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An automated approach for an optimised least cost solution of reinforced concrete reservoirs using site parameters

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ABSTRACT

This paper presents design, development and application of a finite-element based least cost optimisation model (named ResOp) for reservoirs using a Genetic Algorithm. The model makes use of site specific parameters not normally considered at outline design but which are usually available; such as site plan limits, maximum height above ground level and geotechnical conditions.

The results show that such site based parameters have a significant effect on cost which can be easily incorporated at outline design stage without making expensive changes at the detailed design stage of a project. This would also be suitable when considering a selection of sites. Current cost models in the industry are too basic and should become more site specific.

The design of a reservoir constructed in Cornwall was compared to an optimised reservoir design using ResOp. The results show a potential for substantial savings to be made. The aspect ratio and shape found reasonable correlation to best practice, but the developed model suggests a more refined optimisation approach which includes site variables.

1. Introduction

Reinforced Concrete (RC) is extensively used due to its thermal properties and its resilience to chemical attack, particularly in underground or partially buried reservoirs. A reinforced concrete reservoir can be almost any shape or size and the storage tank can be elevated above ground, at ground level or below ground level. In the past waterbars were used extensively for RC reservoirs, but due to leakage and maintenance issues monolithic construction has been more popular. Concrete reservoirs also can have a healing process which can repair cracks that appear on the face that is in contact with water. Autogenous healing can occur for cracks up to 0.3 mm wide [20].

Although many mathematical optimisation techniques have been available in research for decades, it has only been a recent development that the latest structural design software now incorporates these more complex design refinements. As the building project lifecycle has relied more heavily upon software, and the costs and the environmental impact of civil engineering projects have been scrutinised in recent years, a trend has been found toward the optimisation of structures which can lead to cost reductions of design, construction, maintenance and demolition. This in turn reduces material wastage and material transport away from site.

Scia Engineer by Nemetschek is a commercial structural engineering graphical software system for design, calculations and verifying various codes of practice. It uses the latest technology of Object Orientated CAD conforming to buildingSMART's 'openBIM' standards. It is capable of analysing models created using other Building Information Modelling (BIM) compatible software and can use the imported objects directly in the analysis. It conforms to the latest Eurocode 2 Part 3 for the design of liquid retaining and containment structures which can design crack widths propagating from the surface of the concrete. Scia Engineer uses XML (Extensible Mark-up Language) as its main communication between third party programs and its output. The benefit of this language is that the output can easily be created in the form of a readable document.

Visual Basic for Applications (VBA) is the programming language built into all MS Office programs for its Component Object Model (COM) programming model. Excel and Scia Engineer fully support this COM programming model and therefore shall be used in this project as the link between the two programs but the code shall be executed in MS Excel.

Global optimisation is less well known in design of reinforced concrete reservoirs as the procedures are far more complex and require more computation. Scia Engineer has much documentation

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on optimisation and global optimisation using a Genetic Algorithm. MOOT (Multi-Objective Optimisation Tool) can adjust the size, length and properties of almost any element and optimise the location of supports as well as performing cost optimisation [3]. However global optimisation is limited as the relationship between each member can become too complex for the current MOOT release.

This paper presents the development and application of a model that automates the design of reinforced concrete reservoirs using the Finite Element Method (Scia Engineer code) and a Genetic Algorithm. These are used to optimise the shape, structural element sizing and amount of reinforcement determined by least total cost using steel reinforcement and concrete volumes. The reservoir must be rectangular but may be any length and is available for many uses such as storm tanks, service reservoirs, raw water storage or an underground chamber.

The model has been called 'ResOp' (shortened from Reservoir Optimisation) and is based in Microsoft Excel due to its widespread availability and use of its VBA (Visual Basic for Applications) functionality. Some original features of ResOp are that it can either have one or two cells and columns may be included at any equal spacing and to any number required. There is also a parameter which can specify the soil stiffness at different depths of soil to suit conditions found on site. The output is a more accurate estimate of material costs (concrete and steel) which can be applied before the detailed design stage has begun. It can also be an aid at detailed design stage to find an appropriate solution efficiently without manual iteration or 'intelligent guessing'.

The model is intended to integrate a Genetic Algorithm and the latest innovations in research with the latest modelling software to make it more attractive to the wider construction industry. Currently the authors are not aware of any commercial programs that have the ability to optimise such a structure. Some less detailed programs are available but are very limited in their application.

2. Genetic Algorithms

Genetic Algorithms (GAs) as efficient algorithms for solution of optimisation problems have been shown to be effective at exploring large and complex search spaces in an adaptive way guided by the equivalent biological evolution mechanisms of reproduction, crossover and mutation. They are random search algorithms which have been derived based on the "Darwin's theory of survival of the fittest". A Genetic Algorithm operates on a population of trial solutions that are initially generated at random. It seeks to maximise the fitness of the population by selecting the fittest individuals from the population and using their "genetic" information in "mating" operations to create a new population of solutions. Genetic Algorithms have many advantages over the traditional optimisation methods. In particular, they do not require function derivatives and work on function evaluations alone. They have a better possibility of locating the global optimum because they search a population of points rather than a single point and they allow for consideration of design spaces consisting of a mix of continuous and discrete variables. In addition, a GA can be set in a way to provide a set of acceptable optimal or near-optimal solutions (rather than a single solution) from which the most appropriate one can be selected. The probabilistic nature of GA helps to avoid convergence to false optima [15].

2.1. Genetic Algorithm optimisation using GANetXL 2006

GANetXL is an add-in for Microsoft Excel, a leading commercial spreadsheet application for Windows and MAC operating systems. Excel supports programming with Visual Basic for Applications (VBA). GANetXL is a program that uses a Genetic Algorithm to solve a wide range of single and multi-objective problems [22]. The benefit of this add-in program is its ease of use and the implementation of a GA in a spreadsheet environment that can be applied to a variety of problems.

3. Current practice in optimal design of reservoirs

In the past optimisation has mainly concentrated around the improvements that are made to structures by human experience and by following tables of shape ratios and selecting individually designed elements not connected to the overall structure. A popular set of tables found in 'The design of water-retaining structures' provided coefficients that could be applied to moments and forces in order to determine a generally more accurate and optimised result [2]. These ratios were based on research carried out by the Portland Cement Association of America and utilised assumptions such as the type of fixity on the walls and slabs as well as the pressure acting on the structure with the exclusion of soil conditions [4]. It suggested using these tables as a manual check to a computer technique such as FEM. The shapes of these water retaining structures were limited to rectangular, circular and conical shapes between certain size ratios.

Structurally the most efficient shapes are cylindrical and conical, this is because the wall section can be fully utilised under hoop stress from the internal liquid pressure with little bending moment. Any external pressure, so long as it is equal around the perimeter, can be efficiently supported by the concrete under compression. However treatment processes may not work effectively in a circular container which is why rectangular reservoirs are often required.

Rectangular RC reservoirs can either be jointed or monolithic in design. In both cases the optimum aspect ratio is approximately 1.5 in plan when there are two compartments (cells) for maintenance [12,19]. A jointed reservoir was the most popular form of construction in the past.

A jointed reservoir has movement joints to allow for thermal, flexural and tensile movement. The reinforcement usually stops either side of the joint so that a hinge is formed, which cannot transfer bending moment. Although the design can require less reinforcement (particularly in the transverse direction) these joints contain a waterbar which can be poorly constructed and which have become notorious for leakage [16]. Therefore jointed reservoirs have become less well used except in very large reservoirs because of the maintenance issues that are inherent with movement joints in contact with pressurised water.

Since the 1980s to the present, monolithic reservoirs have become more popular due to improved codes of practice that can better model crack widths, ground models can now better represent site conditions and piling has become cheaper allowing monolithic reservoirs to be built in areas previously unfeasible [19]. Steel reinforcement is continuous through the construction joint in the interface and so forces and moments can be transferred. Construction joints in a monolithic reservoir may not require any preparation before the next pour as long as the next concrete pour occurs within a relatively short timescale. If more time is required during construction then a hydrophilic strip may be placed in the centre of the wall as added security against leakage. A hydrophilic strip expands on contact with water which can seal minor breaks in the construction joint.

4. The need for further optimisation

The report entitled 'Rethinking Construction' [13] noted the need to modernise by investing more in research and development of technology which was also highlighted later in 'Constructing