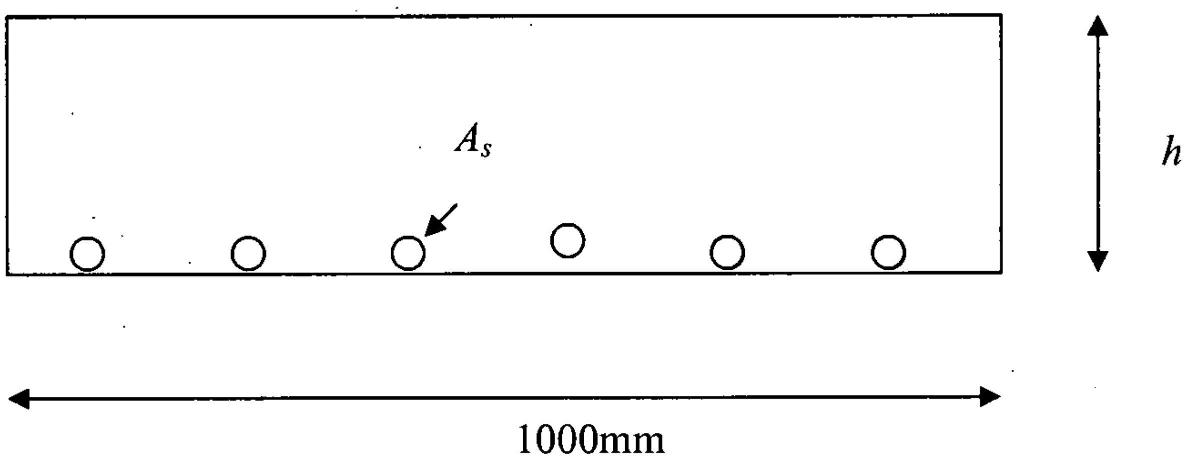

Figure 6.2: Cross Section of the concrete deck

6.2.2 Design constraints

In this problem, reinforced concrete deck was analyzed with respect to the dead load and vehicle (imposed) load cases. In the followings, the design constraints are explained in detail.

6.2.2.1 Dead load case

If the dead load is W_1;

Bending moment per one meter width of the slab is

$$M_1 = \frac{W_1 l^2}{8}$$

Shear force per one meter width of the slab is

$$S_1 = \frac{1}{2} W_1 l$$

In all important case with heavy loading and short spans the bond stress should be calculated on the length given by,

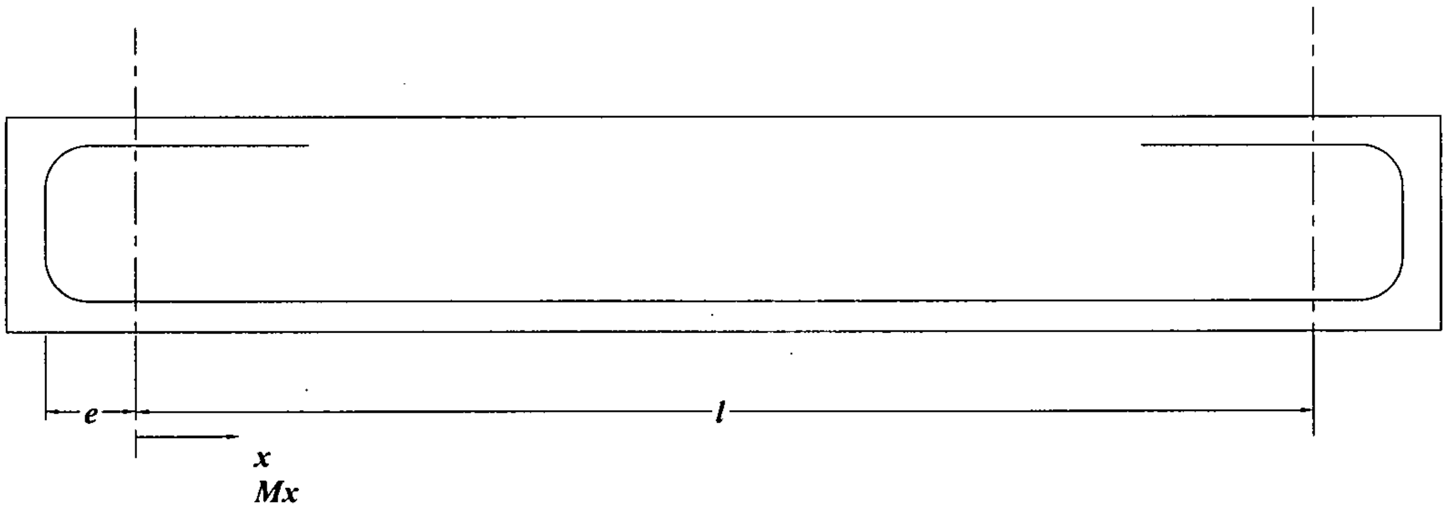

Figure 6.3: Longitudinal Section of the concrete deck

$$x = -e + \sqrt{e(l + e)}$$

Where *e* is the length beyond the axis of support measured to the back of the hook. The bending moment at this point is,

$$M_x = \frac{1}{2} W_1(lx - x^2)$$

Also, $U_1 = \dfrac{Mx}{\frac{7}{8} do(x + e)}$

U_l being the bond stress due to dead loading and *o* the perimeter of the reinforcing bars per meter band of the slab.

6.2.2.2 Imposed load case

For this HA loading was considered. Uniformly distribute load W_2, Knife edge load *W*. Maximum bending moment per one meter width of the slab is

$$M_2 = \frac{W_2 l^2}{8} + \frac{Wl}{4}$$

At supports maximum shear is

$$S_2 = \frac{1}{2}(W_2 l + W)$$

To check the bond stress for imposed loading,

$$x = -e + \sqrt{e(l+e)}$$

As before,

$$M_x = \frac{1}{2}W_2(lx - x^2)$$

$$U_2 = \frac{Mx}{\frac{7}{8}do(x+e)}$$ due to distribution loading, and

$$U_3 = \frac{W(l-x)x}{\frac{7}{8}dol(x+e)}$$ due to knife edge loading

6.2.2.3 Single nominal wheel load alternative to UDL and KEL

One 100 kN wheel, placed on the carriageway and uniformly distributed over a circular contact area assuming an effective pressure of 1.1 N/mm^2 (i.e 340mm diameter), shall be considered. Alternatively, a square contact area may be assumed, using the same effective pressure (i.e 300 mm).

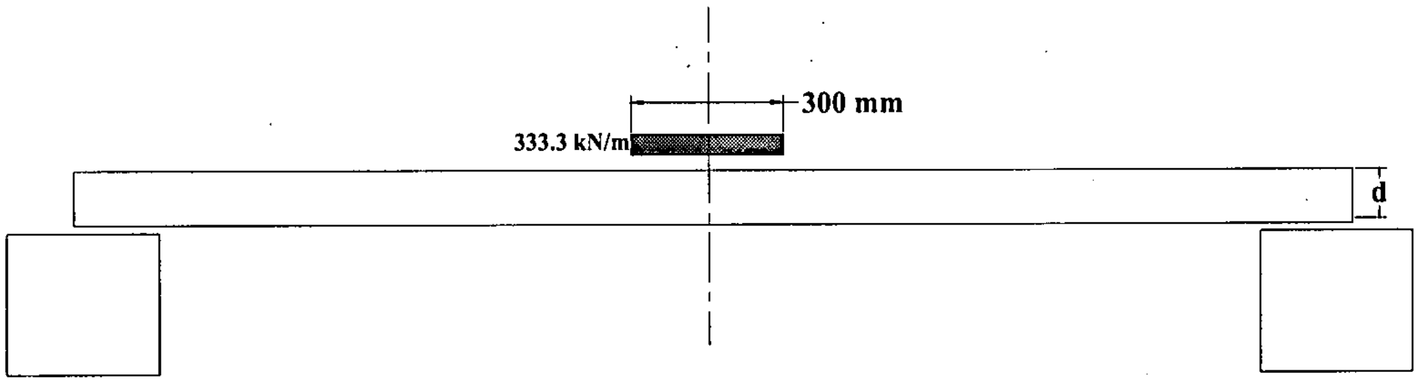

Figure 6.4: Point load acting on a slab panel

Shear stress due to punching, $\sigma_{pun} = \dfrac{100x10^3}{l_p d}$

Where l_p is the length of the punching shear perimeter around the concentrated load.

6.2.2.4 Bending constraint

Due to dead and imposed load,

The total bending moment $M = M_1 + M_2$,it should be less than the ultimate bending moment capacity of the section,

Thus, $M \le M_{ult}$

6.2.2.5 Shear constraint

The total shear force $S = S_1 + S_2$

Therefore shear stress $\sigma = \dfrac{S}{1000d}$, it should be less than the shear capacity of the section,

Thus, $\sigma \le \sigma_{cap}$

6.2.2.6 Bond stress constraint

The total bond stress $U = U_1 + U_{2+} U_3$, it should be less than permissible shear stress

Thus ,$U \le U_{per}$

Where $U_{per}= .1C+25$

$$C = \frac{28 - dayStrength}{3}$$

6.2.2.7 Punching Shear Constraint

The punching shear stress should be less than the shear capacity of the section,

Thus, $\sigma_{pun} \le \sigma_{cap}$

6.2.2.8 Deflection constraint

Deflection at the mid span should be less than the allowable deflection,

Thus $$\left(\frac{Span}{Effectivedepth}\right)_{Actual} \leq \left(\frac{Span}{Effectivedepth}\right)_{Allowable}$$

6.2.2.9 Formulation of the Design Problem

By considering the above design variables, design constraints and objective function, the primary optimal design problem can be then formulated follows,

General optimization problem is;

find X which

minimize $Z(X)$

subject to $g(X)$

$X^L \leq X \leq X^u$

Where X is design variables, $g(X)$ is design constraint, X^L is lower bound of the design variable and X^U is upper bound of the design variables.

Design problem is formulated for one-way concrete slab as follows,

Find h, A_s

Minimize $Z(h, A_s) = A_c C_c L W + A_s C_s$

Subject to

For moment $m - m_{ul} \leq 0$

For deflection $d - d_{\mathrm{al}} \leq 0$

For Shear $\sigma - \sigma_{cap} \leq 0$

For bond stress $U - U_{per} \leq 0$

For punching $\sigma_{pun} - \sigma_{cap} \leq 0$

$$X \leq X_0^U$$

$$X \leq -X_0^L$$

Where h- Overall height of the section

C_c- Cost of concrete per unit volume

A_s- Cross section area of the steel

C_s- Cost of steel per unit length

L – Span of the slab

m, m_{ul} – Applied moment, Ultimate moment, respectively

d, d_{al} - Deflection and Allowable deflection, respectively

σ_c- Ultimate shear stress

σ- Applied shear stress

With respect to these design constraints, suitable design variable "*h*" was found.

6.3 Results

This optimization problem was formulated in *MS-Excel* (Appendix *). Using the Solver Add Ins, optimum design depth was found after some iteration. Following graph shows the relation between the iterations and depth.

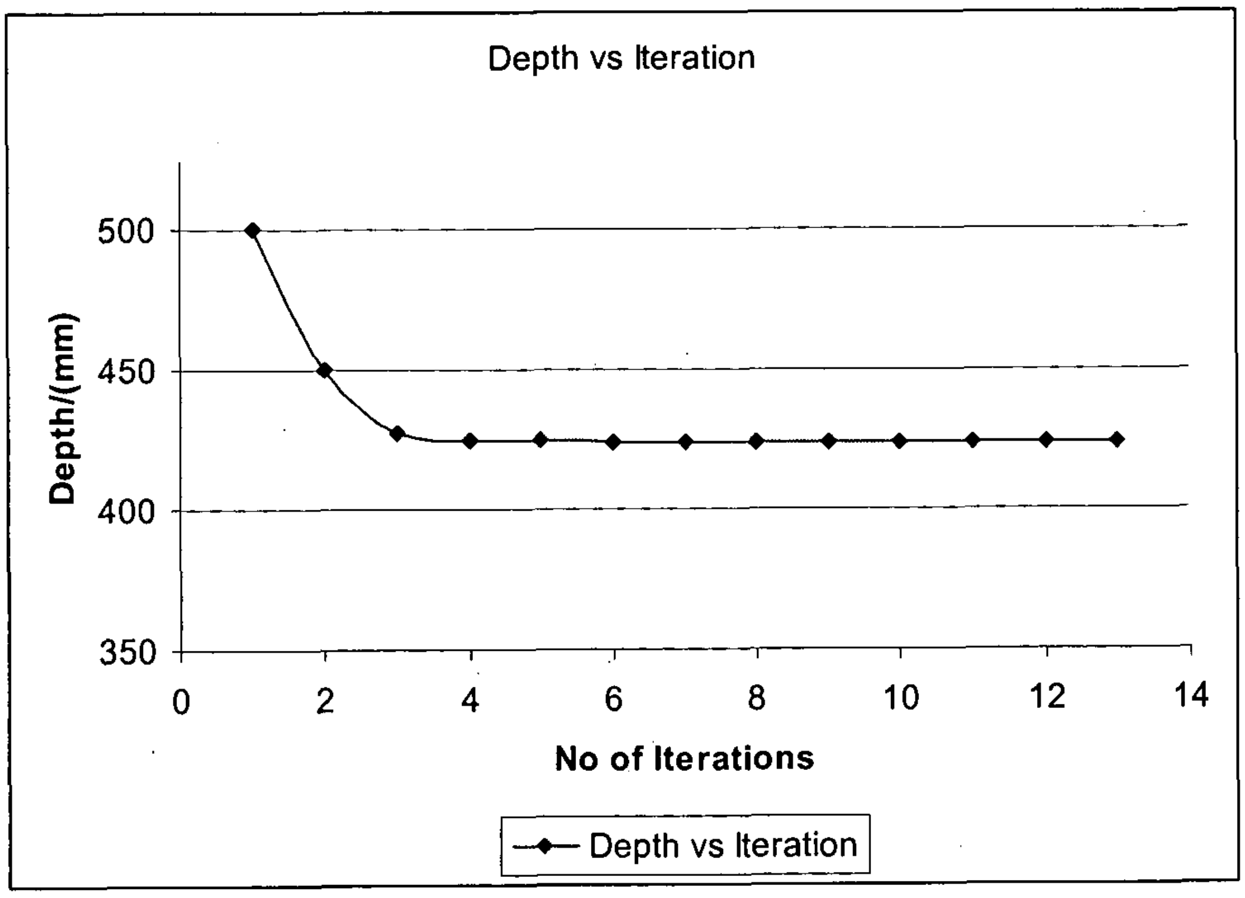

Figure 6.5: Relationship between depth vs No. of Iterations

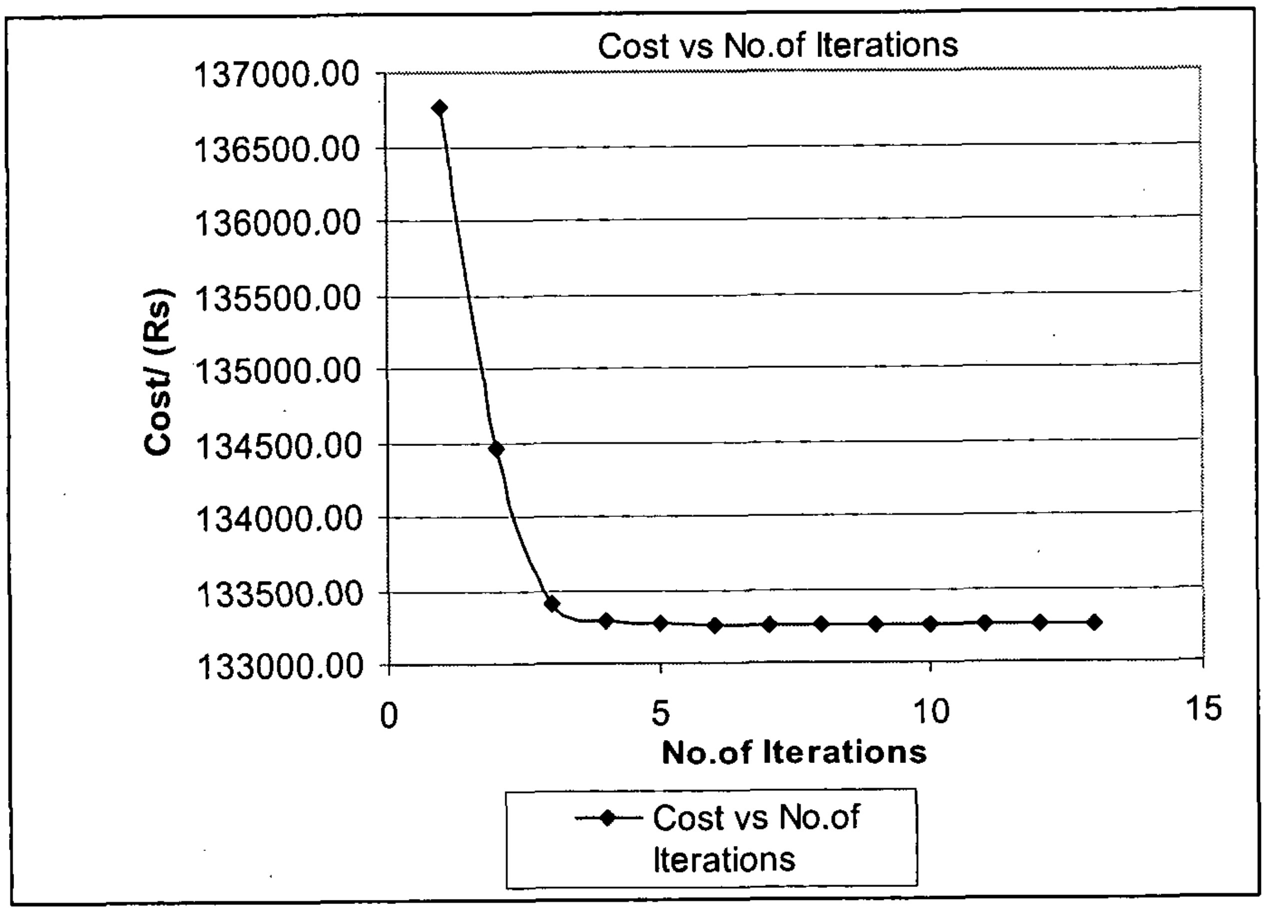

Figure 6.6: Relationship between Cost vs No. of Iterations

CHAPTER 7: CASE STUDY ON PRE-STRESSED BEAM

7.1 Analysis of Pre-Stressed Concrete Beam

The pre-stressed concrete has high fatigue resistance, high capacity for loads and durability. Therefore in our country most of the new bridges are constructed by using pre-stressed beams. So that, the development of an optimum design method for Pre-stressed beam is very important. The design concepts of prestressing, as well as the developed minimum cost design of pre-stressed concrete beams, are described in detail in this chapter.

As a case study, an optimum design method for pre-stressed concrete beam section is studied, in which the most economical pre-stress force, areas of reinforcement and tendon layout and all the cross sectional dimensions are determined subject to both serviceability and ultimate limit state. The objective function is the cost of the pre-stressed concrete beam, design variables are dimensions, pre-stressing force, and eccentricity is considered.

7.2 Formulation of Primary Optimal Design Problem for Pre-Stressed Concrete Beam

7.2.1 Design variables

In this study, the shape of cross section of pre-stressed beam is assumed as "I" shape cross section is shown in figure 7.1. Formulation for this design problem is possible depending on the design variables. Design variables are Pre-stressed force P, eccentricity e from the center of cross section and cross sectional dimensions b_1, b_2, b_3, t_1, t_2, t_3 of the "I" shape cross section shown in the figure 7.1 are taken to the account.

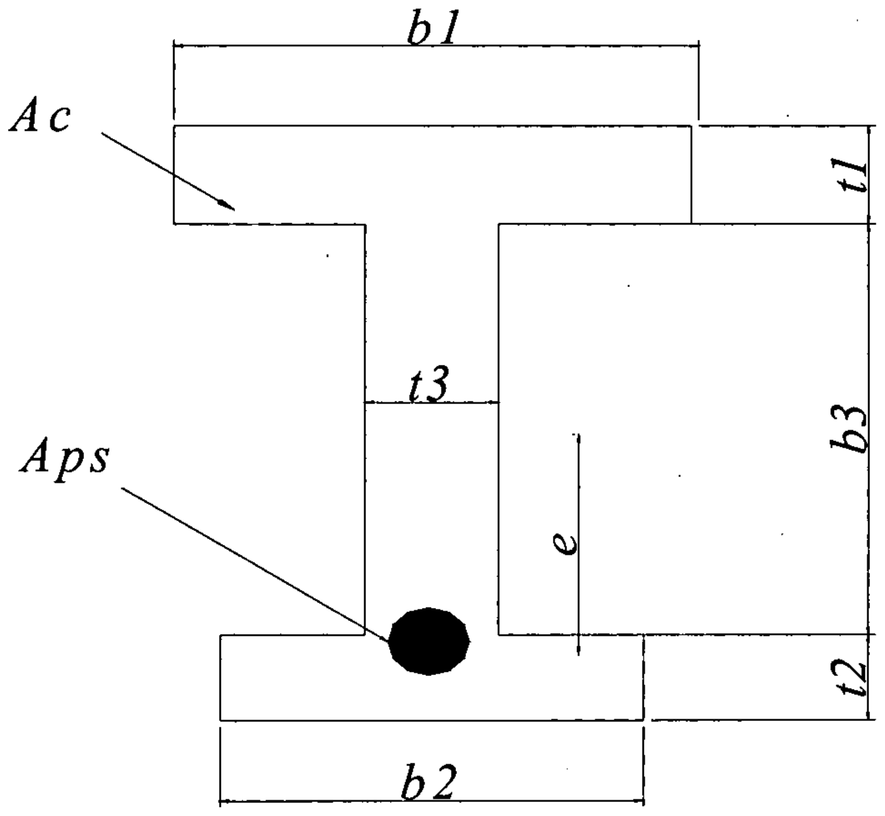

Figure 7.1: Cross Section of the Pre-Stressed Beam

7.2.2 Design constraints

In this problem, allowable tensile and compressive stress were considered at transfer and service condition and also allowable deflection and shear capacity are taken into account as the design constraints. In the followings, these design constraints are explained in detail. Stresses in concrete should not exceed the allowable values during the lifetime of the structure.

7.2.2.1 Stress constraints

- **At transfer condition**

At transfer stage, the dead loads and initial pre-stressing force are considered as external loads. The stress at the top and the bottom of the section can be expressed considering initial pre-stressing force P and bending moment M_d due to dead loads. Before the beam is put into application, it has to withstand pre-stress applied by steel wires and dead loads.

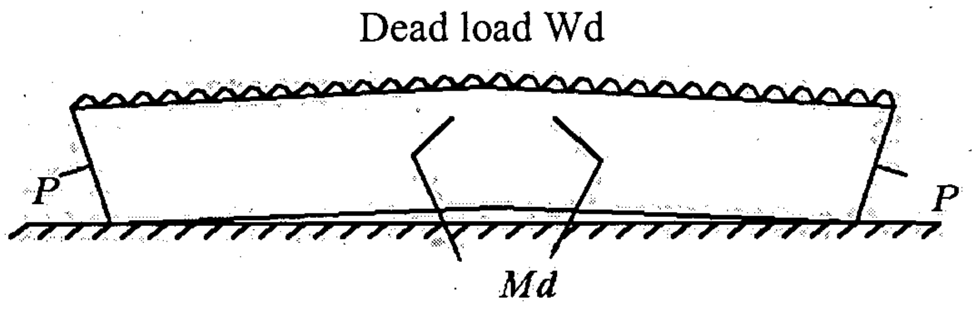

Figure 7.2: Loading Arrangement

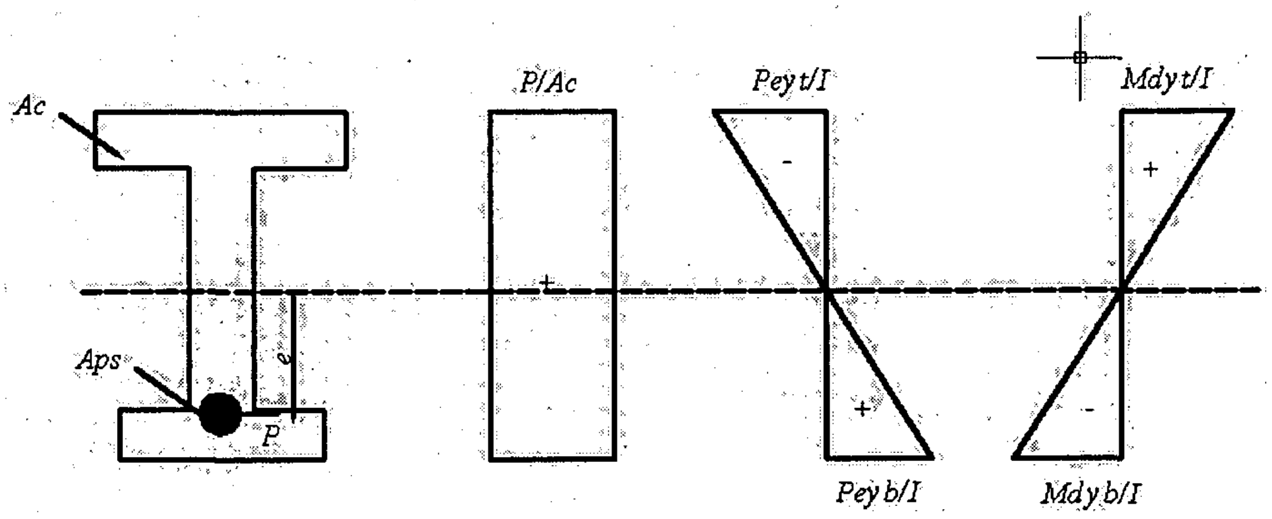

Figure 7.3: combined stress at transfer condition

At Top Fiber (For tension)

$$\sigma^T = -P/A + Pey_t/I - Mdy_t/I \le \sigma_{at} \qquad \text{(eq 7.1)}$$

At Bottom Fiber (For Compression)

$$\sigma^c = P/A + Pey_b/I - Mdy_b/I \le \sigma_{ac} \qquad \text{(eq 7.2)}$$

The above combined stress at transfer condition is shown figure 7.3

- **At Service condition**

At the service stage, the dead loads, live loads and effective pre-stressing force are considered as external loads. The stress at the top and the bottom of the section can be expressed considering effective pre-stressing force *P*, bending moment *Md* due to dead loads and *Mi* due to imposed loads. With the pre-stressing force gets reduced and it has to undergo the imposed load, under service condition.

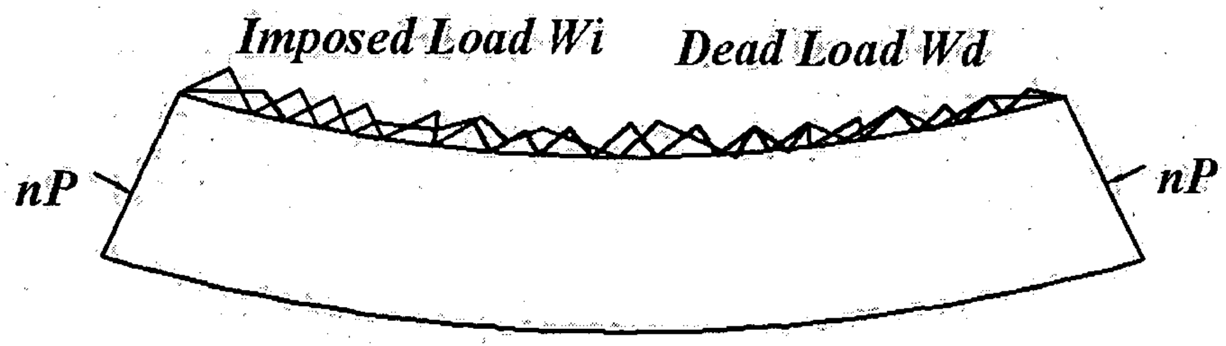

Figure 7.4: Loading Arrangement

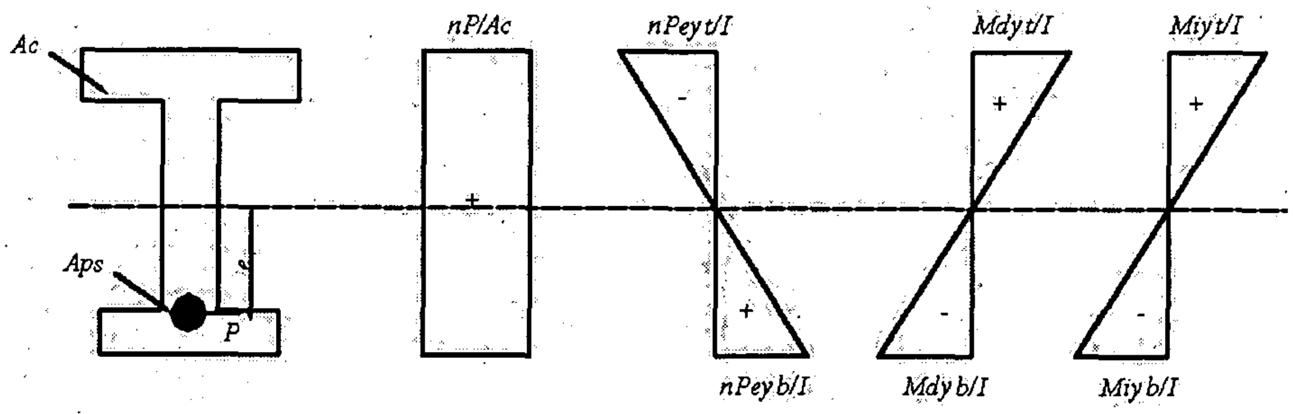

Figure 7.5: combined stress at transfer condition

At Top Fiber (For compression) : Loading Arrangement

$$\sigma^T = nP/A - nPey_t/I + Mdy_t/I + Miy_t/I \leq \sigma_{at} \qquad \text{(eq 7.3)}$$

At Bottom Fiber (For Tension)

$$\sigma^c = -nP/A - nPey_b/I + Mdy_b/I + Miy_b/I \leq \sigma_{ac} \qquad \text{(eq 7.4)}$$

The above combined stress at transfer condition is shown figure *7.5*

From constraints equations 1, 2, 3 & 4, can plot a grape $1/P$ vs e, it is known as "Magnel Diagram".

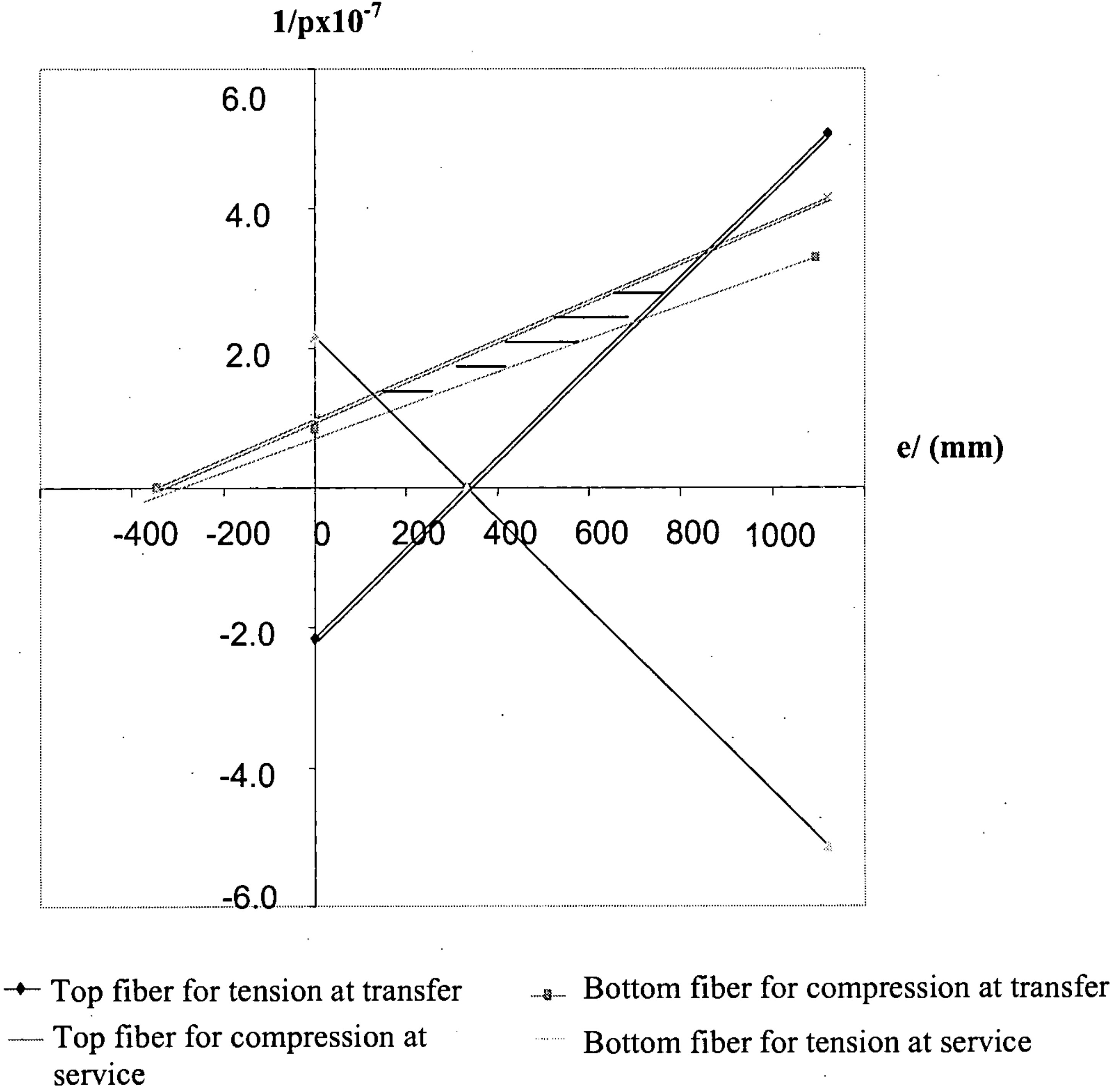

Figure 7.6: Magnel diagram

The area common to all the 4 lines Magnel Diagram in the Magnel diagram gives the magnitude of 1/P and e, which would satisfy all four stress constraints “feasibility region”.

7.2.2.2 Deflection constraints

In pre-stress concrete beam design, deflection is checked as a short-term deflection and long-term deflection.

- **Short-term deflection**

a) Due to Pre-stressing

$$\delta_1 = -PeL^2 / 8EI$$

b) Due to dead load

$$\delta_2 = -5WL^4 / 384EI$$

Therefore, short-term deflection constraint is,

$$\delta_s = \delta_1 + \delta_2 \leq \delta_{all}$$

Where δ_{all} is Span/360.

- **Long-term deflection**

c) Due to Pre-stressing

$$\delta_1 = -5nPeL^2 / 48EI$$

d) Due to uniformly distributed dead load and imposed load

$$\delta_2 = -5WL^4 / 384EI$$

c) Due to Knife edge load

$$\delta_3 = -PL^3 / 48EI$$

d) Due to creep

$$\delta_4 = \phi.\{(F_i + F_f)/2\}e/EI$$

Therefore, long-term deflection constraint is,

$$\delta_l = \delta_1 + \delta_2 + \delta_3 + \delta_4 \leq \delta_{all}$$

Where δ_{all} is Span/360.

7.2.2.3 Losses constraints

Total loss due to elastic shortening, Anchorage set, friction, relaxation loss, shrinkage loss, and creep loss should be less than 15 percentage of the pre-stress force.

7.2.2.4 Side constraints

This defines bounds on the design variables ***X***, and so is referred to as a side constraint.

$$X_i^l \leq Xi \leq X_i^u \qquad i= 1,l$$

In the case of ultimate limit state moment capacity and shear capacity are taken as a constraint. That means,

Design moment ≤ Ultimate moment capacity.

Applied shear stress ≤ Ultimate shear stress

7.2.3 Formulation of the Design Problem

General optimization problem is;

find	***X*** which
minimizes	$Z(X)$
subject to	$g(X)$
	$\mathbf{X}^L \leq \mathbf{X} \leq \mathbf{X}^u$

Where X the vector of design variables, $g\ (X)$ is design constraints, X^L is lower bound of the design variables and X^U is upper bound of the design variables.

Design problem, formulated for pre-stressed concrete beam is follows;

Find $b_1, b_2, b_3, t_1, t_2, t_3, P, e,$ in order to

Minimize $A_cC_cL + A_{ps}C_sL = Z\ (b_1, b_2, b_3, t_1, t_2, t_3, P, e)$

Subject to

For tensile stress $\sigma^T - \sigma_{at} \leq 0$

For compressive stress $\sigma^C - \sigma_{ac} \leq 0$

For shear stress $V - V_c \leq 0$

For short term deflection $\delta_s - \delta_{all} \leq 0$

For long term deflection $\delta l - \delta_{all} \leq 0$

For losses $l - 0.15P \leq 0$

$$X \leq X_0^U$$

$$X \leq -X_0^L$$

Where A_c - Cross section area of the section = $b1\ t_1 + b_2\ t_2 + b_3\ t_3$

C_c - Cost of concrete per unit volume

A_p - Cross section area of the steel = $P/\sigma_{steel,\ allowable}$

C_s - Cost of steel per unit volume

L – length of the pre-stressed beam

σ^T, σ^C- Maximum Tensile, Compressive stresses, respectively in concrete

σ_{at}, σ_{ac}- Allowable Tensile and Compressive stresses, respectively in concrete

V_c - Ultimate shear stress

V - Applied shear stress

δ_s -Short term deflection

δ_s -Long term deflection

δ_{all} -Allowable term deflection

l -Total Pre-stress losses

The beam is simply supported at the ends and is subjected a uniformly distributed load (udl) and a point load at the center.

In order to analyze and design a pre-stressed beam a spreadsheet was created. This spread sheet provides the basic data needed and sets the design boundaries of the problem for the optimization process to operate within.

7.3 Analysis using *Sap2000*

To model the pre-stressed beam, *SAP*2000 was used. In the case study 28.2 m span pre-stressed beam was considered.

Number of Nodes = 200

Number of 8 Nodes Elements = 92

Number of materials =2(concrete, steel)

Number of load cases = 3

Following results are obtained by using *sap*2000

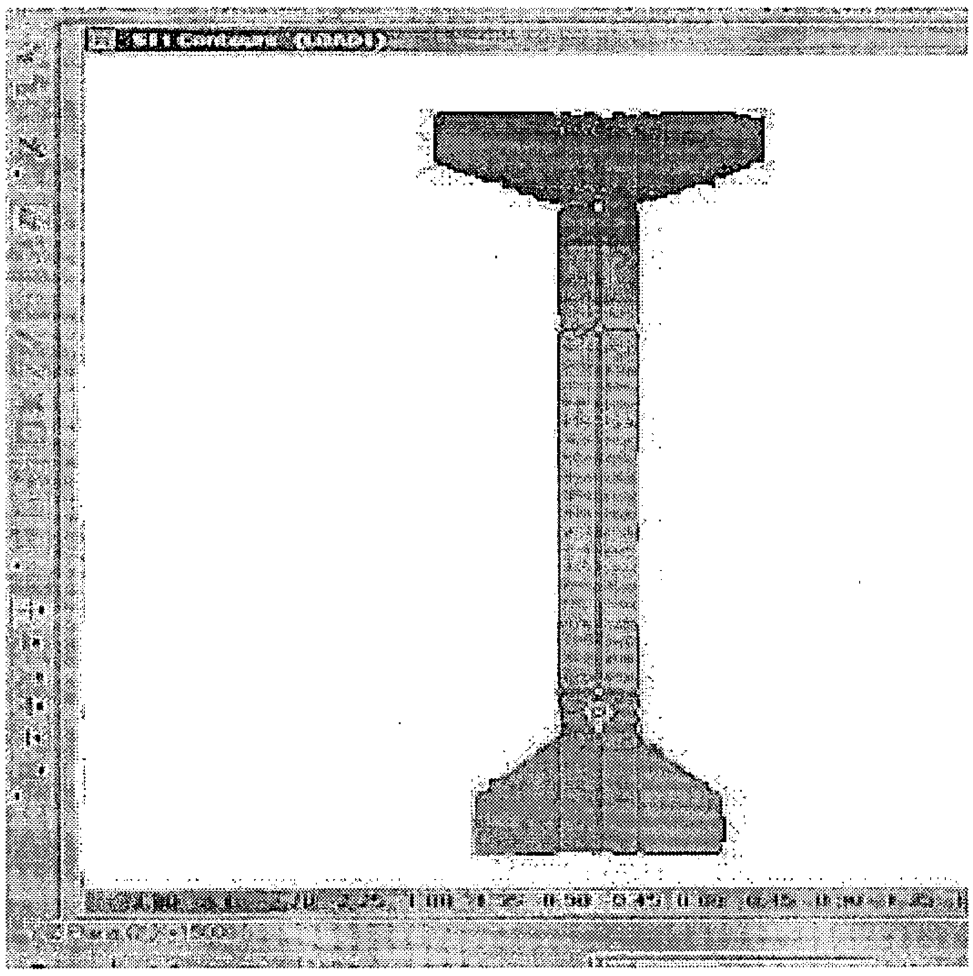

Figure 7.7: Stress along the Cross Section of the Pre-Stressed Beam

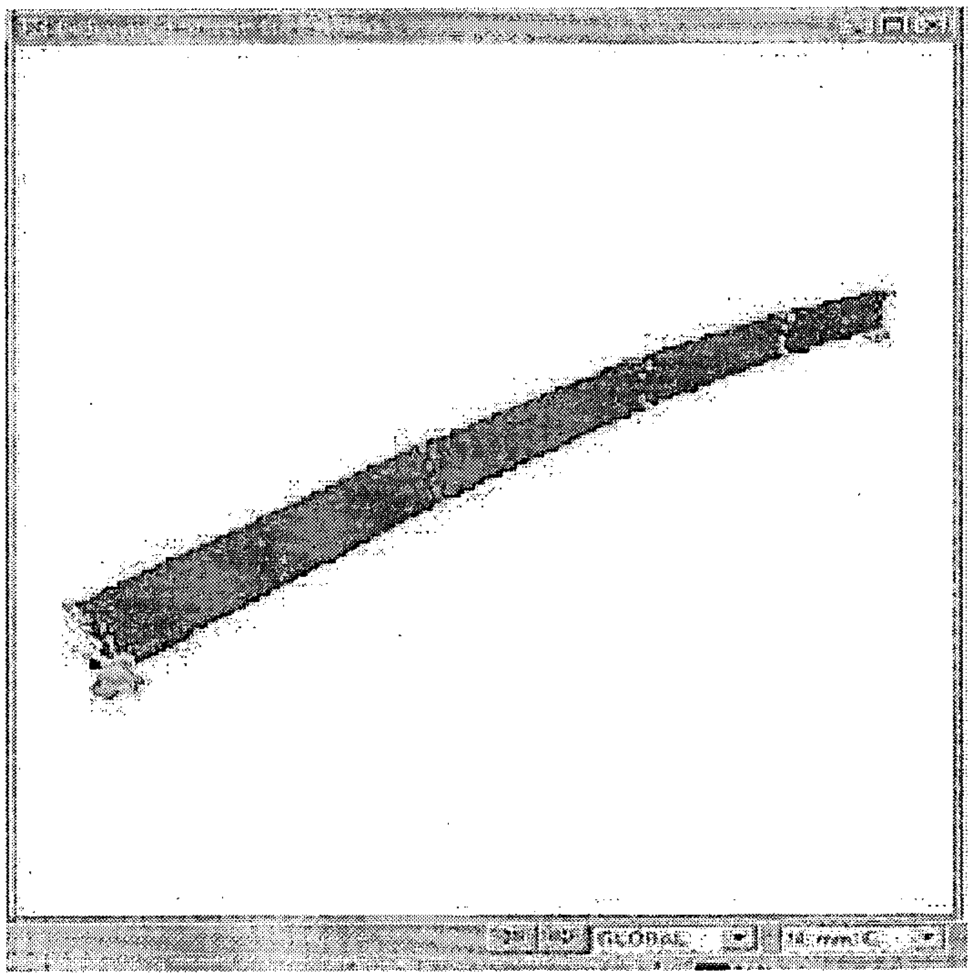

Figure 7.8: Deformed shape due to Pre-stressed force

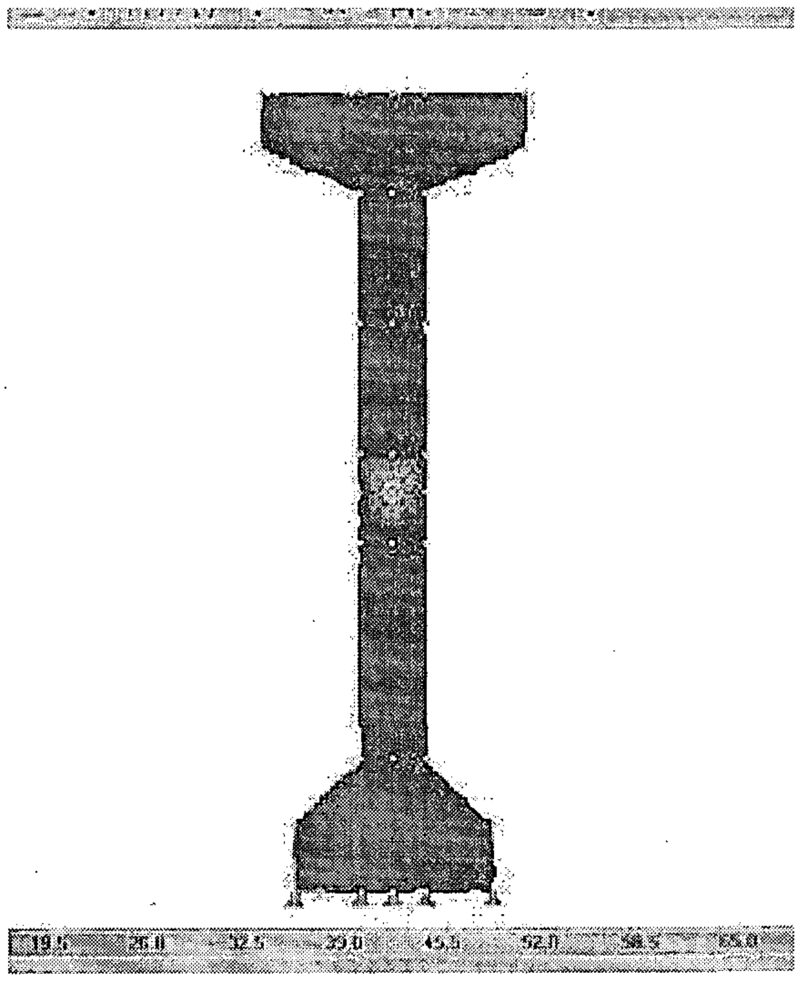

Figure 7.9: Stress along the Cross Section of the Pre-Stressed Beam At the Support

7.5 Results

Using *Solver* tool in *MSExcel* optimum variables were obtained. The optimum geometry results and pre-stress force was model in *SAP 2000.* In all load cases, stresses of every element and deflection of every node were checked in *Sap 2000* model.

Using the MSExcel program, considering *HA* loading case following optimum dimensions, pre-stressing forces and eccentricities were obtained, with C_c= Rs. 9000.00, C_s= Rs. 528900.00, σ_{at}= 2.13 N/mm^2 , σ_{ac}=20 N/mm^2 , V_c=5.3 N/mm^2

SPAN (m)	IMPOSED LOAD		b_1, (mm)	b_2 (mm)	t_1 (mm)	t_2, (mm)	t_3 (mm)	b_3 (mm)	P (MN)	e (mm)	Z (Rs)
	Udl (kN/m)	Point (kN)									
10	15	60	280	300	122	150	152	482	1.28	235	17159.00
20	15	60	357	406	235	289	152	608	2.7	442	69492.00
28.2	15	60	379	327	225	225	152	1830	2.85	878	138678.00

Table 7.1: Results obtained with MS-Excel

CHAPTER 8: CASE STUDY FOR OPTIMUM ABUTMENT DESIGN

8.1 Introduction

The objective of this project was to create an "easy-to-use" optimize design methodology and design aids to assist Sri Lankan Engineers to develop, design, and construction of various types of bridge abutment. Commonly used types of abutments are;

- Mass concrete
- Reinforced concrete- a) Reinforced concrete wall
  b) Reinforced concrete column (open abutment)

In this case study, it was considered only the mass concrete abutment for optimization process. To optimize the abutment construction, it is essential to understand basic components of the abutment and their purposes. The basic components of an abutment are

- Abutment footer
- Abutment wall
- Capping beam
- Ballast wall

In the mean time, it is important to finding the actual loads coming through the superstructure and the retaining soil.

Loads transmitted from the bridge deck to the abutment are:

- Vertical loads due to self weight of deck
- Vertical loads from live loads

- Horizontal loads due to temperature changes, creep movements and wind
- Horizontal loads due to breaking and skidding effects of vehicles.

These loads are carried by the bearings, which are fixed on the abutment bearing platform. The horizontal loads may reduce and it will depend on the coefficient of friction of the bearings at the movement joint in the structure. However, the full breaking effects must be taken from both directions. In addition to the structure loads, a horizontal pressure exerted by the fill material against the abutment walls is to be considered. Also a vertical loading from the weight of the fill acts on the footing.

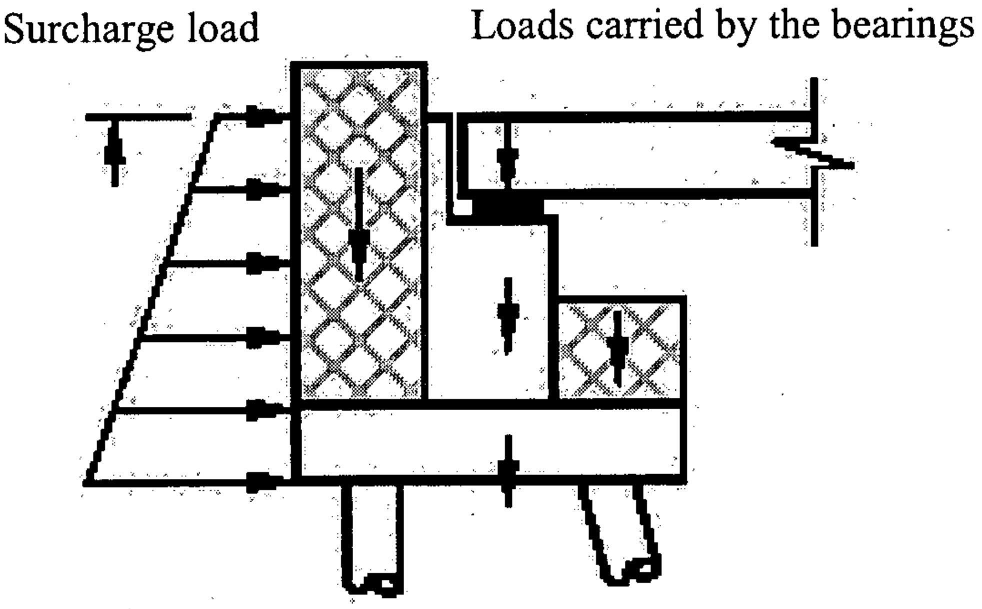

Figure 8.1: loads on abutment

8.2 Formulation of Primary Optimal Design Problem for Abutment

8.2.1 Design Variables

In this study, mass concrete abutment was considered. The cross section of abutment is shown in Figure 8.2. Formulation for this design problem is possible depending on the design variables. Design variables are cross sectional dimensions b_1, b_2,

$b_3, b_4, b_5, b_6, b_7, b_8, b_9, h_1, h_2, h_3, h_4, h_5, h_6, h_7,$ of the abutment is shown in the figure 8.2 are taken to the account.

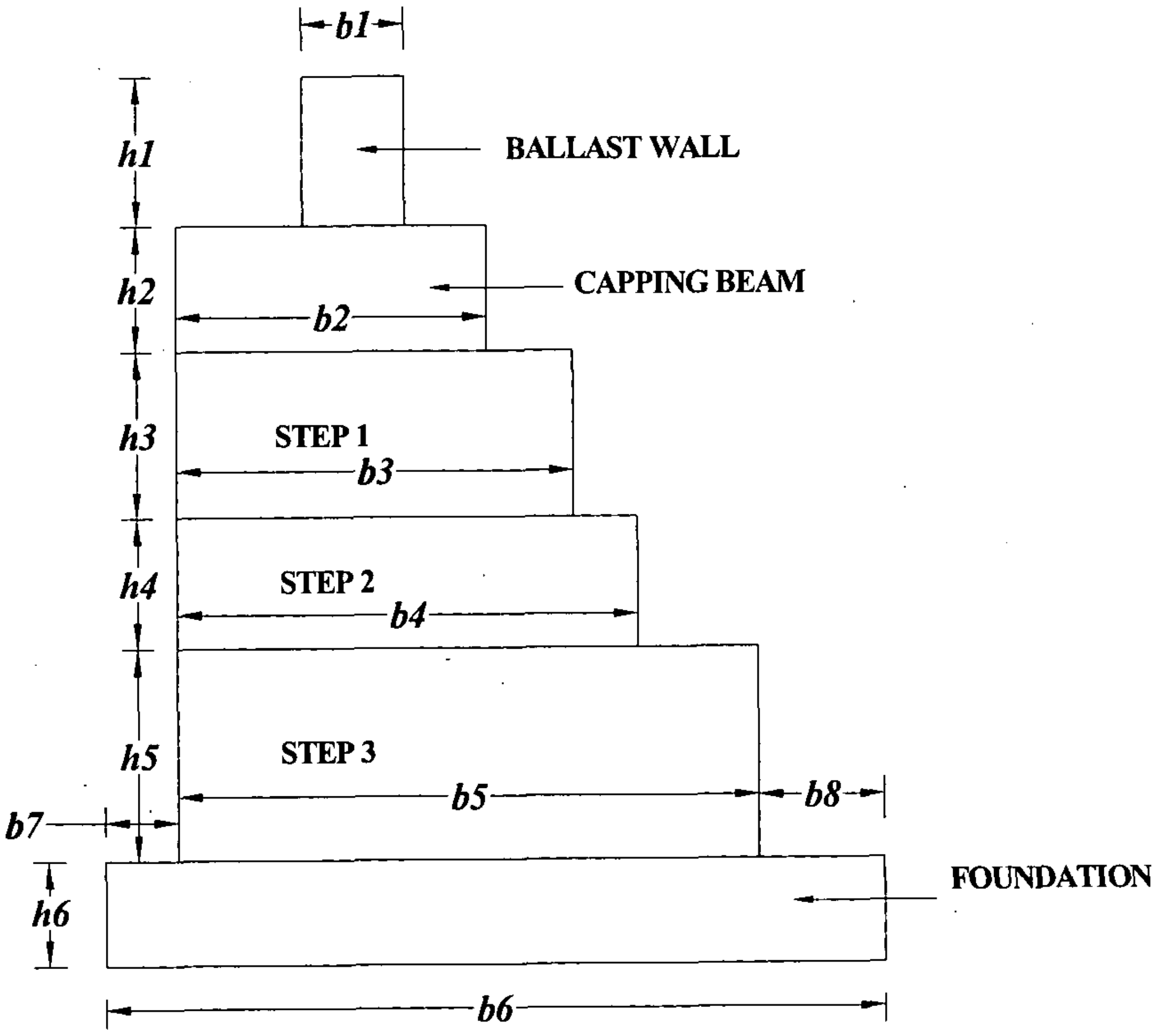

Figure8.2: Abutment Cross Section

8.2.2 Design Constraints for Capping Beam and Ballast wall Design

In this problem, every sub components of the abutment was analyzed separately with respect to the critical load case. In the followings, the design constraints are explained in detail.

8.2.2.1 Overturning Constraint

Overturning effect is considered at capping beam bottom level. In this case Factor of Safety (F.O.S) is taken as greater than 1.3

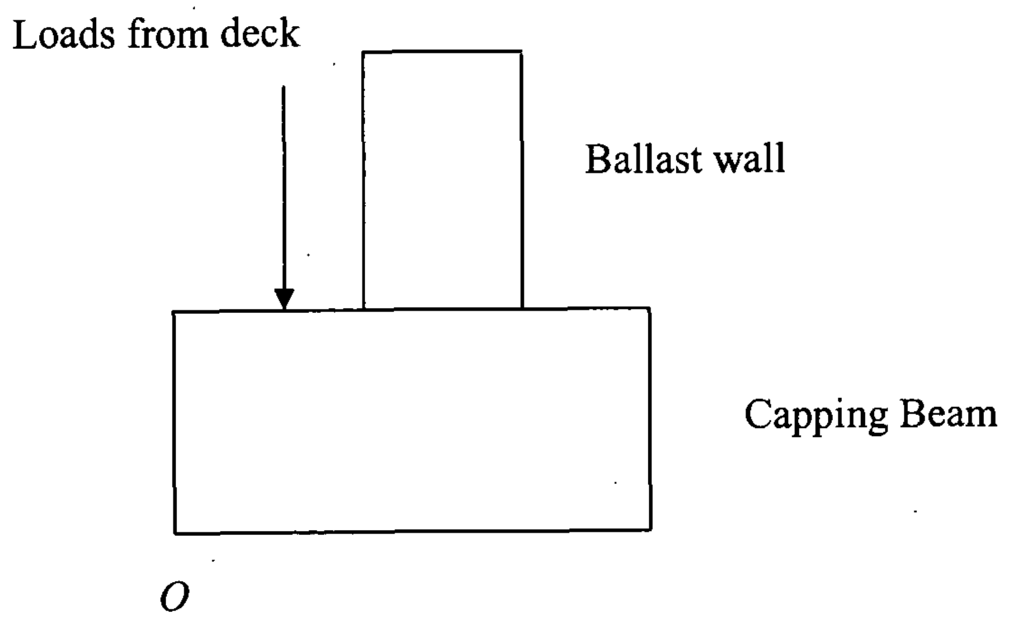

Figure 8.3: Section of Capping Beam

$$g(1) = \text{F.O.S} = \frac{\text{Stability Moment (Ms)}}{\text{Overturning Moment (Ms)}} \geq 1.3$$

The Stability moment and Overturning moment are taken about point "*O*" shown in the figure 8.3.

8.2.2.2 Stress Constraint

Capping beams are designed for bending moments and shear forces due to loads acting on them.

If we considered one meter length capping beam,

$$\text{Direct Stress} = \frac{V}{b_2}$$

$$\text{Bending Stress} = \frac{V}{6b2}$$

$$\text{Total Stress} = \frac{V}{b_2} \pm \frac{V}{6b2}$$

Where V = Total vertical force acting on the capping beam

b_2 = width of the capping beam

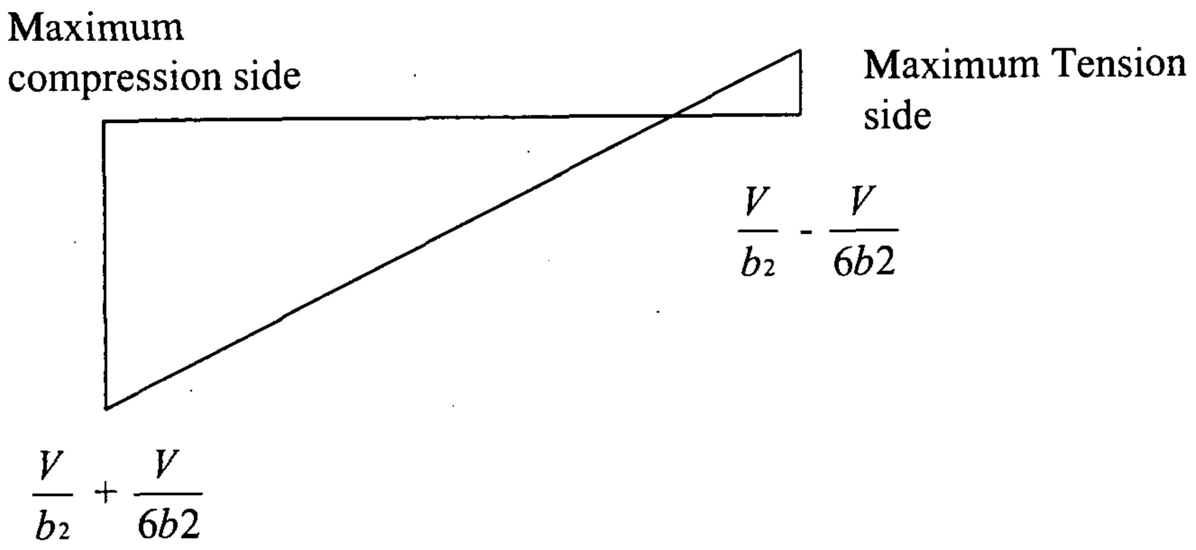

Figure 8.4: Stress diagram

$$g\,(2) = \frac{V}{b_2} + \frac{V}{6b2} \leq \text{ Allowable maximum compressive stress of concrete}$$

$$g\,(3) = \frac{V}{b_2} - \frac{V}{6b2} \geq \text{ Allowable minimum compressive stress of concrete}$$

8.2.3 Design Constraints for Abutment wall Design

8.2.3.1 Overturning Constraint

Every steps of the abutment wall should be checked for against overturning.

$$g\,(4) = \text{F.O.S} = \frac{\text{Stability Moment (Ms)}}{\text{Overturning Moment (Ms)}} \geq 1.3$$

The Stability moment and Overturning moment are taken about point *"Oi"* shown in the Figure 8.5.

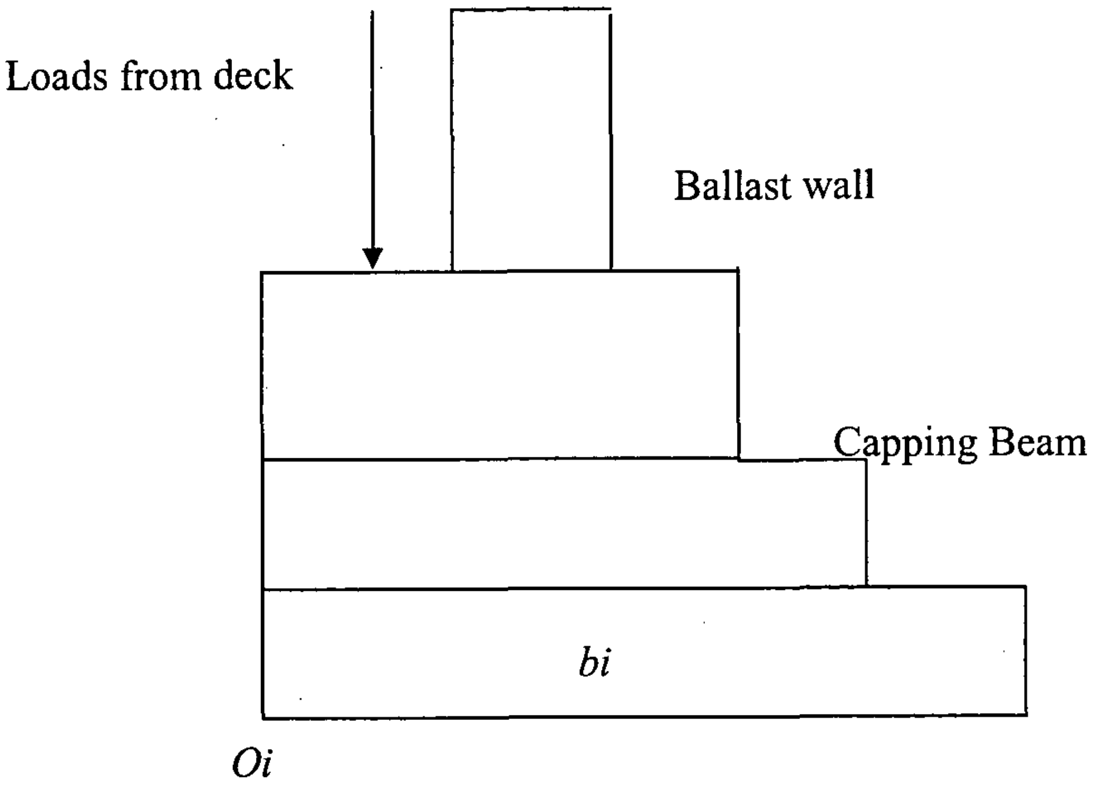

Figure 8.5: Section of "i"th step

8.2.3.2 Stress Constraint

Stress at the bottom side of the every section should satisfy following conditions,

$$g\,(5) = \frac{V}{bi} + \frac{V}{6bi} \leq \text{ Allowable maximum compressive stress of concrete}$$

$$g\,(6) = \frac{V}{bi} - \frac{V}{6bi} \geq \text{ Allowable minimum compressive stress of concrete}$$

8.2.4 Design Constraints for Abutment Foundation Design

8.2.4.1 Overturning Constraint

Foundation should be satisfied for overturning constraint as mention above.

$$g\,(7) = \text{F.O.S} = \frac{\text{Stability Moment (Ms)}}{\text{Overturning Moment (Ms)}} \geq 1.3$$

In addition to that should check for sliding and bearing of the soil.

8.2.4.2 Sliding Constraint

$$g\,(8) = \text{F.O.S} = \frac{\text{Resisting force } (Fr)}{\text{Sliding force } (Fs)} \geq 1.5$$

8.2.4.3 Bearing Constraint

Foundation type is mainly depending on the safe bearing pressures of the bearing stratum,

$$g\,(9) = \frac{V}{b_f} + \frac{V}{6b_f} \leq \text{ Allowable Bearing capacity of Soil}$$

$$g\,(10) = \frac{V}{b_f} - \frac{V}{6b_f} > 0$$

8.2.5 Formulation of the design problem

General optimization problem is;

find	X which
minimizes	$Z\,(X)$
subject to	$g\,(X)$
	$X^L \leq X \leq X^u$

Where X the vector of design variables, $g\,(X)$ is design constraints, X^L is lower bound of the design variables and X^U is upper bound of the design variables.

Design problem, formulated for Abutment is follows;

Find	$b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8, h_1, h_2, h_3, h_4, h_5, h_6,$ *in* order to
Minimize	$\sum A_s W C_c = Z\,(b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8, h_1, h_2, h_3, h_4, h5, h_6,)$
Subject to	$g\,(1) - 1.3 \geq 0$

$g(2) - \sigma_{ac,max} \leq 0$

$g(3) - \sigma_{ac,min} \geq 0$

$g(4) - 1.3 \geq 0$

$g(5) - \sigma_{ac,max} \leq 0$

$g(6) - \sigma_{ac,min} \geq 0$

$g(7) - 1.3 \geq 0$

$g(8) - 1.5 \geq 0$

$g(9) - \sigma_{as,max} \leq 0$

$g(6) \geq 0$

$X \leq X_0^U$

$X \leq -X_0^L$

Where A_s - Cross section area of the section = $b_1 h_1 + b_2 h_2 + b_3 h_3 + b_4 h_4 + b_5 h_5 + b_6)$

C_c - Cost of concrete per unit volume

W – Width of the abutment

σ^T, σ^C - Maximum Tensile, Compressive stresses, respectively in concrete

$\sigma_{ac,max}$,$\sigma_{ac,min}$ - Allowable maximum and minimum Compressive stresses, respectively in concrete

$\sigma_{as,max}$ - Allowable bearing capacity of soil

In order to analyze and design a bridge abutment a spreadsheet was created to store the various design criteria. Running the Solver command is very easy and requires the definition of the problem (design variables, objective function, and constraints) only once, and upon running the solver, it is yield the optimum solution.

8.3 Results

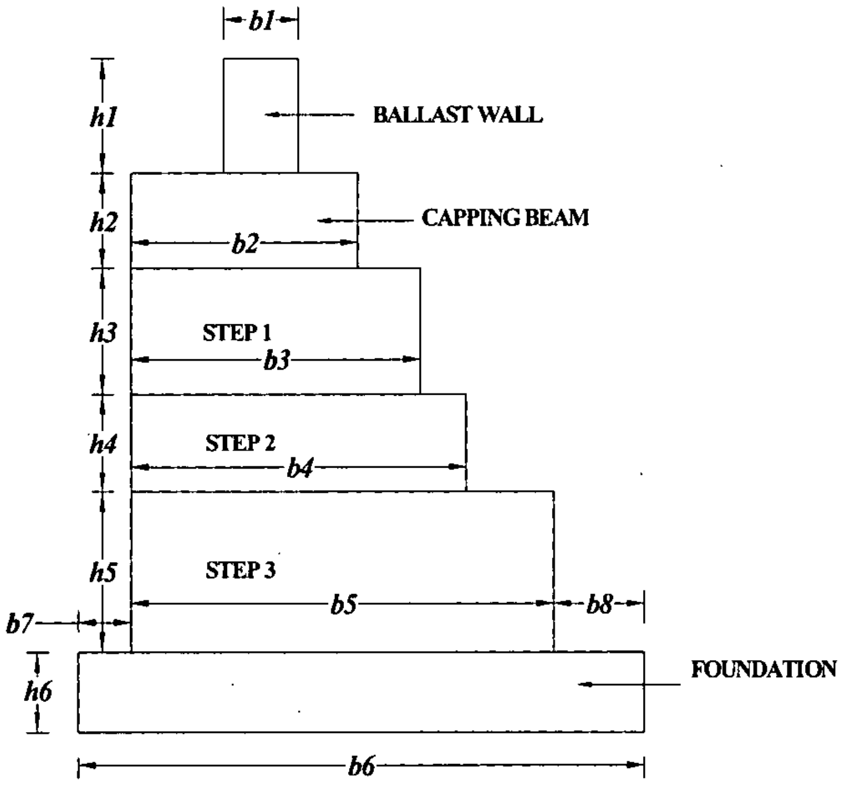

Figure 8.6: Abutment Cross Section

Design Variables	Initial Values/(m)	Optimum Values/(m)
b_1	0.3	0.5
b_2	1.7	0.8
b_3	1.9	0.8
b_4	2.2	1.35
b_5	2.5	1.35
b_6	4.0	3.85
b_7	0.8	1.0
b_8	0.9	1.5
h_1	1.03	0.75
h_2	0.6	0.5
h_3	0.5	2.18
h_4	1.05	0.5
h_5	1.05	0.5
h_6	0.5	0.2

Table8.1: Results

Above Table 8.1 is shown the comparison between the initial values and the final optimum value. The initial values are taken from one of the actual design. Following graph shows the relation between the iterations and the cost.

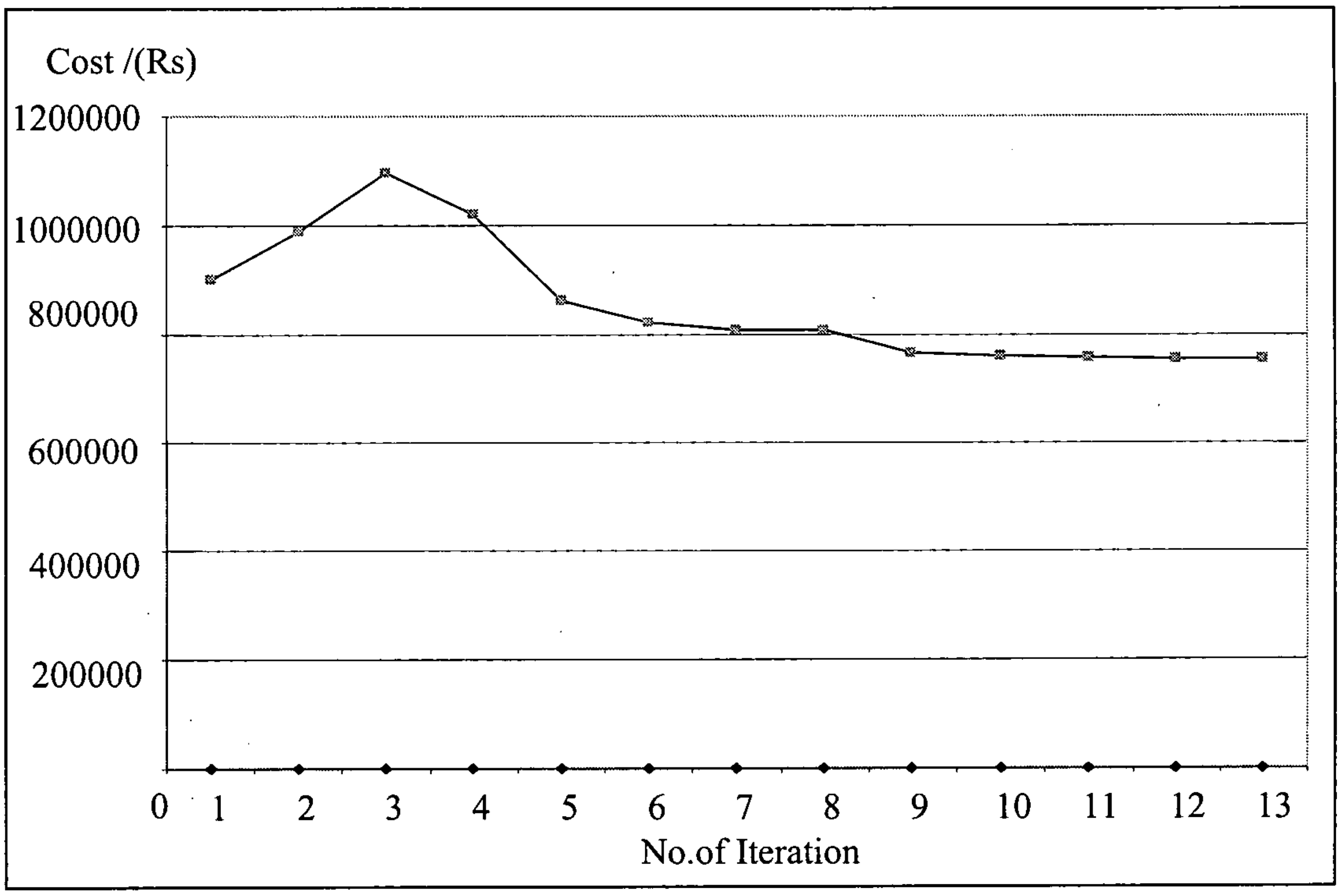

Figure 8.7: Relationship between Cost vs No. of Iterations

CHAPTER 9: CASE STUDY ON WING WALL DESIGN

9.1 Introduction

A wing wall is a structure that holds back earth. Wing walls stabilize soil, rock from down slope movement or erosion and provide support for vertical or near-vertical grade changes.

Wing walls are essentially retaining walls adjacent to the abutment. The walls can be independent or integral with the abutment wall.

Different types of wing walls commonly used are;

- Wing walls cantilevered from abutments
- Mass concrete wing walls
- Reinforced concrete wing walls
- Sheet pile wing walls

9.1.1 Design Considerations

Loads effects to be considered on the rear of the wall are:

- Earth pressures from the backfill material.
- Surcharge from live loading or compacting plant.
- Hydraulic loads from saturated soil conditions.

The most important consideration in proper design and installation of wing walls is that the retained material is attempting to move forward and down slope due to gravity. This creates a soil pressure behind the wall (depending on the angle of internal friction and the cohesive strength of the material). This pressure is smallest at the top and increases toward the bottom and will push the wall forward or overturn it if nor properly addressed.

Wing walls are made from a large mass of stone, concrete, or composite materials. Gravity walls depend on the size and weight of the wall mass to resist pressures from behind. Wing will often have a slight setback, or batter, to improve wall stability by leaning back into the retained soil. In this case study, mass concrete abutment was considered. The optimized mass concrete stepped section is to be designed as sloped back retaining wall on the stepped side.

9.2 Formulation of Primary Optimal Design Problem for Wing wall

9.2.1 Design Variables

In this study, mass concrete stepped wing wall was considered. The cross section of abutment is shown in Figure 9.1. Formulation for this design problem is possible depending on the design variables. Design variables are cross sectional dimensions b_1, b_2, b_3,b_4, b_5, b_6, b_7,b_9, h_1, h_2, h_3 , h_4, h_5, h_6,, of the wing wall is shown in the figure 9.1 are taken to the account.

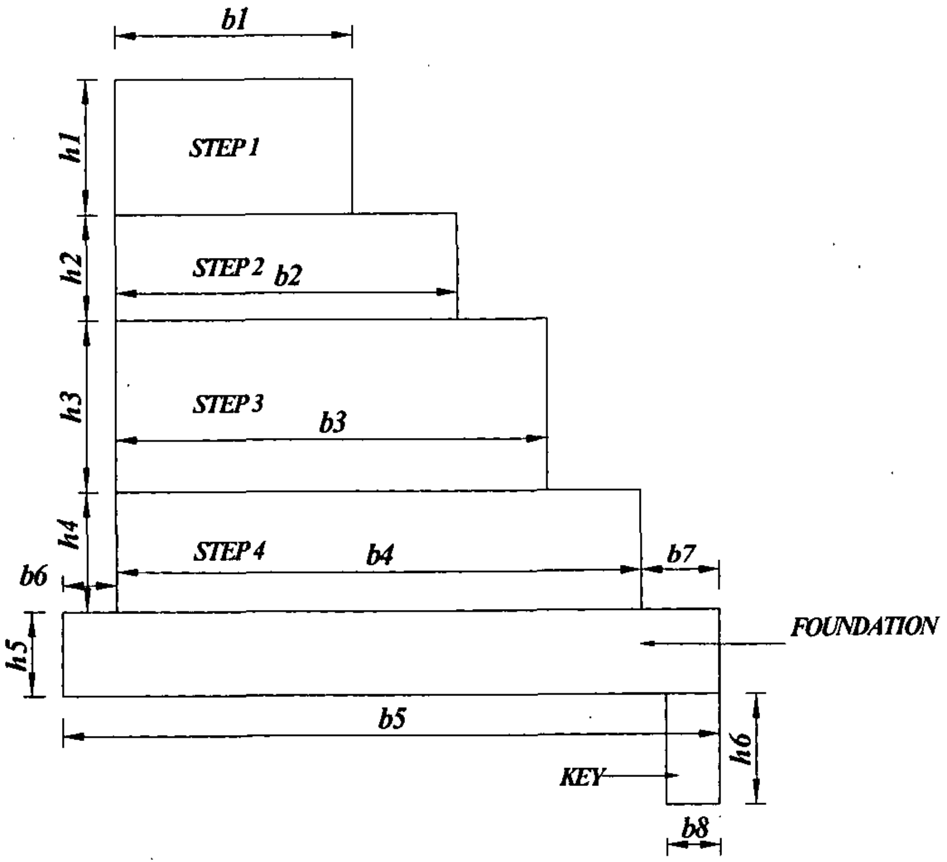

Figure 9.1: Cross section of wing wall

9.2.2 Design constraints for Wing wall steps Design

In this problem, every steps of the wing wall was analyzed separately with respect to the critical load case. In the followings, the design constraints are explained in detail.

9.2.2. 1 Overturning Constraint

Every steps of the abutment wall should be checked for against overturning.

$$g\,(1) = \text{F.O.S} = \frac{\text{Stability Moment (Ms)}}{\text{Overturning Moment (Ms)}} \geq 1.3$$

The Stability moment and Overturning moment are taken about point *"Oi"* shown in the figure 9.2.

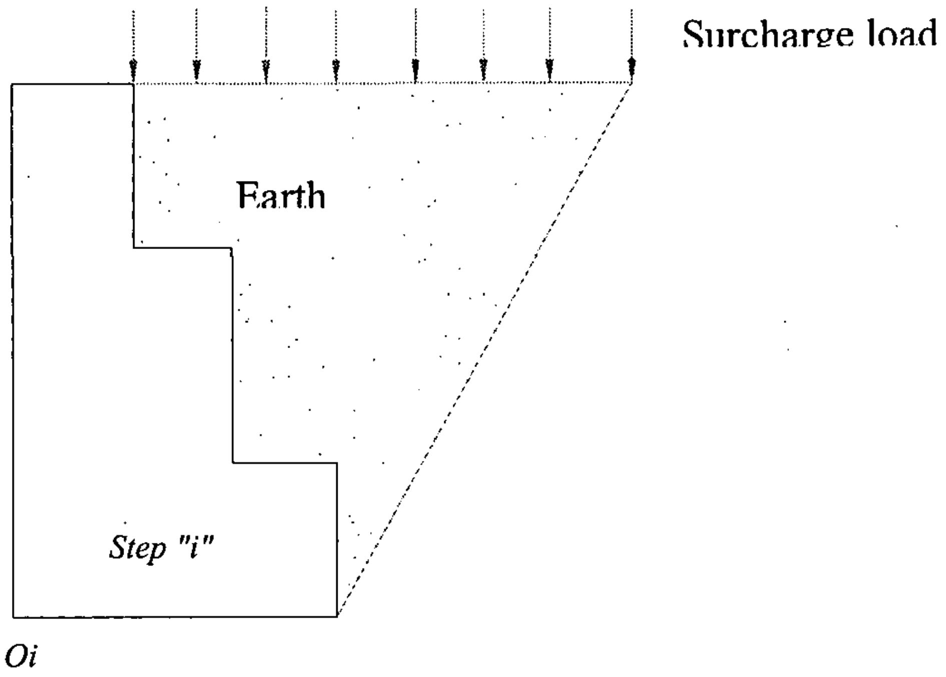

Figure 9.2: Section of " i"th step

9.2.2.2 Stress Constraint

Stress at the bottom side of the every section should satisfy following conditions,

$$g\,(2) = \frac{V}{bi} + \frac{V}{6bi} \leq \text{ Allowable maximum compressive stress of concrete}$$

$$g\,(3) = \frac{V}{bi} - \frac{V}{6bi} \geq \text{ Allowable minimum compressive stress of concrete}$$

9.2.3 Design constraints for Wing wall Foundation Design

9.2.3.1 Overturning Constraint

Foundation should be satisfied for overturning constraint as mention above.

$$g\,(4) = \text{F.O.S} = \frac{\text{Stability Moment (Ms)}}{\text{Overturning Moment (Ms)}} \geq 1.3$$

In addition to that should check for sliding and bearing of the soil.

9.2.3.2 Sliding Constraint

$$g\,(5) = \text{F.O.S} = \frac{\text{Resisting force } (Fr)}{\text{Sliding force } (Fs)} \geq 1.5$$

9.2.3.3 Bearing Constraint

Foundation type is mainly depending on the safe bearing pressures of the bearing stratum,

$$g\,(6) = \frac{V}{b_f} + \frac{V}{6b_f} \leq \text{ Allowable Bearing capacity of Soil}$$

$$g\,(7) = \frac{V}{b_f} - \frac{V}{6b_f} > 0$$

9.2.4 Formulation of the design problem

General optimization problem is;

find X which

minimizes $Z(X)$

subject to $g(X)$

$\mathbf{X}^L \leq \mathbf{X} \leq \mathbf{X}^u$

Where X the vector of design variables, $g(X)$ is design constraints, X^L is lower bound of the design variables and X^U is upper bound of the design variables.

Design problem, formulated for wing wall is follows;

Find $b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8, h_1, h_2, h_3, h_4, h_5, h_6,$ *in* order to

Minimize $\sum A_s W C_c = Z(b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8, h_1, h_2, h_3, h_4, h5, h_6,)$

Subject to $g(1) - 1.3 \geq 0$

$g(2) - \sigma_{ac,max} \leq 0$

$g(3) - \sigma_{ac,min} \geq 0$

$g(4) - 1.3 \geq 0$

$g(5) - 1.5 \geq 0$

$g(6) - \sigma_{as,max} \leq 0$

$g(7) \geq 0$

$X \leq X_0^U$

$X \leq -X_0^L$

Where A_s - Cross section area of the section = $b_1 h_1 + b_2 h_2 + b_3 h_3 + b_4 h_4 + b_5 h_5 + b_6)$

C_c - Cost of concrete per unit volume

W – Width of the wingwall

σ^T, σ^C- Maximum Tensile, Compressive stresses, respectively in concrete

$\sigma_{ac,max}$,$\sigma_{ac,min}$- Allowable maximum and minimum Compressive stresses, respectively in concrete

$\sigma_{as,max}$ - Allowable bearing capacity of soil

In order to analyze and design a bridge wing wall a spreadsheet was created to store the various design criteria. Running the Solver command is very easy and requires the definition of the problem (design variables, objective function, and constraints) only once, and upon running the solver, it is yield the optimum solution.

CHAPTER 10: CASE STUDY ON PIER DESIGN

10.1 Introduction

Today it is common practice to build bridge pier with reinforced concrete. Economy and aesthetics are probably the main reasons. It is reasonable to build piers of reinforced concrete, for by using different configurations most conditions can be accommodated. In this case study Hammerhead Circular shaft Pier type was selected for the optimization process. The hammer head pier is economical for high river heights; and the multiple columns bent is practical on wider structures when river debris collection is not a problem. Circular shafts have some advantages, such as ease in forming and the added confining strength that results from spirals incorporated in the section. The close spacing of spirals reinforcing also provides excellent buckling strength characteristics to the main reinforcement. Loads transmitted by the bridge deck onto the pier are:

- Vertical loads due to self weight of deck
- Vertical loads from live loading conditions
- Horizontal loads due to temperature, creep movements etc and wind
- Rotations due to deflection of the bridge deck.

Piers perform a support function. They convey vertical and horizontal loads from the superstructure via the bearing shelf, stem and foundation slab to the supporting soil. In many instances, piers stand on saturated soils for most or all of the year: they do not retain soil embankments but are designed to withstand hydraulic pressures and impact loads. Piers are often more susceptible to scour damage than abutments and need to orientated carefully with respect to flow direction. Their foundations should be located well below maximum scour depth.

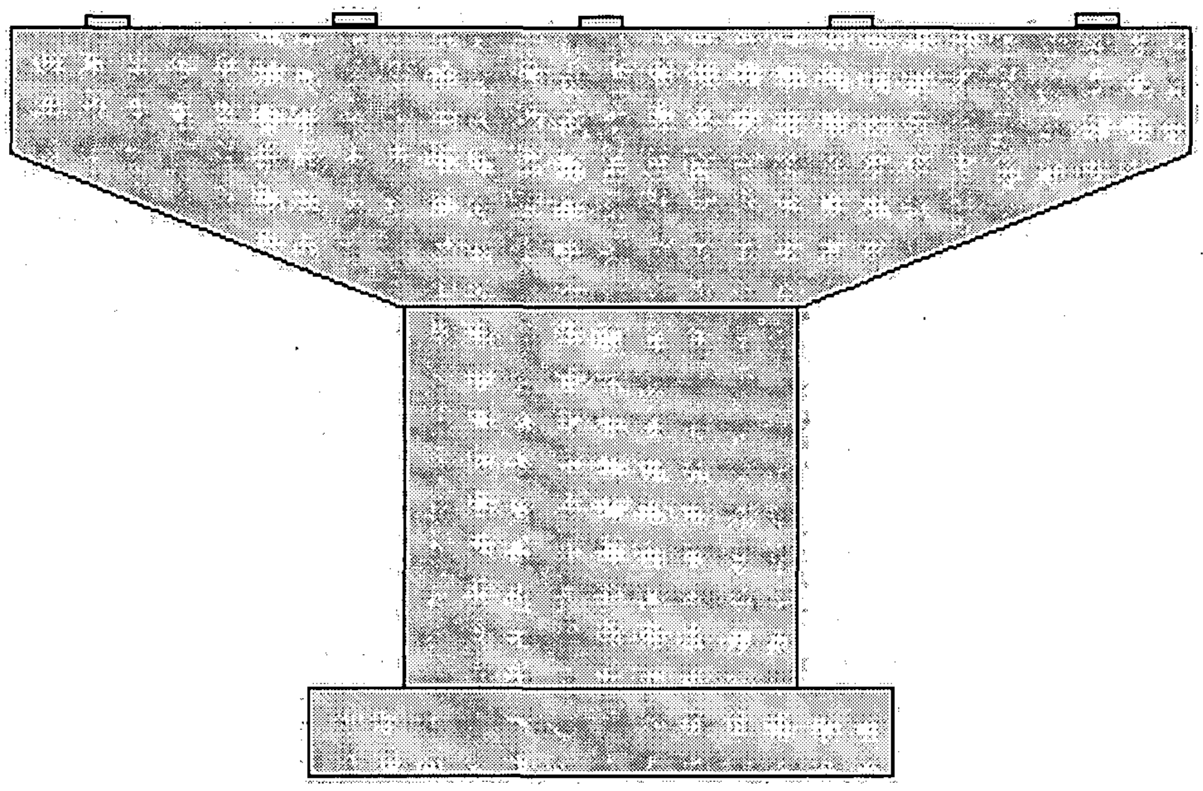

Figure 10.1: Typical Hammerhead Pier

10.2 Formulation of Primary Optimal Design Problem for Pier

10.2.1 Design variables

In this study, Hammerhead Circular shaft Pier type was considered. The cross section of pier is shown in Figure 10.1. Formulation for this design problem is possible depending on the design variables. Design variables are cross sectional dimensions b_1, b_2, d, h_1, h_2, h_3, h_4 of the abutment is shown in the figure 10.1 are taken to the account.

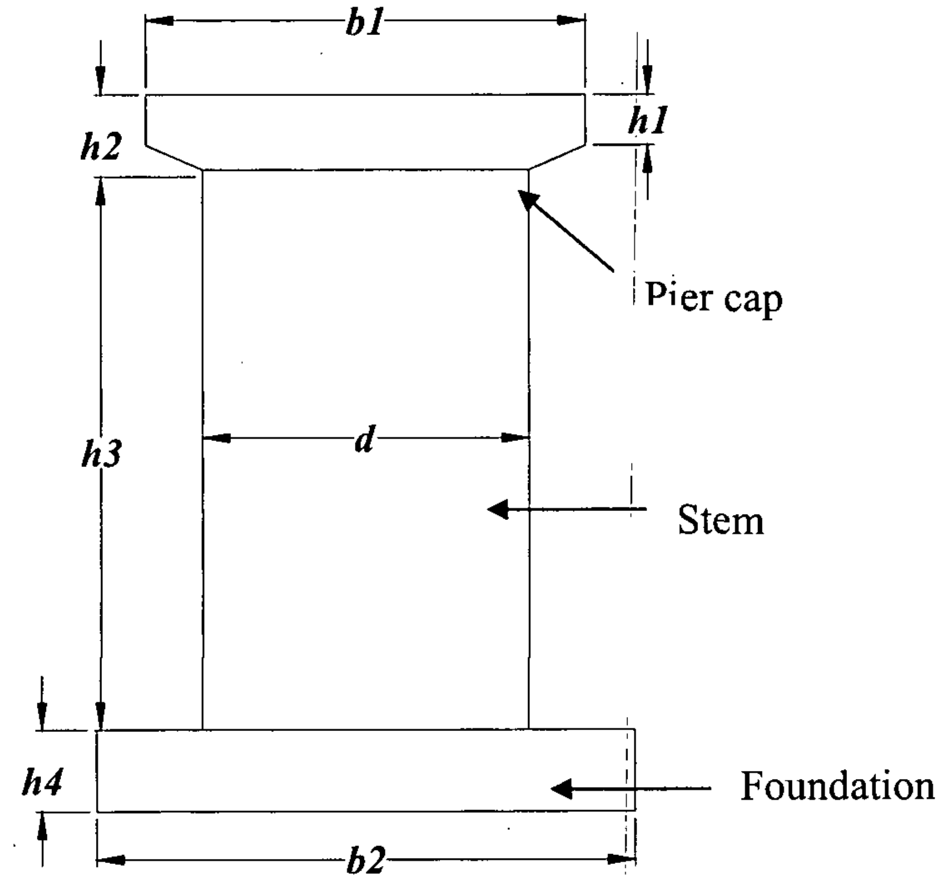

Figure 10.2: Cross Section of Pier

10.2.2 Design Constraints

In this problem, following design constraints are analyzed for critical load case.

10.2.2.1 Slenderness ratio check

For the column it should be checked for the slenderness limits,

i.e $g(1) = \frac{le}{d} < 30$

10.2.2.2 Over turning moment check

Stability for over turning was checked at one span fully loaded at high flood level (HFL) condition. The factor of safety should be greater than 1.3. Moments were taken at the bottom corner of the foundation.

$$g(2) = \text{F.O.S} = \frac{\text{Stability Moment (Ms)}}{\text{Overturning Moment (Ms)}} \geq 1.3$$

10.2.2.3 Sliding check

Sliding was check at one span fully loaded at HFL condition.

$$g(3) = \text{F.O.S} = \frac{\text{Resisting force } (Fr)}{\text{Sliding force } (Fs)} \geq 1.5$$

10.2.2.4 Bearing Constraint

Foundation is mainly depending on the safe bearing pressures of the bearing stratum,

$$g(4) = \frac{V}{b_f} + \frac{V}{6b_f} \leq \text{Allowable Bearing capacity of Soil}$$

$$g(5) = \frac{V}{6b_f} - \frac{V}{b_f} \leq 0$$

10.2.3 Formulation of the design problem

General optimization problem is;

find X which

minimizes $Z(X)$

subject to $g(X)$

$$\mathbf{X}^L \leq \mathbf{X} \leq \mathbf{X}^u$$

Where X the vector of design variables, $g(X)$ is design constraints, X^L is lower bound of the design variables and X^U is upper bound of the design variables.

Design problem, formulated for pier is follows;

Find $b_1, b_2, d, h_1, h_2, h_3, h_4$, which

Minimize $\sum V_s C_c = Z\ (b_1, b_2, d, h_1, h_2, h_3, h_4,)$

Subject to

For slenderness $g\,(1) - 30 < 0$

For overturning $g\,(2) - 1.3 \geq 0$

For sliding $g\,(3) - 1.5 \geq 0$

For bearing $g\,(4) - \sigma_{as,max} \leq 0$

For tensile at base $g\,(5) \leq 0$

$$X \leq X_0^U$$

$$X \leq -X_0^L$$

Where V_s - Total volume of the section

C_c - Cost of concrete per unit volume

$\sigma_{as,max}$ – Allowable bearing pressure of soil

10.2.4 Design program

A computer program is developed for the optimal design of single column circular reinforced concrete bridge piers for bridge loading. For a given column height, and axial load level, results indicate the existence of an optimal column diameter.

10.3 Results

This optimization problem was formulated in *MS-Excel*. Using the Solver Add Ins, optimum design diameter was found after some iteration. Following graphs shows the relation between the Diameter of the pier stem vs No. of iterations and cost for the concrete vs No. of iterations.

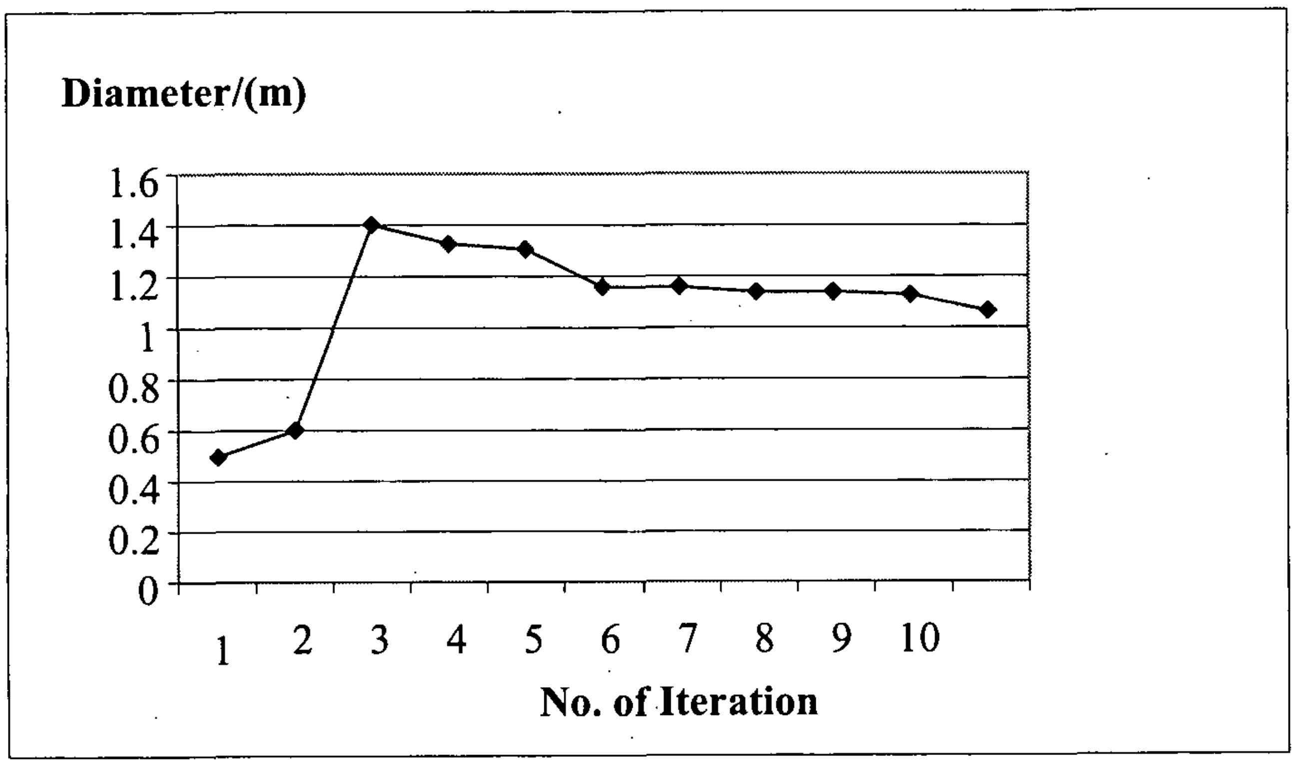

Figure 10.3: Relationship between Diameter vs No. of Iterations

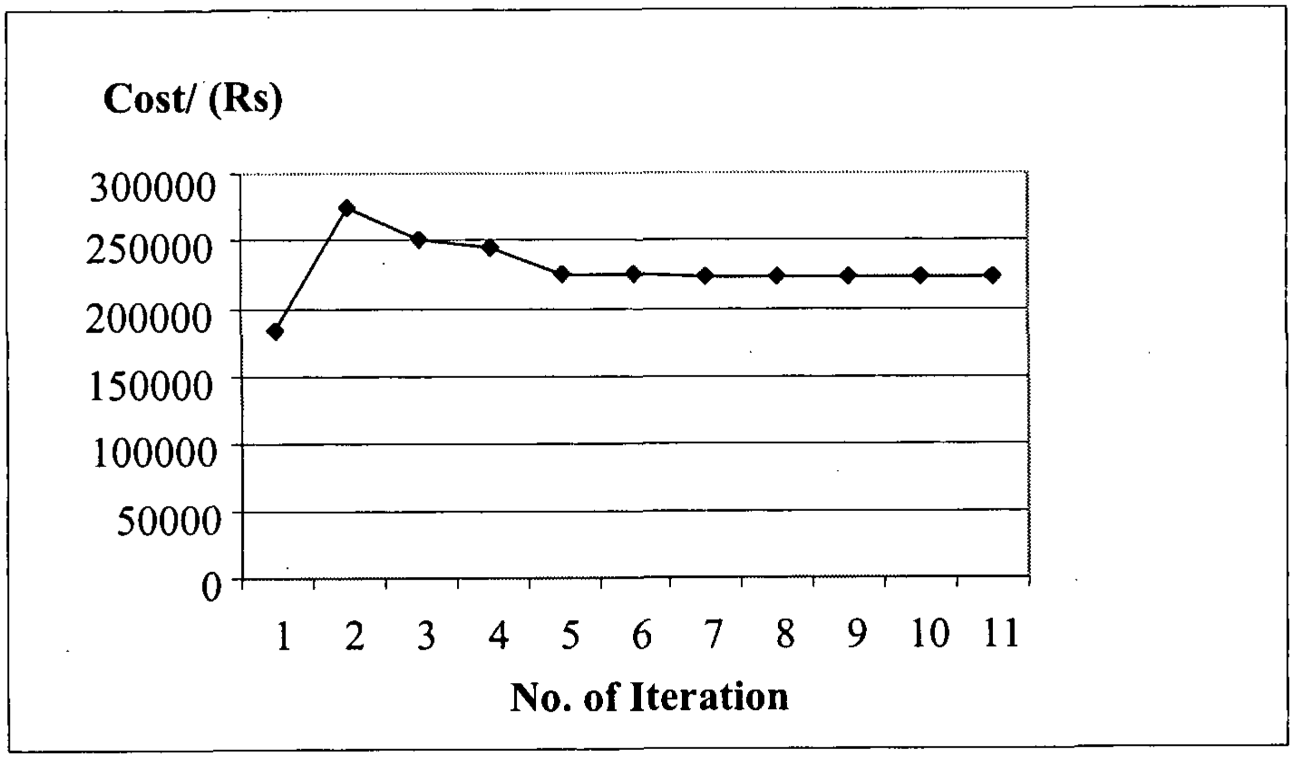

Figure 10. 4: Relationship between Cost vs No. of Iterations

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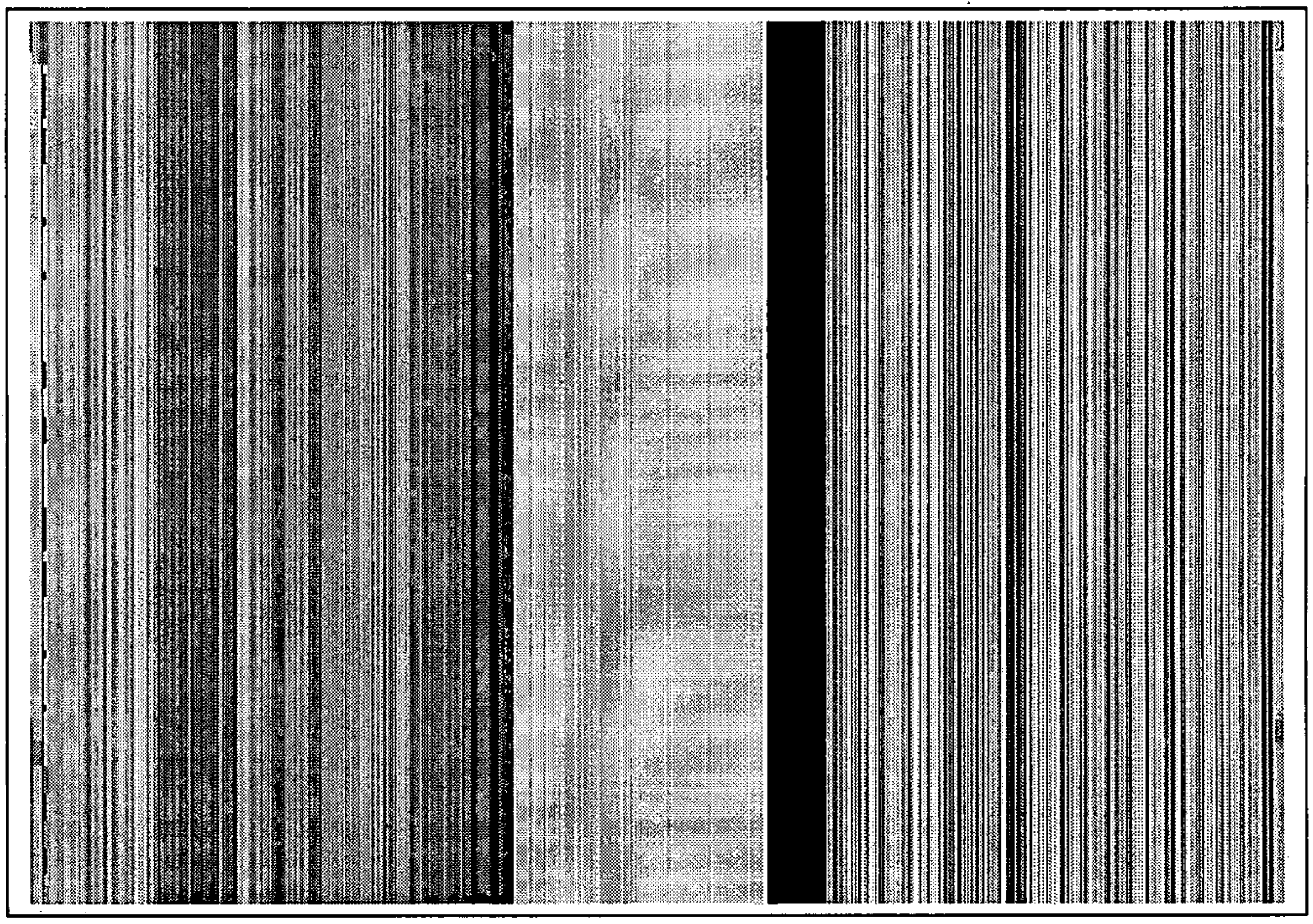
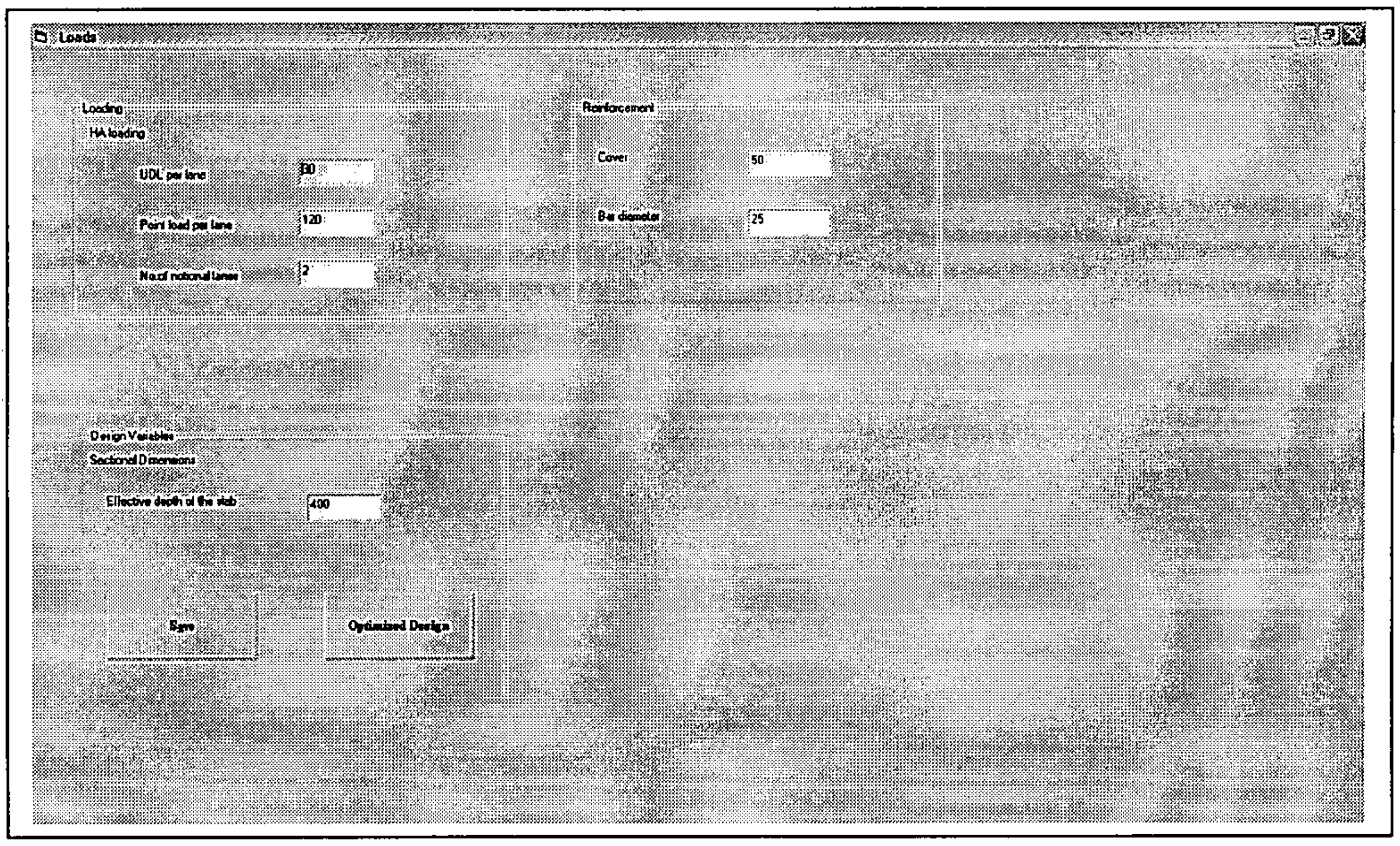
Appendix

Main window:



Design of Reinforced slab:



UDL per lane: 30

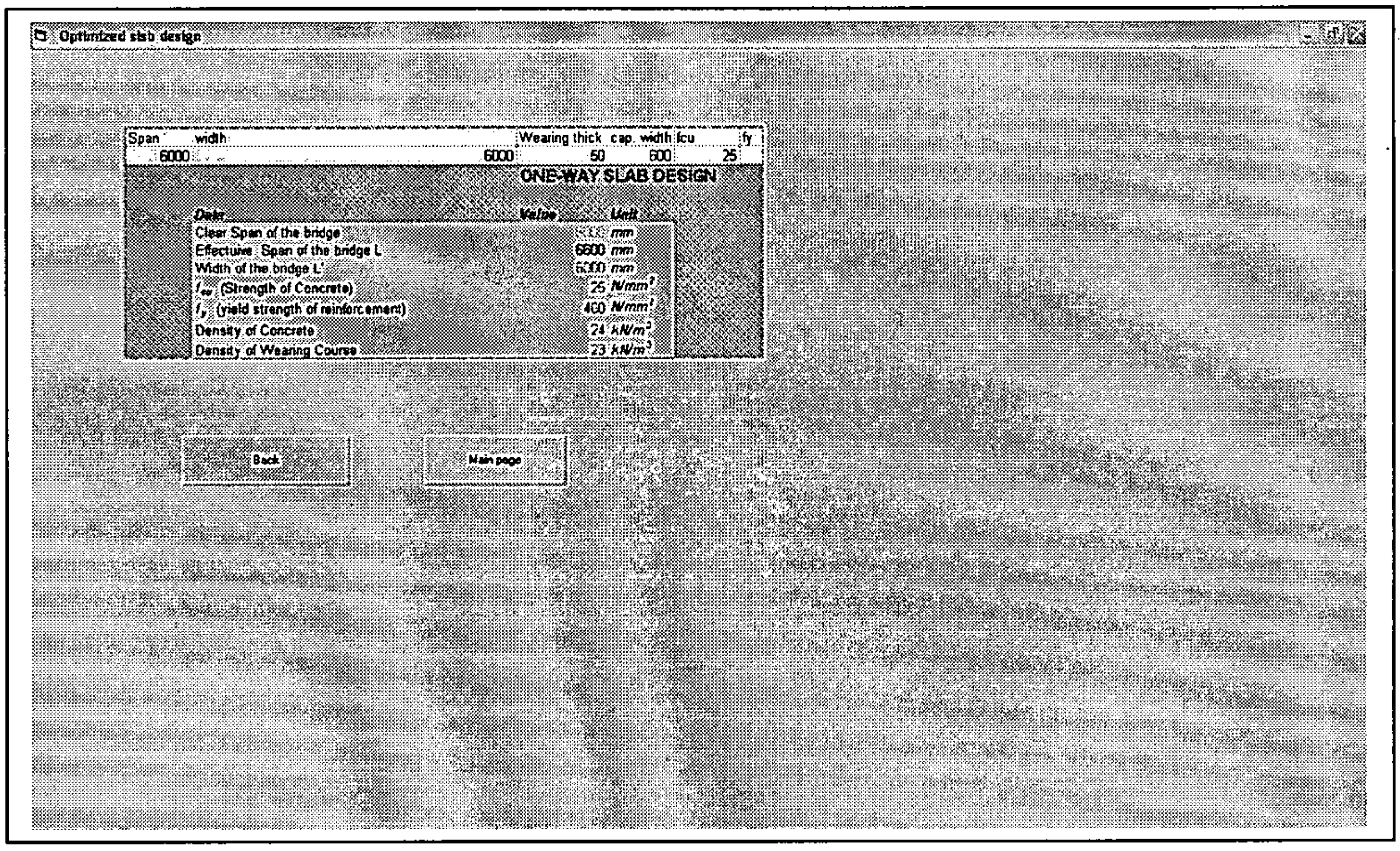
Point load per lane: 120

No.of notional lanes: 2

Cover: 50

Bar diameter: 25

Effective depth of the slab: 400

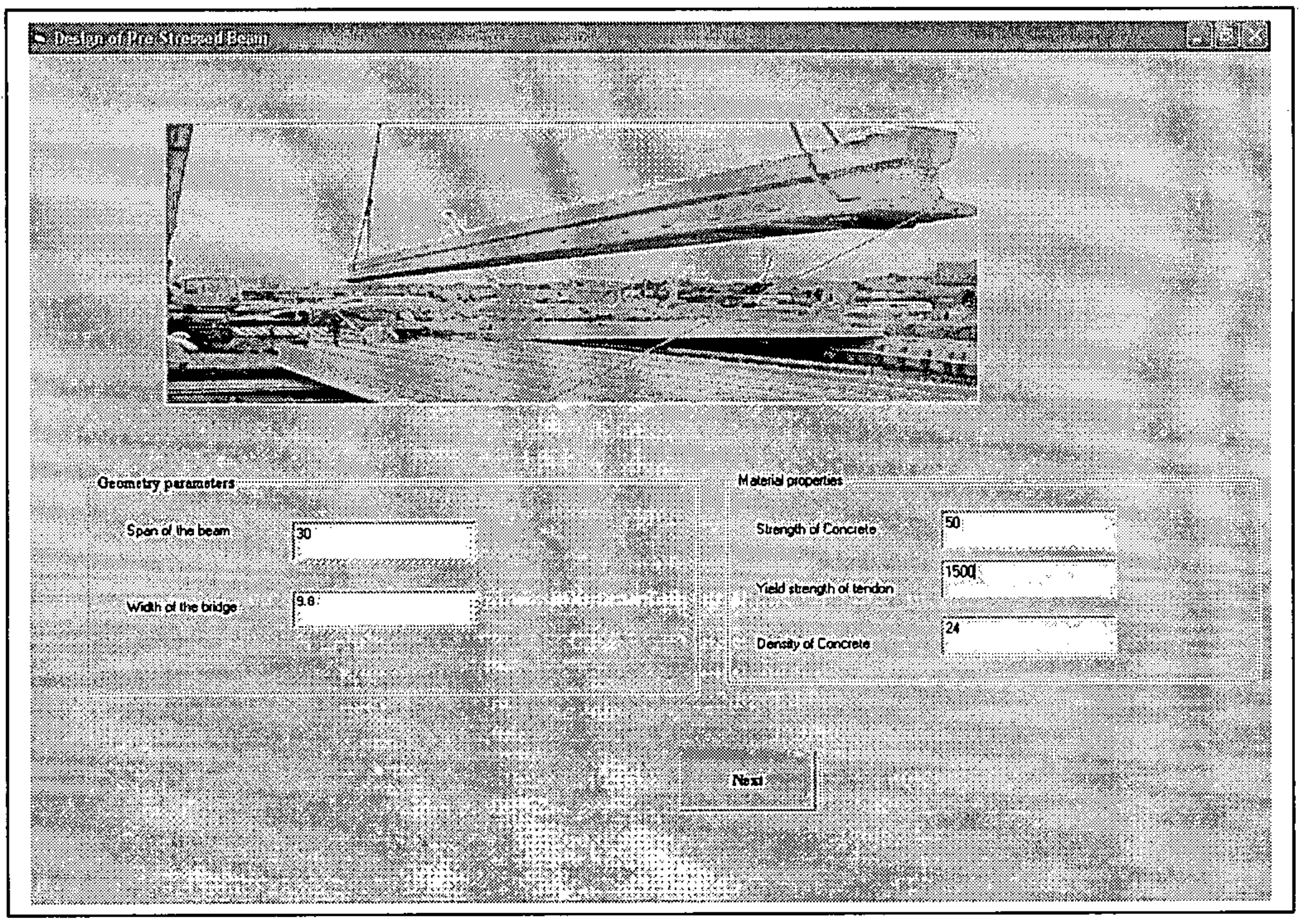


Span	width	Wearing thick	cap. width	fcu	fy
6000	6000	50	600	25	

ONE-WAY SLAB DESIGN

Data	Value	Unit
Clear Span of the bridge	6000	mm
Effective Span of the bridge L	6600	mm
Width of the bridge L'	6000	mm
f_{cu} (Strength of Concrete)	25	N/mm^2
f_y (yield strength of reinforcement)	400	N/mm^2
Density of Concrete	24	kN/m^3
Density of Wearing Course	23	kN/m^3

Design of Pre-Stressed beam:



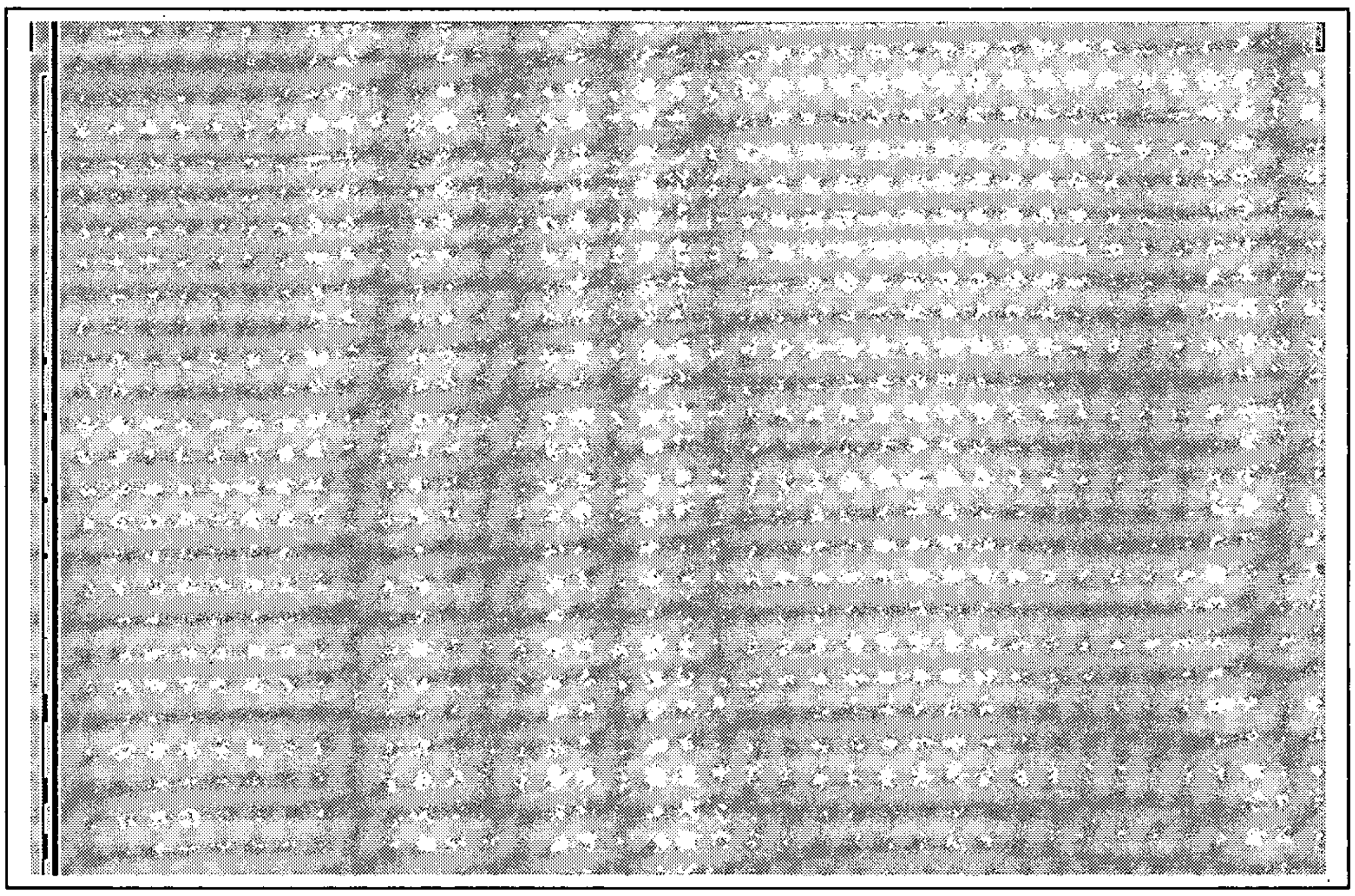
Span of the beam: 30

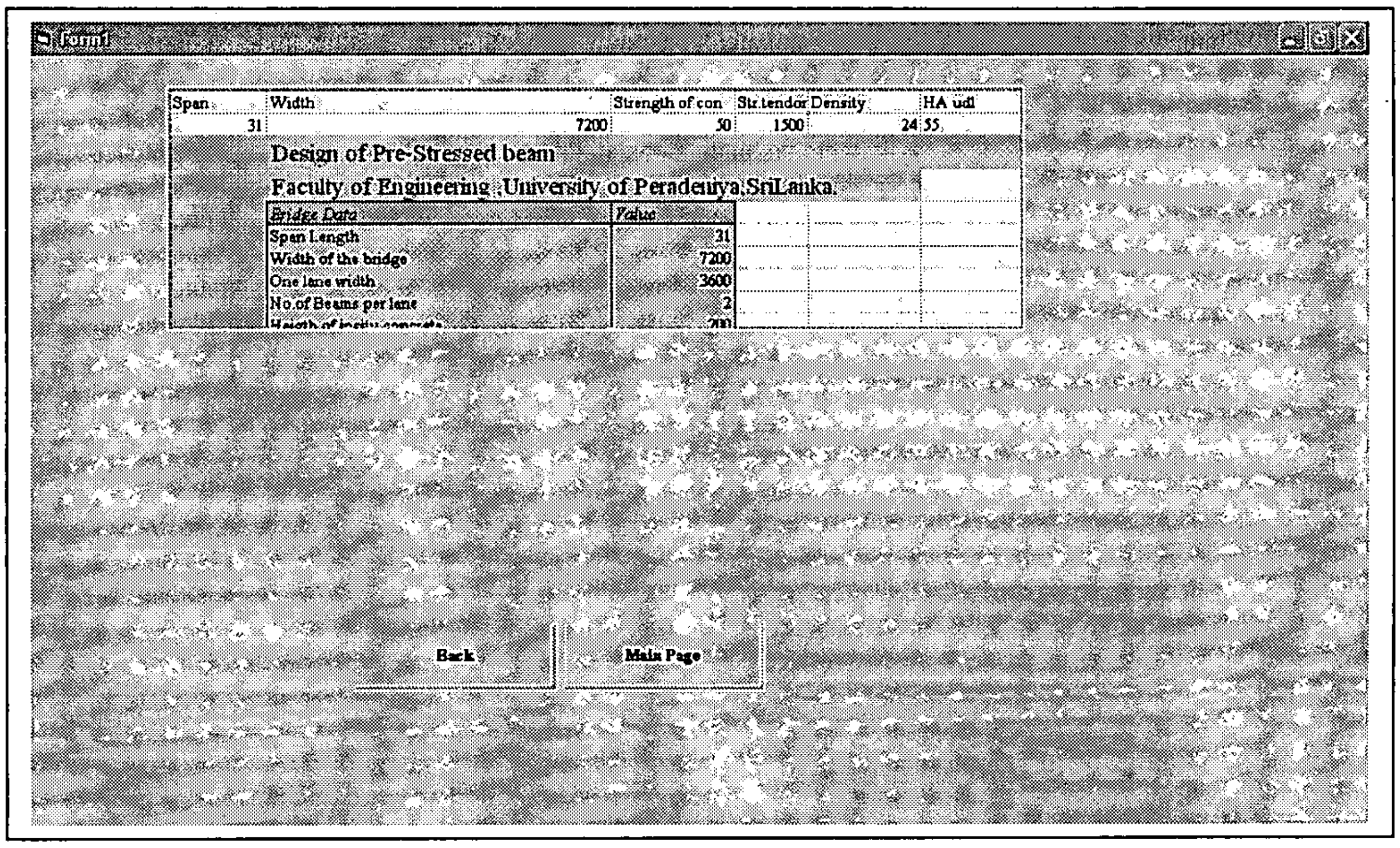
Width of the bridge: 9.6

Strength of Concrete: 50

Yield strength of tendon: 1500

Density of Concrete: 24





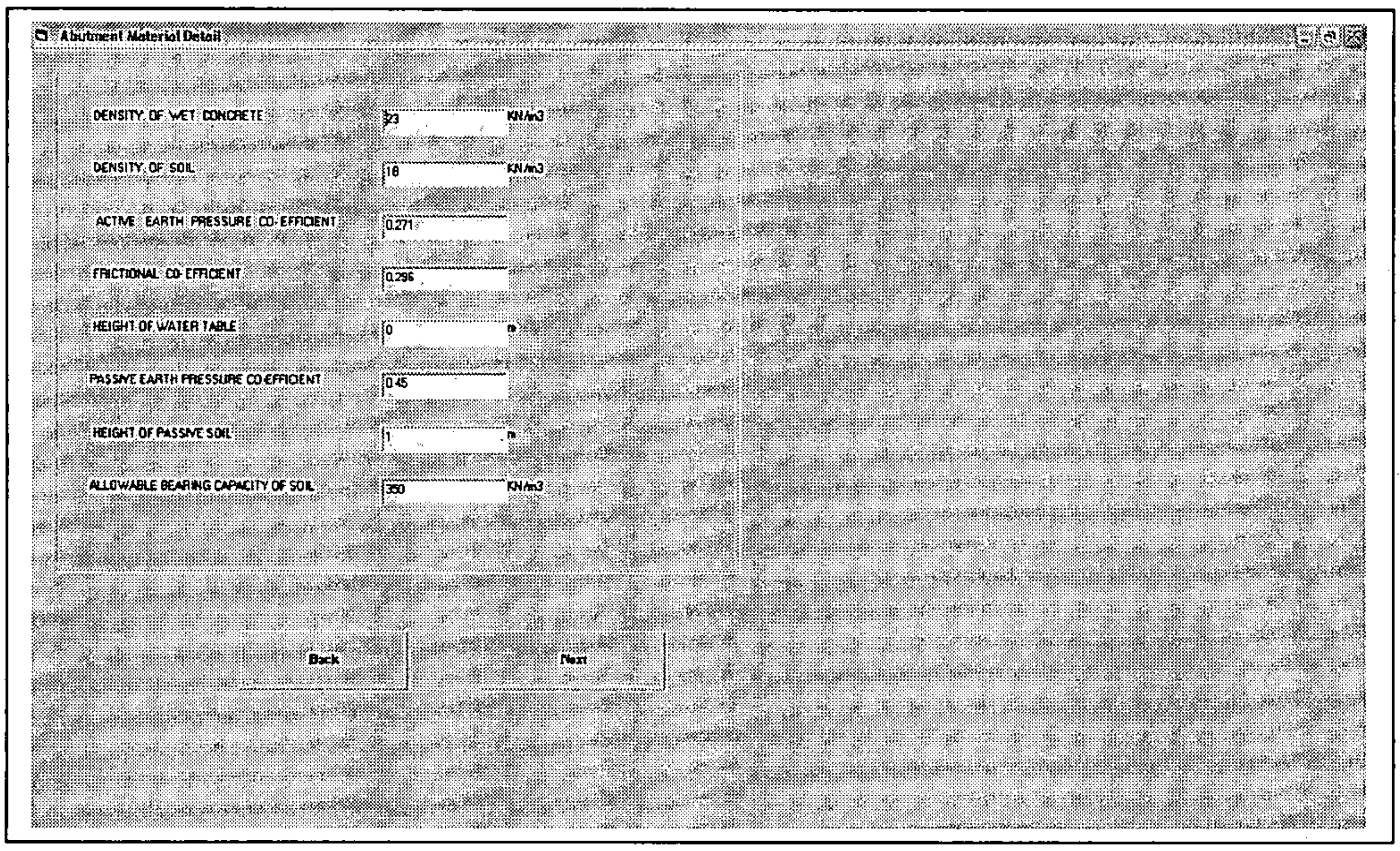
Span	Width	Strength of con	Str.tendor	Density	HA udl
31	7200	50	1500	24	55

Design of Pre-Stressed beam

Faculty of Engineering ,University of Peradeniya,SriLanka.

Bridge Data	*Value*
Span Length	31
Width of the bridge	7200
One lane width	3600
No.of Beams per lane	2

Design of Abutment:



DENSITY OF WET CONCRETE: 23 KN/m3

DENSITY OF SOIL: 18 KN/m3

ACTIVE EARTH PRESSURE CO-EFFICIENT: 0.271

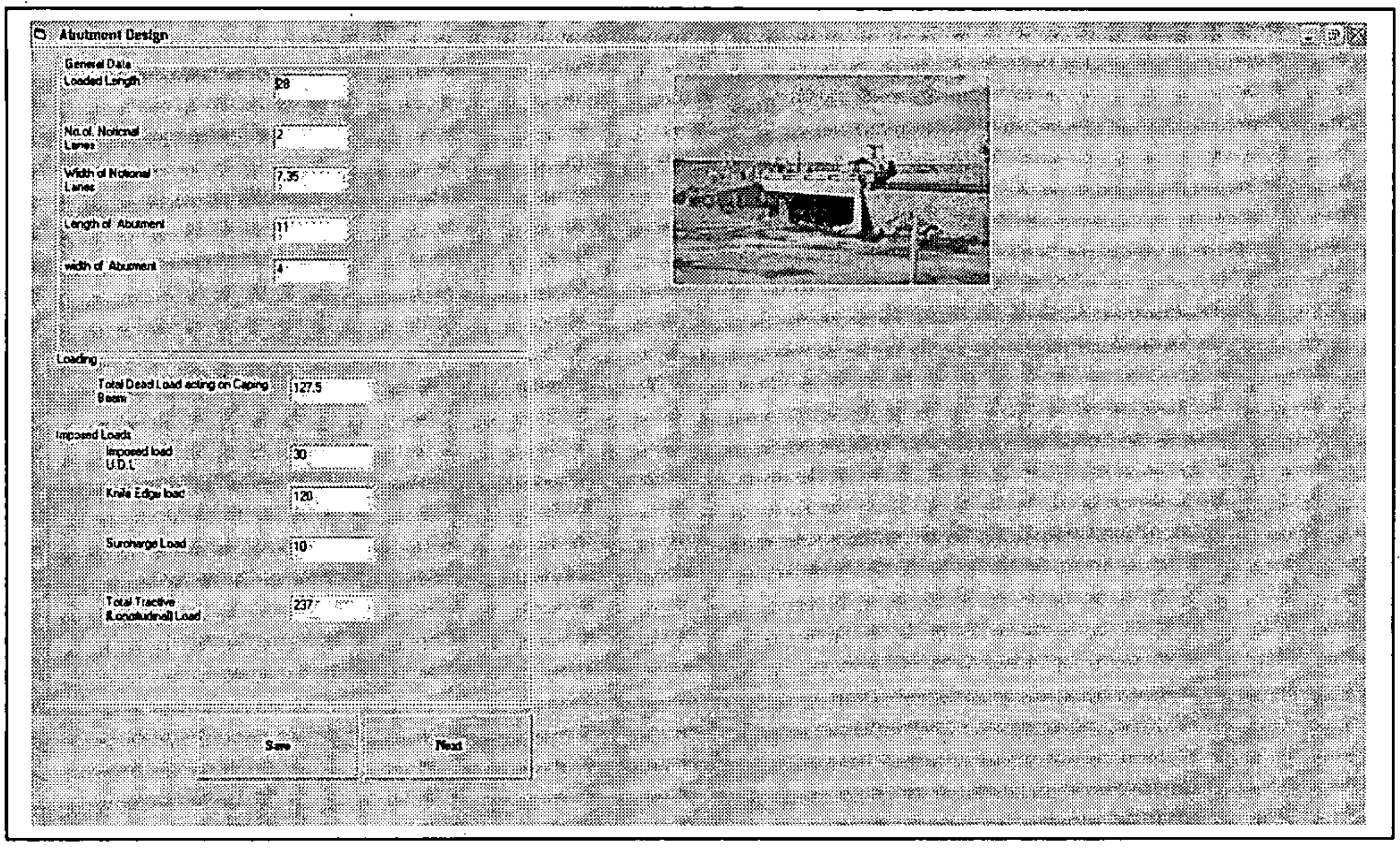
FRICTIONAL CO-EFFICIENT: 0.296

HEIGHT OF WATER TABLE: 0 m

PASSIVE EARTH PRESSURE CO-EFFICIENT: 0.45

HEIGHT OF PASSIVE SOIL: 1 m

ALLOWABLE BEARING CAPACITY OF SOIL: 350 KN/m3



General Data

Loaded Length: 28

No.of. Notional Lanes: 2

Width of Notional Lanes: 7.35

Length of Abutment: 11

width of Abutment: 4

Loading

Total Dead Load acting on Caping Beam: 127.5

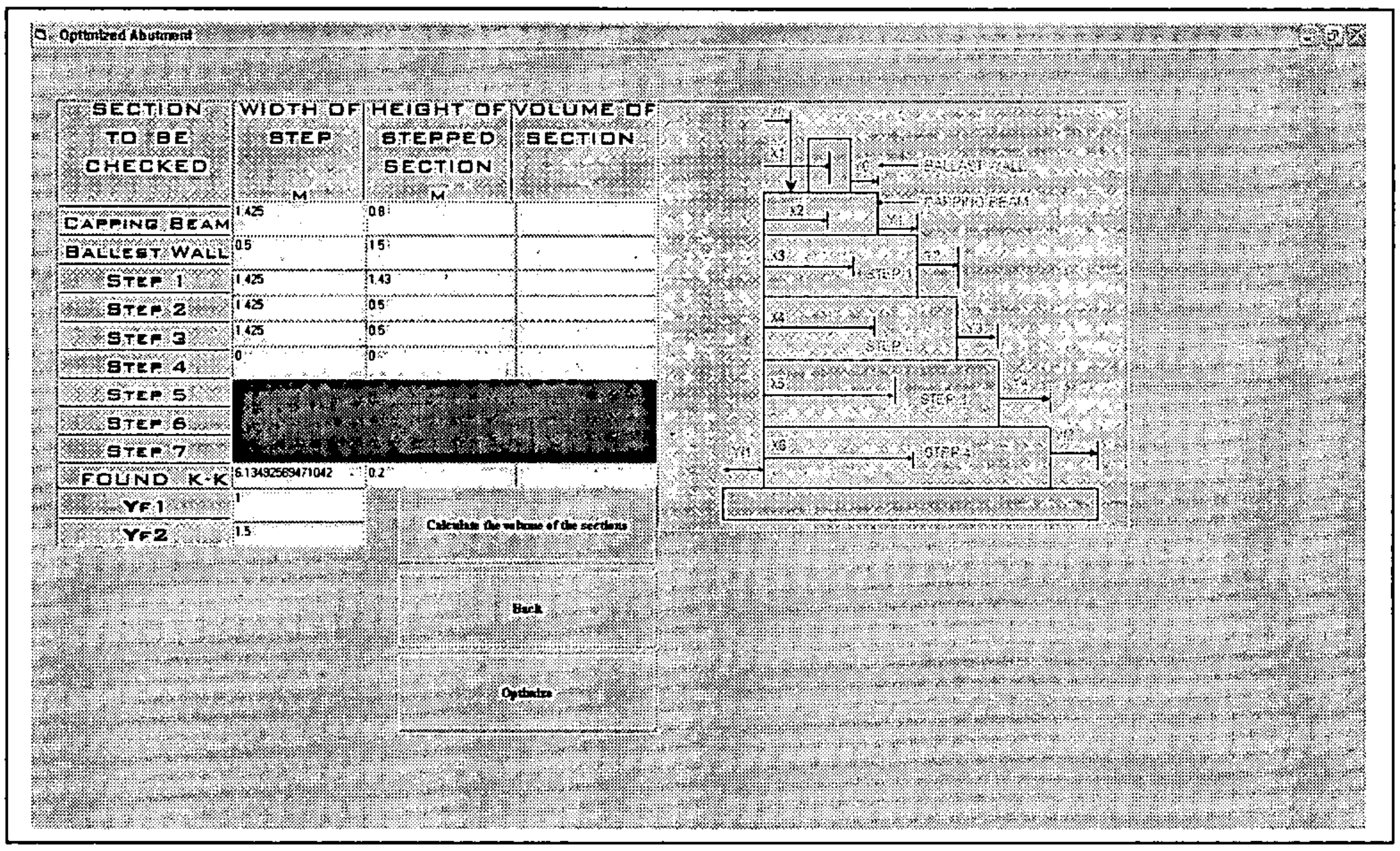
Imposed Loads

Imposed load U.D.L: 30

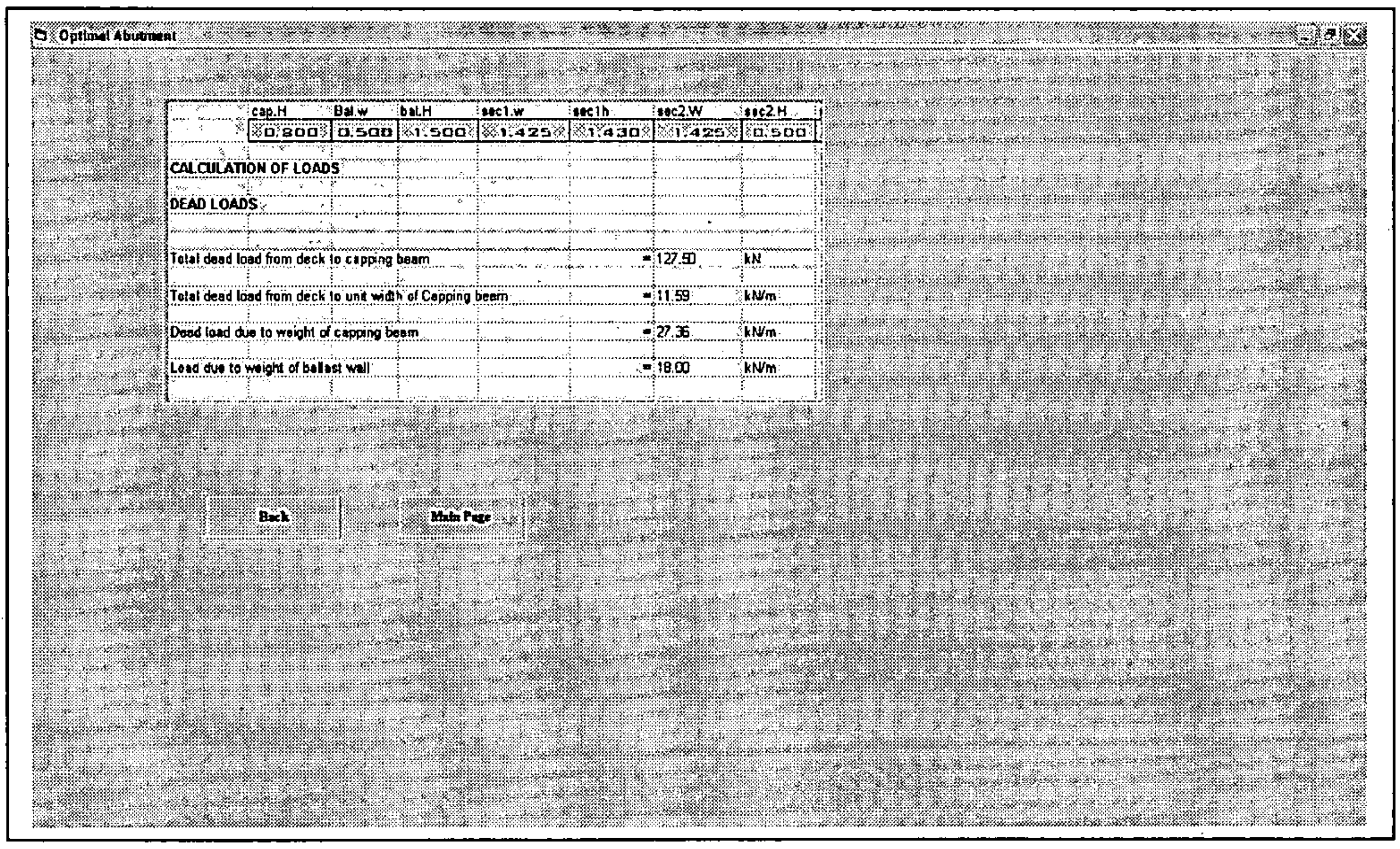
Knife Edge load: 120

Surcharge Load: 10

Total Tractive (Longitudinal) Load: 237



SECTION TO BE CHECKED	WIDTH OF STEP M	HEIGHT OF STEPPED SECTION M	VOLUME OF SECTION
CAPPING BEAM	1.425	0.8	
BALLEST WALL	0.5	1.5	
STEP 1	1.425	1.43	
STEP 2	1.425	0.5	
STEP 3	1.425	0.5	
STEP 4	0	0	
STEP 5	[redacted]	[redacted]	[redacted]
STEP 6	[redacted]	[redacted]	[redacted]
STEP 7	[redacted]	[redacted]	[redacted]
FOUND K-K	6.13492569471042	0.2	
YF1	1		
YF2	1.5		



	cap.H	Bal.w	bal.H	sec1.w	sec1h	sec2.W	sec2.H
	0.800	0.500	1.500	1.425	1.430	1.425	0.500

CALCULATION OF LOADS

DEAD LOADS

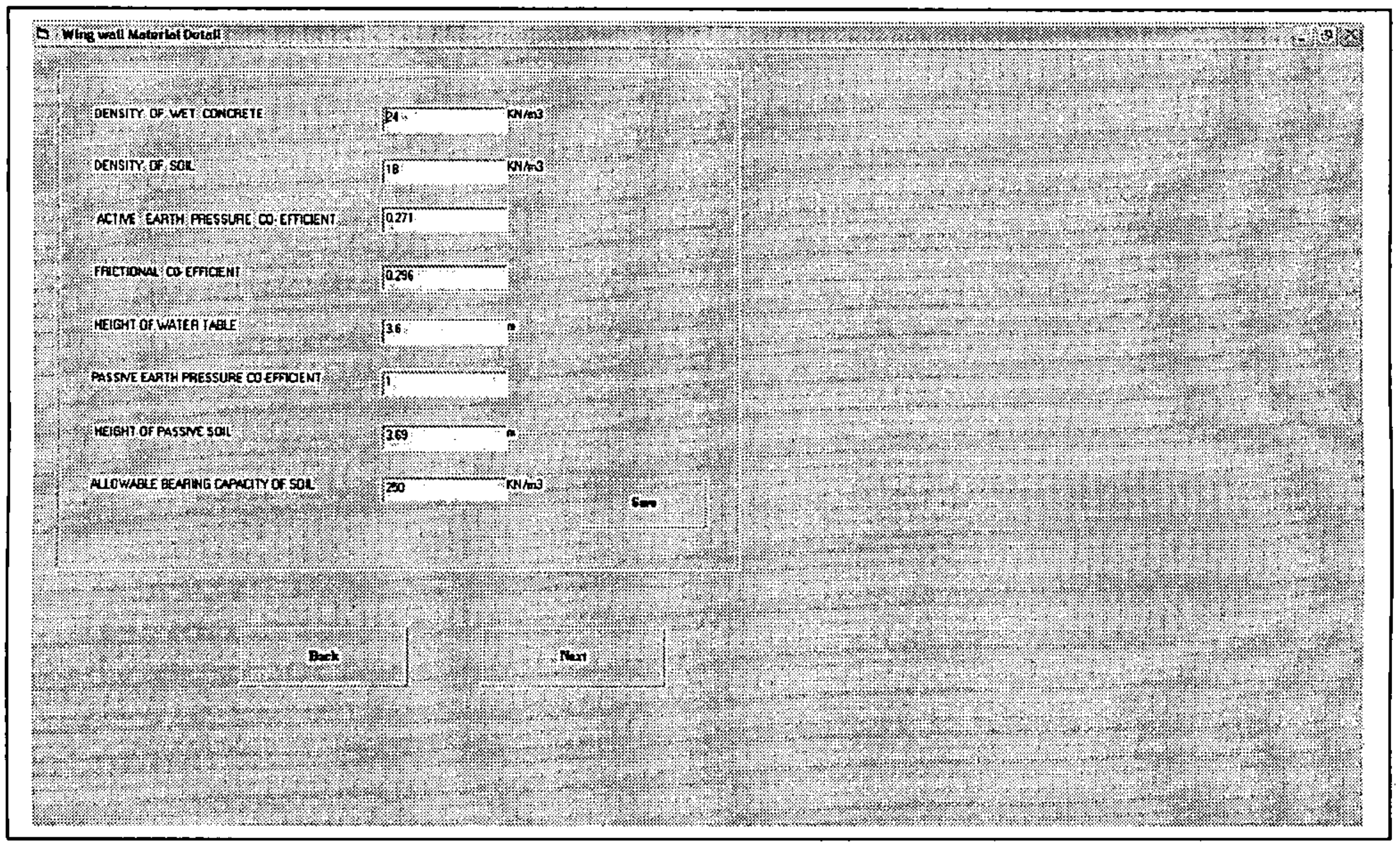
Total dead load from deck to capping beam = 127.50 kN

Total dead load from deck to unit width of Capping beam = 11.59 kN/m

Dead load due to weight of capping beam = 27.36 kN/m

Load due to weight of ballast wall = 18.00 kN/m

Design of Wing wall:



DENSITY OF WET CONCRETE 24 KN/m3

DENSITY OF SOIL 18 KN/m3

ACTIVE EARTH PRESSURE CO-EFFICIENT 0.271

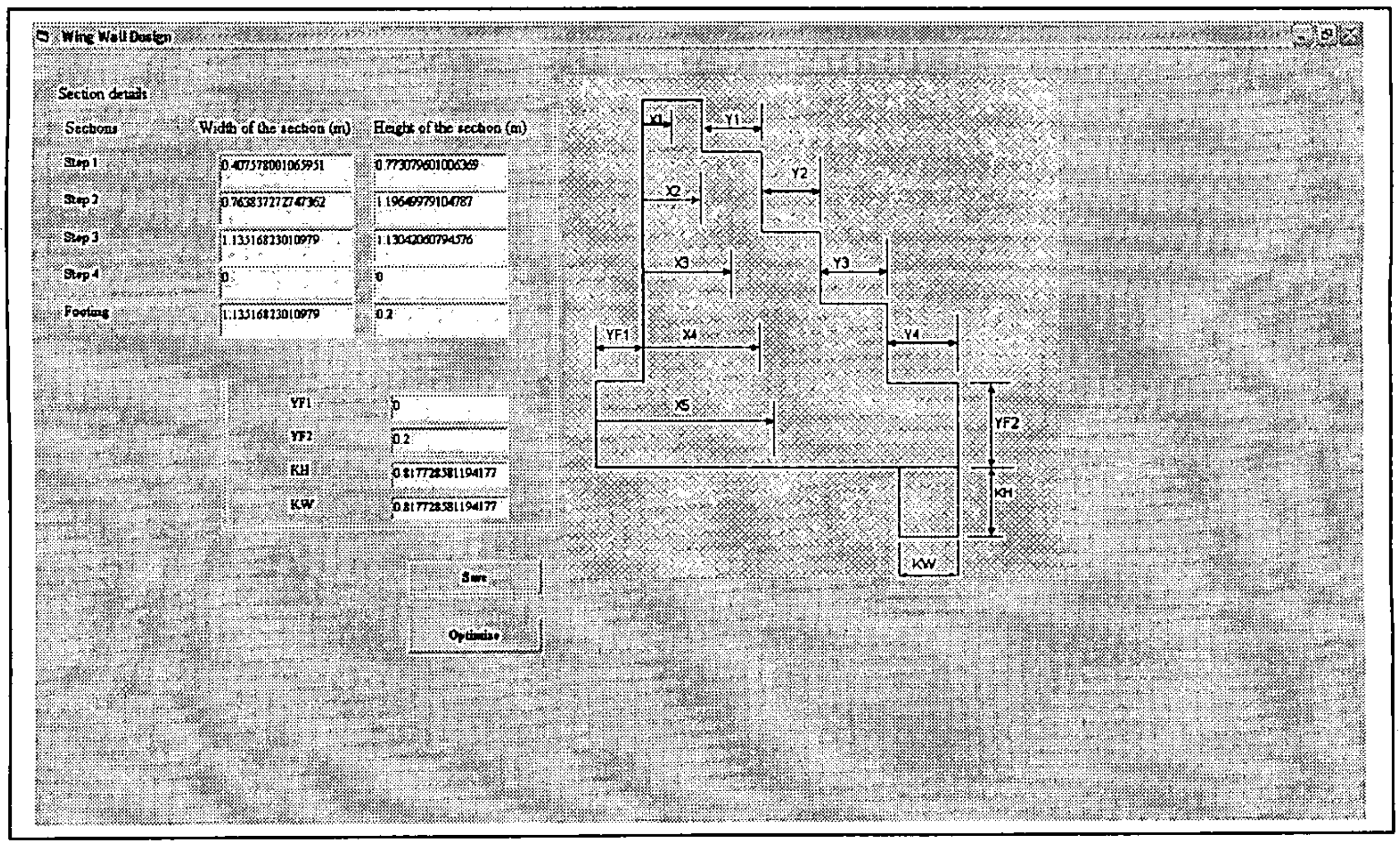
FRICTIONAL CO-EFFICIENT 0.296

HEIGHT OF WATER TABLE 3.6 m

PASSIVE EARTH PRESSURE CO-EFFICIENT 1

HEIGHT OF PASSIVE SOIL 3.69 m

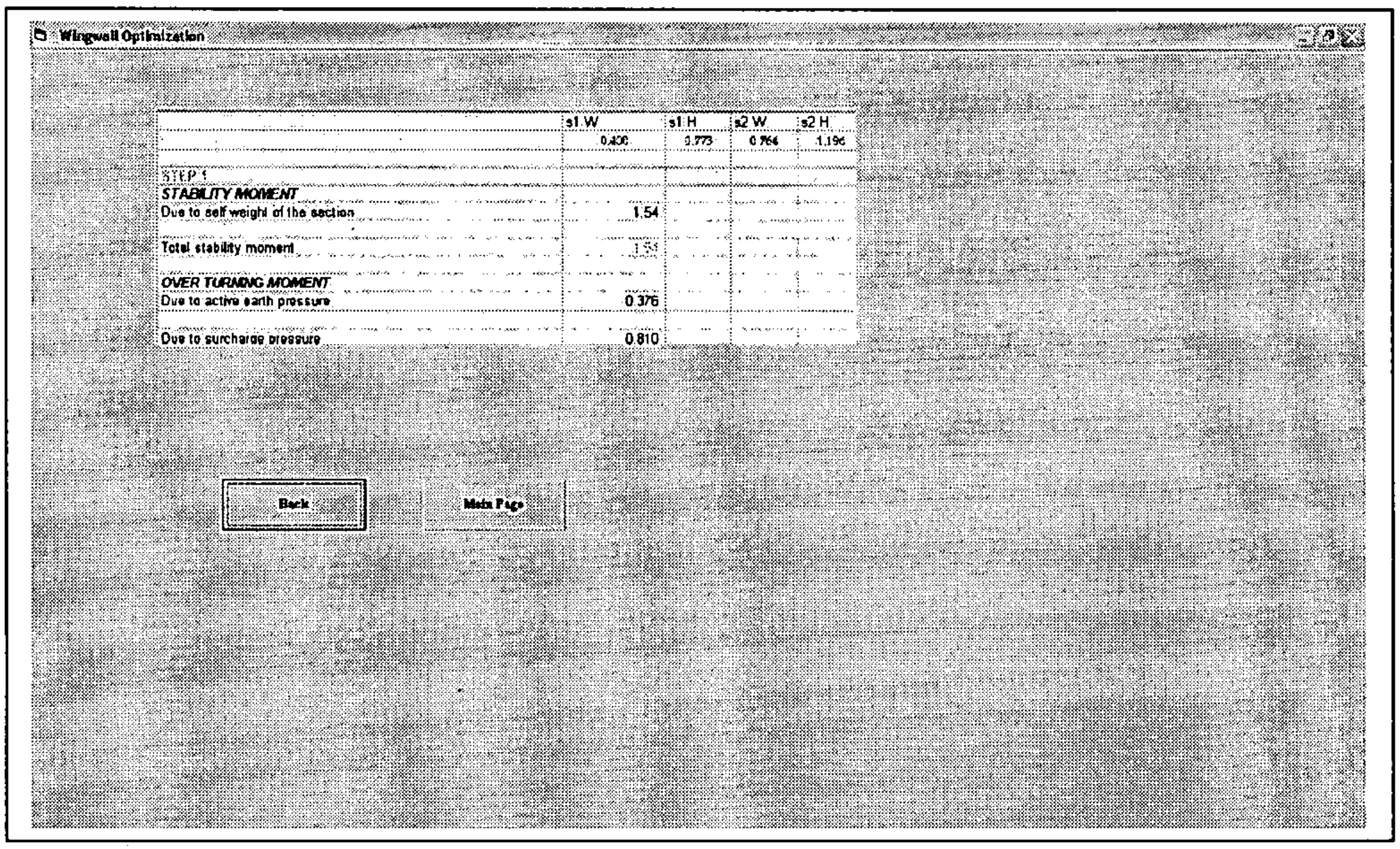
ALLOWABLE BEARING CAPACITY OF SOIL 250 KN/m3



Section details

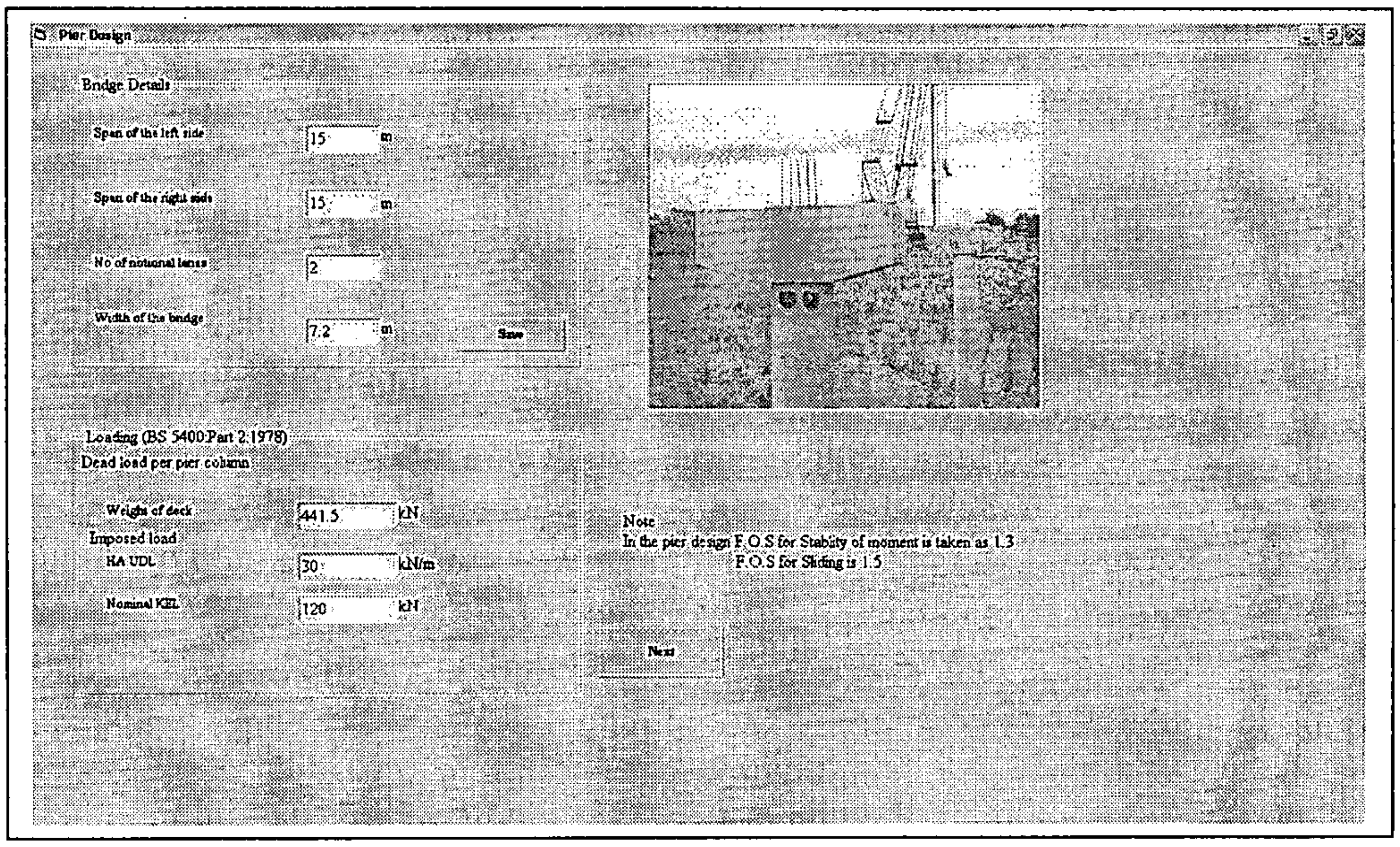
Sections	Width of the section (m)	Height of the section (m)
Step 1	0.407578001065951	0.773079601006369
Step 2	0.763837272747362	1.19649979104787
Step 3	1.13516823010979	1.13042060794576
Step 4	0	0
Footing	1.13516823010979	0.2

YF1	0
YF2	0.2
KH	0.817728581194177
KW	0.817728581194177



	s1 W	s1 H	s2 W	s2 H
	0.400	0.773	0.764	1.196
STEP 1				
STABILITY MOMENT				
Due to self weight of the section	1.54			
Total stability moment	1.54			
OVER TURNING MOMENT				
Due to active earth pressure	0.376			
Due to surcharge pressure	0.810			

Design of Pier:



Bridge Details

Span of the left side 15 m

Span of the right side 15 m

No of notional lanes 2

Width of the bridge 7.2 m

Loading (BS 5400 Part 2:1978)

Dead load per pier column

Weight of deck 441.5 kN

Imposed load

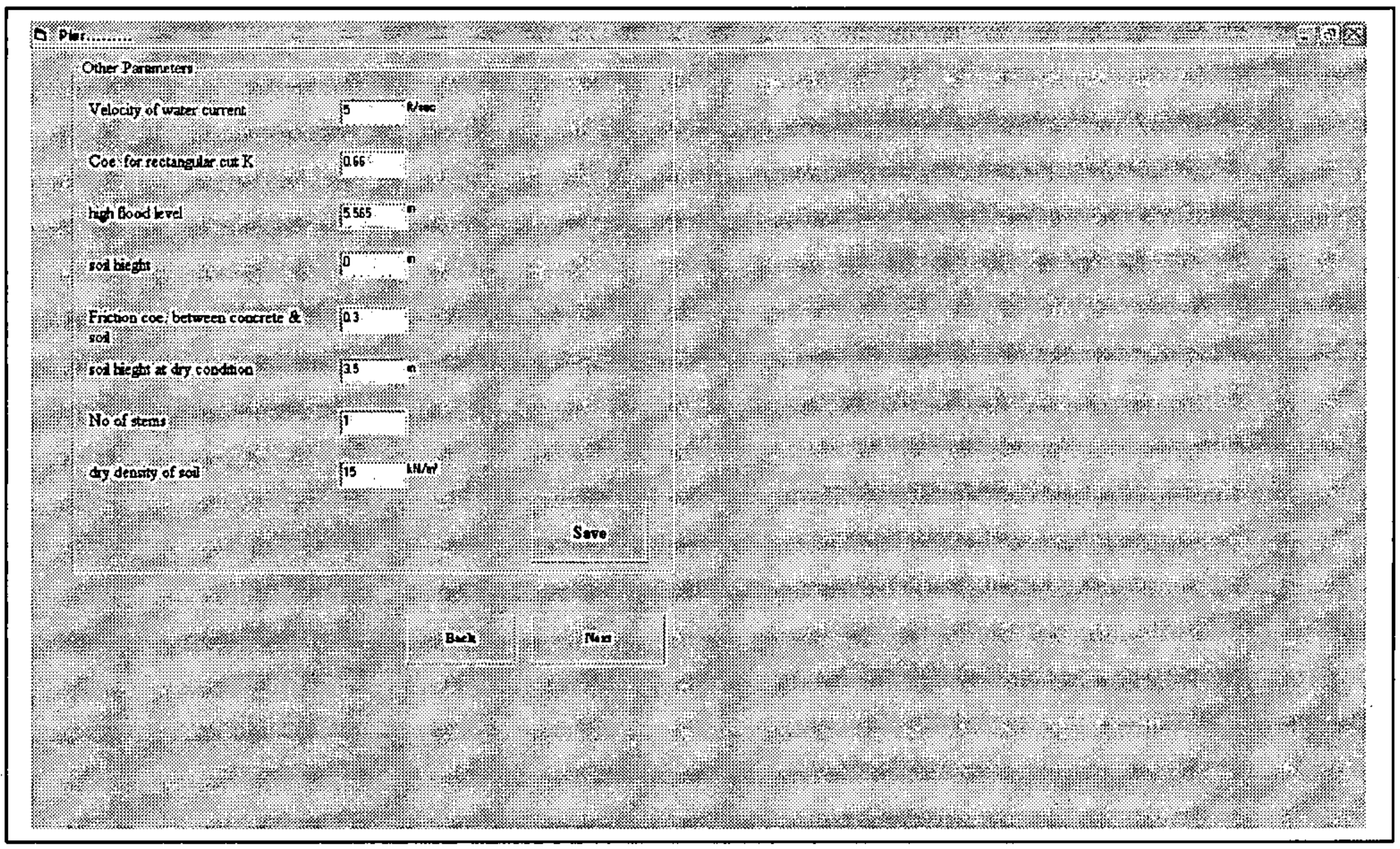
HA UDL 30 kN/m

Nominal KEL 120 kN

Note

In the pier design F.O.S for Stabilty of moment is taken as 1.3

F.O.S for Sliding is 1.5



Other Parameters

Velocity of water current 5 ft/sec

Coe: for rectangular cut K 0.66

high flood level 5.565 m

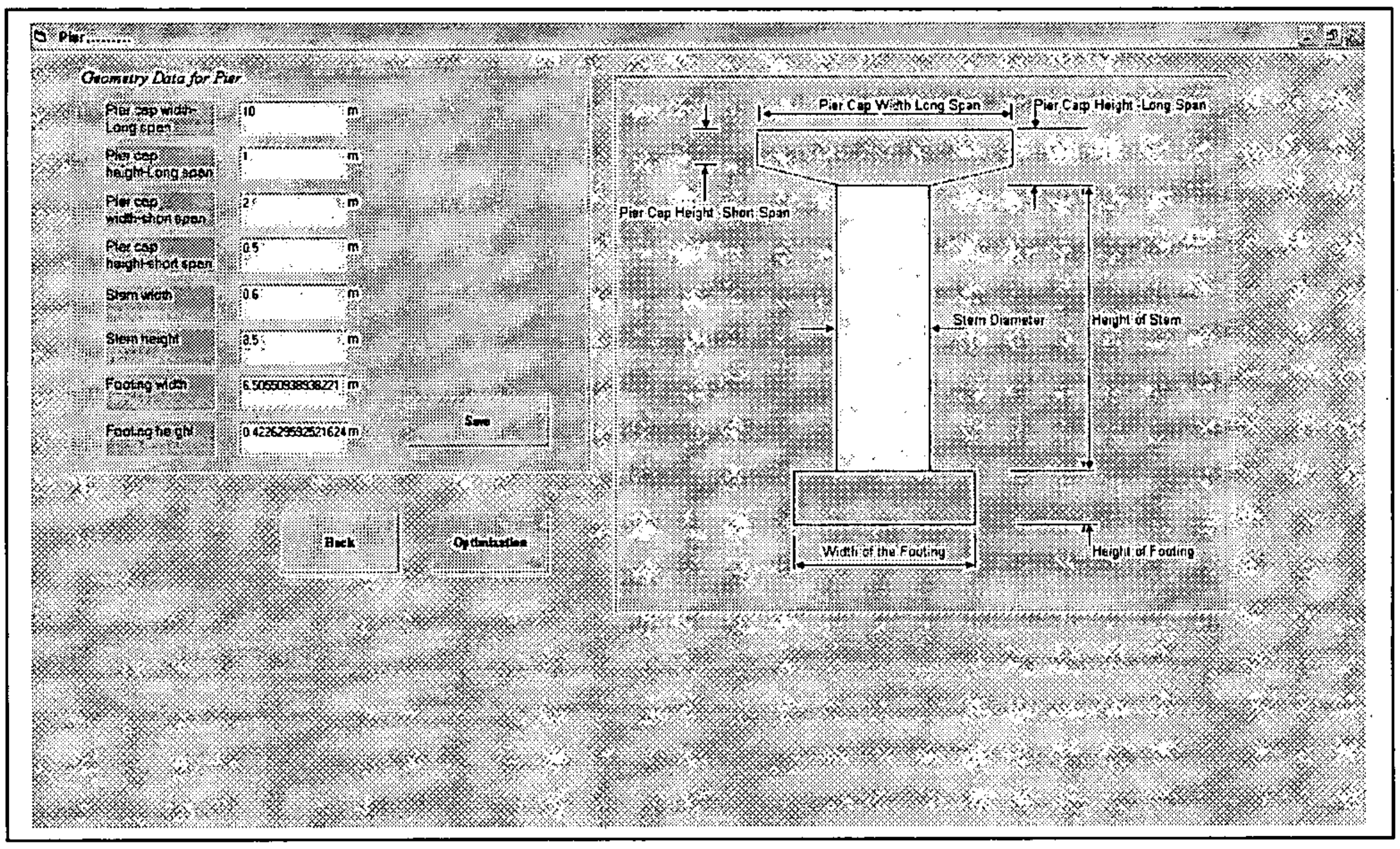
soil hieght 0 m

Friction coe: between concrete & soil 0.3

soil hieght at dry condition 3.5 m

No of stems 1

dry density of soil 15 kN/m³



Geometry Data for Pier

Pier cap width-Long span 10 m

Pier cap height-Long span 1 m

Pier cap width-short span 2 m

Pier cap height-short span 0.5 m

Stem width 0.6 m

Stem height 8.5 m

Footing width 6.50550938938221 m

Footing height 0.422629592521624 m