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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 the Team' [17]. This is occurring with BIM which instigates a need for better communication between clients, designers and contractors throughout the building lifecycle. Due to developments in technology and speed of computation, the optimisation process can be shifted closer to conceptual stage of a project. This will improve processes at the phase where changes are more likely to affect the overall project cost. By considering the structural concept early in design one is able to avoid the costs of possible redesign later in the project where changes to the design (or during construction) are more expensive. For projects such as reservoirs there is usually detailed site information early in the design or concept stage.

5. Latest optimisation methods

There are relatively few research papers on the subject of optimising the structural elements of a building and even fewer papers on reservoirs. A two-dimensional frame was optimised by a GA and proved that it could handle discreet elements effectively [10]. The probability of crossover was 0.85 and the probability of mutation was 0.05 for a population of 50 over 50 generations. Further research was found into the optimisation of concrete structures using a heuristic flexible tolerance method, however, this research was done before mathematical optimisation algorithms were well established in civil engineering applications and does not go into detail about water tanks [21]. Sarma and Adeli [21] state that most optimisations of concrete structures were for concrete beams and girders. Conical steel water tanks have been optimised by utilising FEM and GA's particularly on elevated water towers with reductions of around 30% from standard design methods without optimisation [14]. A population size of 100 was used in the simulation. El Ansary et al. noted the superiority of Genetic Algorithms in many previous structural problems.

The optimisation of reinforced concrete reservoirs has been performed against the respective codes of practice in the country of research. Tan et al. [23] presented design of reinforced concrete cylindrical tanks using the British Standard BS8007 with a simple FEM analysis and direct optimisation techniques stating that initial feasible designs can be found using this method. This analysis was useful at the time due to the speed of this calculation, however, when compared to current FEM packages and high computational capacity this is less relevant. A more recent paper using analytical models optimised both circular and rectangular reservoirs but used simplistic optimisation methods for parametric study without the use of FEM [18]. The results showed that this was able to reduce the cost of the reservoir by shape optimisation based on the Indian codes of practice. Another relevant paper was the optimisation of a cylindrical and conical reservoir by three evolutionary algorithms and FEM. The models were based on the American Concrete Institutes building code requirements ACI 318M/318R-99. Although this optimisation uses complex algorithms, it has been limited by the fixed radius of the base and varies only by the angle of wall from vertical. Using a size of the mesh between 50 mm and 150 mm the results of this paper found the Shuffled Complex Evolution algorithm to produce the best results against the Simulated Annealing and the Genetic Algorithm. Genetic Algorithm, however, provided some similar results to the Shuffled Complex Evolution algorithm but this did take longer to run. The cost optimisation was found to be between 20% and 40% but the authors of the paper concede that there was no global reference available [1]. Recent literature has found the Shuffled Complex Evolution algorithm to be critically deficient when optimising complex nonlinear hydrological systems and improvements were made to this technique [11]. Again, no single optimisation technique has been effective for all global optimisation problems.

Optimisation found, in the limited number of research papers on the subject, was inclined towards the cost of materials and not necessarily labour, plant, formwork or temporary works [1]. This is because each of these additional costs change by region and the material costs of formwork do not necessarily represent its total cost.

Review of the current literature has highlighted a lack of application to genuine civil engineering problems of construction material costs to site constraints. Although many of the theories presented have been applied to theoretical problems they have not been used in the context of a practical design tool in real world projects of RC reservoirs. All research found did not consider partially or fully buried liquid retaining structures or 'site specific' issues. Soil conditions were not specifically considered although many were based upon elevated structures that directly connect to the structure base, which was not designed as part of the model. Soil conditions are known to be an important aspect in the design of RC reservoirs due to high loading [16] and high groundwater levels increase the risk of flotation particularly when a tank is empty [19]. Also the research found did not investigate large rectangular reservoirs with columns and so limited the length of the walls considerably.

This paper aims to utilise known site parameters to determine material volumes that can improve the accuracy of the overall project cost along with the best sizing and location of the reservoir. This is directed at a stage in the construction project where engineering concepts are usually rudimentary and cost models are not based on current site information. Site parameters such as topography and soil conditions on projects involving reservoirs are usually known reasonably early in a project to investigate concept viability (a 'yes or no' analysis). Once a site is viable then a tool such as that proposed in this paper could be utilised before detailed design. Furthermore this tool could form the beginning of an optimal concrete reservoir within detailed design, using the latest codes of practice and optimisation techniques in an easy to use interface for planning engineers and technical engineers alike.

6. Development of the model

The program ResOp (Reservoir Optimisation) has been created which can automatically generate a model and loadings that can be calculated using FEM analysis and optimised using a Genetic Algorithm. The program, based in MS Excel, is a spreadsheet with an input sheet containing all of the parameters and variables required to calculate the most structurally efficient rectangular reservoir. Certain variables partially dictated by the user, called chromosomes, are used in the optimisation process of the Genetic Algorithm.

6.1. Connection to Scia Engineer

Scia Engineer is a design software that uses the latest Eurocodes and the latest modelling tools which were utilised for this project. The method of transferring information into Scia Engineer is through the use of an XML document. An XML document can be compiled with any parameters or outputs from the calculated current model in Scia Engineer. Using this XML output this may then form the basis of the automated updated model.

Scia Engineer has a program that runs directly in the Windows Command Prompt executable, and therefore does not use its graphical display, which is useful for third party programs. However to view the same process that occurs with ESA_XML one can manually insert the XML document into Scia Engineer's graphical interface to prove its application. ESA_XML updates an original model, performs a specified calculation and then exports the required data into a text file (or .xls file).

An XML file is created which includes all of the variables and set engineering values shown in Fig. 1. Scia Engineer updates a basic model file to the parameters specified in the XML file and a structural solution is modelled and then calculated. An additional calculation is then performed for the design of steel reinforcing bars. Once the calculation is completed the reinforcement output is exported into a spreadsheet.

It is worth noting that the steel design being used is based on EC 2 part 1 and not specifically for water retaining structures ; although codes are available they were not incorporated into Scia Engineer at time of writing [6–9]. Therefore the yield strength of steel was adjusted to 200 N/mm^2 and the result combination of SLS + ULS was used. This was done to provide similar reinforcement requirements to BS8007 water retaining structures code which can be adequate as a cost model [5].

6.2. Connection with GANetXL in Excel

GANetXL used the following reservoir variables as genes in the Genetic Algorithm:

- Length of reservoir *X* direction,
- Length of reservoir *Y* direction,
- Depth of reservoir below ground level,
- Width of base slab strip surrounding external wall (for local thickening),
- Base slab edge strip depth,
- Base slab main depth,
- Column spacing (ResOp uses this value and calculates to the nearest whole column),
- External wall thickness,
- Spine wall thickness,
- Roof thickness.

The fixity condition (pinned, sliding or fixed) at the top of the walls could be included as part of the optimisation; however, this is often a preference in terms of the construction sequence. Again the requirement to divide a reservoir into two cells is usually a specification and so cannot be optimised. A storm tank or tank for a similar purpose, however, may be specified as both a single-celled or double-celled tank and so could be optimised in this way to determine the lowest cost.

These genes are all constrained to upper and lower bounds which are mostly specified by the user. It is important that the upper and lower bounds are as wide as possible so that the best solution can be sought. The single objective from the Genetic Algorithm is minimum cost.

As described earlier, the steel reinforcement output from the program is sent to a separate spreadsheet once the FEA and design have been completed. The reinforcement results are then brought into the ResOp spreadsheet (Area&Volume sheet) and the whole cost of the reservoir is calculated for the Single Objective Genetic Algorithm. A penalty is given to the chromosome for errors in the calculation and for flotation failure.

The whole process is repeated with different gene values until the certain number of generations completes. The time to process each chromosome is between 1 min and 15 min depending upon the size of the model.

Certain parameters can be changed in the generic Scia Engineer model such as the size of the mesh (which if enabled in ResOp, can reduce the length and width of the element during progression of generations) and the use of iterative calculations. These parameters will also change the length of time to calculate a single chromosome. The Scia Engineer command executable calculation is the most time intensive part of ResOp's simulation. The whole simulation program is described in Fig. 2.

6.3. Investigation with soil conditions

Simple parametric modelling was performed to study the effects of soil stiffness seen in Fig. 3. The cost of the reservoir decreased with increasing soil stiffness of a reservoir with constant geometric dimensions. The volume of concrete remained the same and so only the reinforcement affected the resultant cost. These models were created to as an example of how soil conditions are important when considering cost models, particularly in poor ground conditions.

The resulting total costs of this example decrease with increasing soil stiffness in the form of a parabolic curve. This demonstrates that the cost of materials is more influenced at lower values of soil stiffness. As an example the difference in cost between 5 MN/m^2 and 50 MN/m^2 is 7% of the total maximum cost or £49,927 as seen in Fig. 3 of a 13Ml reservoir.

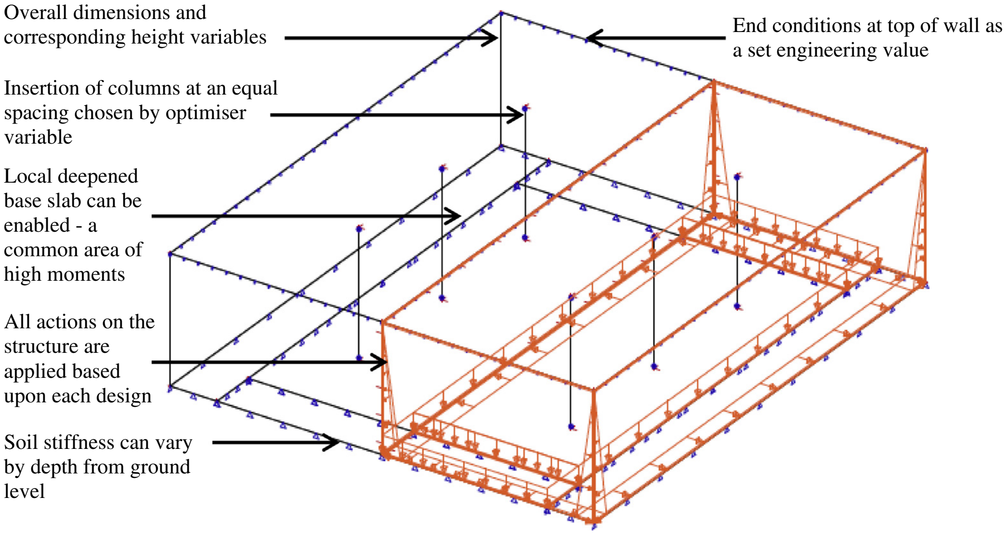

Fig. 1. Variables and set engineering values illustration.

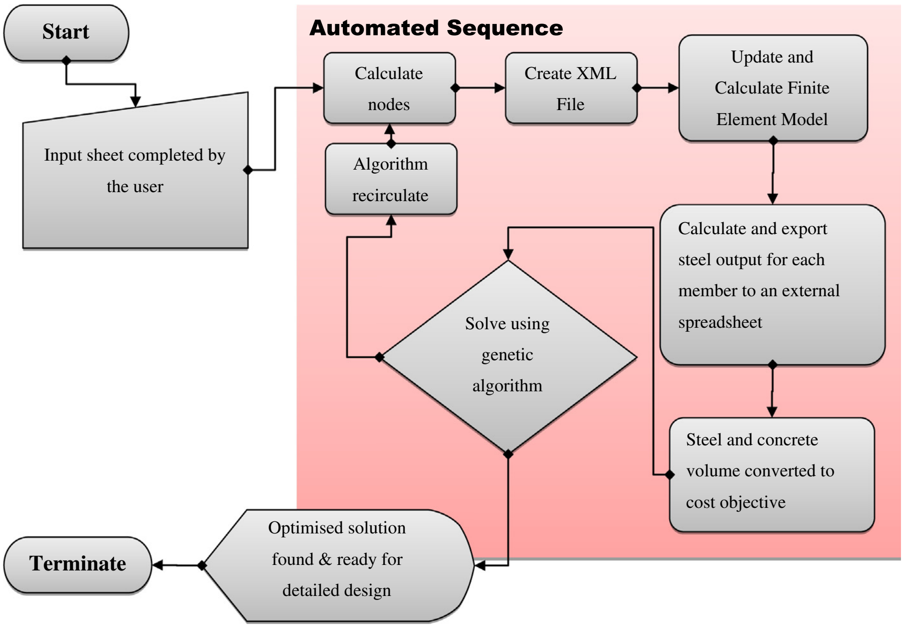

Fig. 2. High-level process chart describing ResOp.

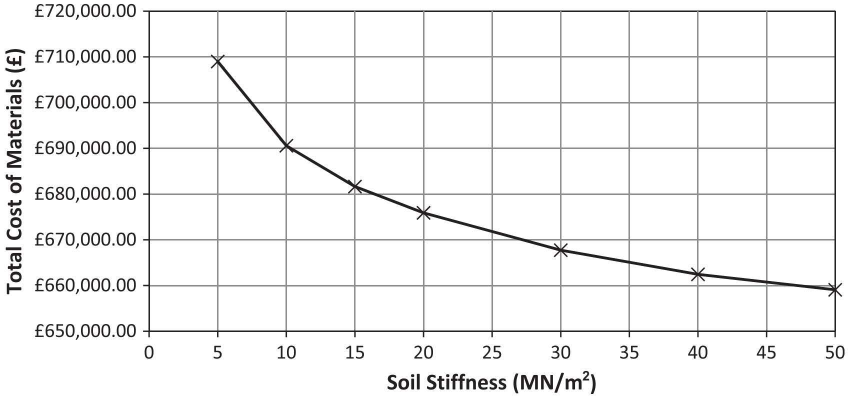

Fig. 3. Effect of soil stiffness on the material cost for a 13Ml reservoir (volume: 65 m × 30 m × 7 m with spine wall).

Although not conclusive, this exercise suggests that the soil stiffness curve will be at an even steeper gradient at the lower stiffnesses when applying additional liquid volume without an increase in area on plan. This conclusion is suspected because an increase in load on the base and walls could extenuate the amount of reinforcing steel as the settlement of soil increases. Further analysis could be conducted using this method for both higher and lower mass using the same plan dimensions as well as using the same analysis on a reservoir without a spine wall and without a roof and fixity conditions at the top of the wall. Therefore accurate geotechnical information can make a large difference to the overall cost of a reservoir, which is why it is included as a parameter in ResOp.

7. Model set-up

The Genetic Algorithm was set to a population of 50, a probability of single point crossover of 0.90 and a mutation rate of 0.10 over 50 generations. These values were chosen for several reasons including previous research, from instructions for GANetXL (and experts who have used the software in other applications) and due to time constraints. A wider population and further generations would have been preferable but would have taken more time to calculate. However the results were found to be adequate for its current purpose.

7.1. Reservoir optimisation design conditions for 13,000 m^3 volume

Design conditions for this reservoir are specified in and are based on a real-world example of site conditions for a water treatment works (see Table 1).

7.2. Results of reservoir optimisation for 13,000 m^3 volume

The results are compared to an existing project for a double celled reservoir 13,000 m^3 in Cornwall, UK. The optimisation process, starting from a random seed, reduced the cost from £641,706 to £506,706[1] which produced a reduction of £131,308 (over 21%) as shown in Fig. 4. The graph shows that there is a general trend towards a more optimised solution with a lowering of the

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[1] This cost figure increased when considering the final optimised solution. The more fine mesh at a 600 mm^2 average size found the cost to be £508,352. This higher figure and model was consequently used in the comparison of results.

Table 1
Design conditions for the optimisation of a 13,000 m^3 reservoir.

Condition	Value
Storage volume	13,000 m^3
Minimum head	5 m
Length 1 minimum	15 m
Length 1 maximum	85 m
Length 2 minimum	15 m
Length 2 maximum	85 m
Freeboard to top of reservoir	0.3 m
Soil stiffness between 99 and 92 m (Ground level @ 100 m)	Varies from 6 to 12 MN/m^2
Base slab	Variable depth
Column fixity	Pinned (top and bottom)
Spine wall	Yes
Roof slab	Yes
Height of soil	Dictated by depth into soil
Cost of concrete (per m^3)	£120.00
Cost of steel (per tonne)	£1,200.00
Average size of square mesh	1000 mm reducing to 600 mm[a]
Population size	50
Number of generations	50

[a] Mesh convergence analysis based on cost of a similar sized reservoir.

average cost for each generation. This proves the Genetic Algorithm is working towards a least cost solution.

The lowest cost model is shown at every generation progressing towards an optimal solution. The last lowest cost solution remained the same for 14 generations which may indicate a global optimal solution.

Due to the length of time required to calculate a solution the size of population and number of generations was quite low. The total time used for a computer with the specification; 2.40 Quad-Core Intel i5-2430 with 6 GB RAM running Windows 7 OS, took approximately 300 h. Each chromosome took between approximately 6 min and 12 min to process. The most time-intensive process of the calculation was the output of steel reinforcement quantities which included error checking. The entire process was automated with no errors preventing the program to finish successfully.

Fig. 5 compares displacement of both the optimised and the Cornwall design models. Settlement and displacements are within tolerable levels and are generally lower than the Cornwall reservoir. Bearing stresses for both reservoirs are within tolerable levels. The optimised reservoir requires some adjustment to the soil model due to some high bearing pressures on the external walls:

$$\text{Maximum Allowable Displacement} = \frac{4500}{300}$$
$$= 15\ \text{mm (based on column spacing)}$$

Fig. 6 illustrates the differences in cost between the optimal reservoir design in comparison to the Cornwall reservoir model. In particular the figure shows a difference in cost of the external walls and the base slab which produces a substantial saving for the optimised reservoir. Cost of concrete is directly related to its volume and reinforcement is related to averaged values of reinforcement areas. The volume of concrete for the optimised reservoir is lower overall than the model of the Cornwall reservoir. There is also a substantial reduction in the reinforcement as the steel costs are lower for every structural element except for the roof and columns which are only marginally higher. The roof for the optimised reservoir is larger in plan area and the number of columns is greater which can account for the increase in cost.

When interogating the steel reinforcement results the highest amount of steel reinforcement was found to be at the wall and the slab connections as this is where transfer of horizontal moments take place. The highest area of reinforcement was found to be 9566 mm^2/m although this was very localised so the reinforcement could be B32’s @ 100 mm c/c (8042 mm^2/m). Much of the reinforcement requirements can be achieved with B16’s @ 100 mm c/c (2010 mm^2/m). This indicates that the design is buildable after further detailed checks. The reservoir in Cornwall had a combination of bars ranging from B16’s @ 150 mm (1340 mm^2/m) to B32’s @ 150 mm (5360 mm^2/m) designed using a different FEM software.

The shape and size of the reservoir optimised by ResOp (Table 2) and the one designed and built in Cornwall (Table 3) had similarities indicating engineering experience and judgement are beneficial optimisation tools. However there were differences such as the height of the optimised solution, which was 1.9 m lower, and therefore has reduced forces acting on the wall. The remaining two prominent differences are those of the plan area and the section thicknesses. Firstly the plan area of the optimised reservoir is squarer, and requires a greater plan (although wider) area than the Cornwall reservoir. Secondly the wall and slab thicknesses are greatly reduced in the optimised solution except for the roof slab, which is equal in thickness. The column spacing for the optimised design is also similar to the spacing for the Cornwall.

As shown in Table 4, 13Ml reservoir optimised using ResOp has been found to be lower in cost than the 13Ml reservoir designed and constructed in Cornwall. There is a notable difference between the model reinforcing steel quantities, which was created using ResOp without the optimisation algorithm, and the actual construction reinforcing steel quantities. This can be partly explained by the inclusion of a valve chamber, sump, upstands and staired access into both cells and other details which were not included in ResOp. Also the factor for standardising the steel reinforcement for detailing may need to be increased. Thus increasing this factor

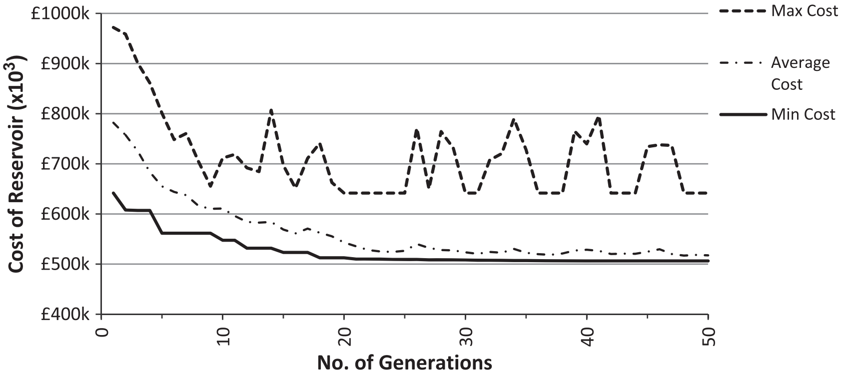


Fig. 4. Graph showing a reservoir optimised for 13,000 m^3 over 50 generations.

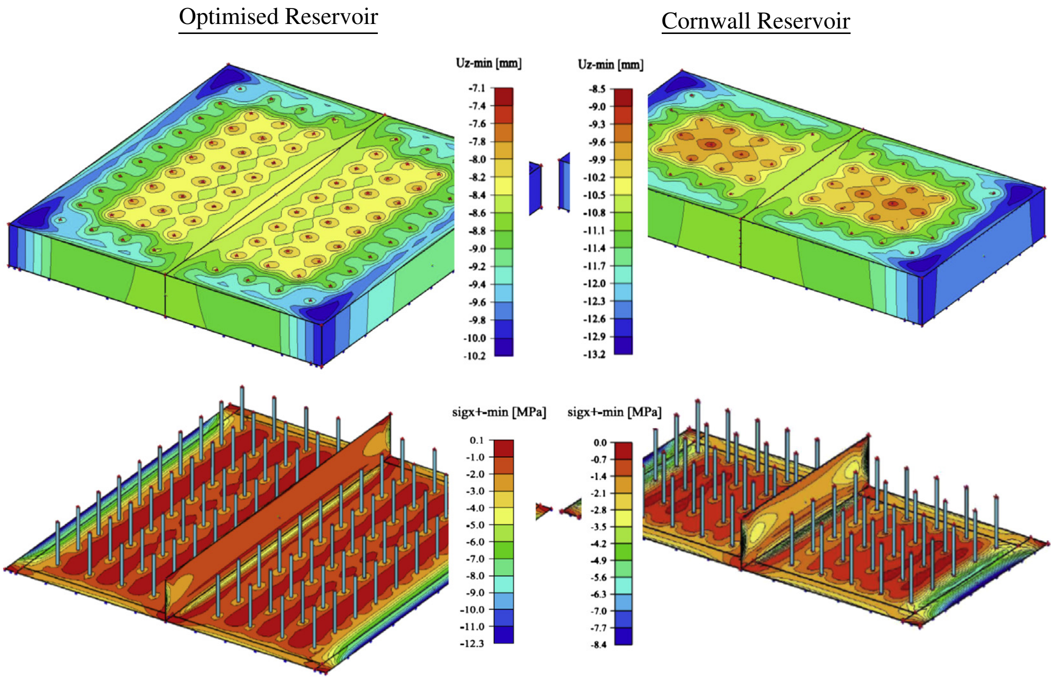
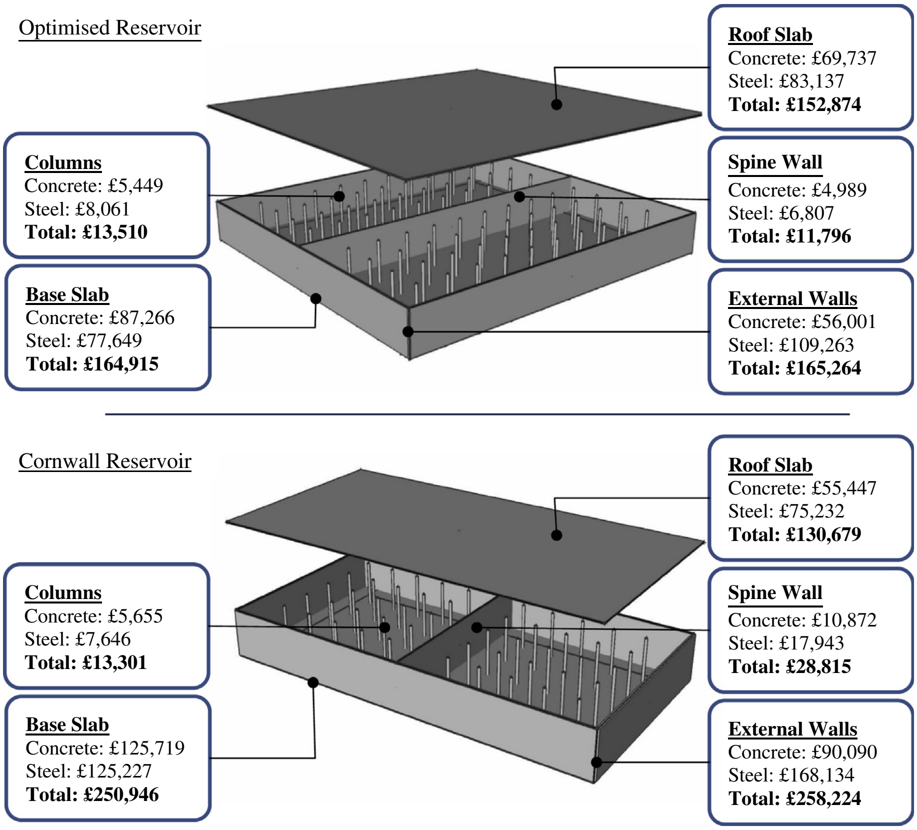


Fig. 5. Vertical displacement and bearing stress for both the optimal solution and the Cornwall 13,000 m^3 reservoirs.



Optimised Reservoir

Roof Slab
Concrete: £69,737
Steel: £83,137
Total: £152,874

Columns
Concrete: £5,449
Steel: £8,061
Total: £13,510

Spine Wall
Concrete: £4,989
Steel: £6,807
Total: £11,796

Base Slab
Concrete: £87,266
Steel: £77,649
Total: £164,915

External Walls
Concrete: £56,001
Steel: £109,263
Total: £165,264

Cornwall Reservoir

Roof Slab
Concrete: £55,447
Steel: £75,232
Total: £130,679

Columns
Concrete: £5,655
Steel: £7,646
Total: £13,301

Spine Wall
Concrete: £10,872
Steel: £17,943
Total: £28,815

Base Slab
Concrete: £125,719
Steel: £125,227
Total: £250,946

External Walls
Concrete: £90,090
Steel: £168,134
Total: £258,224

Fig. 6. Cost of concrete and steel comparison by key structural elements.

will bring the total cost of the model closer to the total actual construction cost. This is discussed in more detail later.

Direct comparison of the two models found that substantial savings can be made using the optimised solution. However this is not the final detailed design solution and there are two points worth noting. The first is that there was a very limited design area when considering the Cornwall reservoir which would have restricted the two length genes. The ResOp solution was not restricted to such a degree because the authors felt that a more open solution would prove the programs' intelligence more so than nar-

Table 2
Summary of output for 13,000 m^3 reservoir optimised by ResOp.

Storage volume	13,000 m^3
Length	46.98 m
Width	49.48 m
Height of reservoir	5.900 m
Depth of base below GL	6.408 m (soil stiffness 10.6 MN/m^2)
Edge of base depth	0.40 m
Middle base depth	0.30 m
Number of columns	80
Column spacing	4.70 m *X* direction 4.50 m *Y* direction
Spine wall thickness	0.30 m
External walls thickness	0.41 m
Roof slab thickness	0.25 m

Table 3
Summary of constructed service reservoir in Cornwall.

Storage volume	13,000 m^3
Length	60.4 m
Width	30.6 m
Height of reservoir	7.8 m
Depth of base below GL	7.200 m approx. (soil stiffness 6–12 MN/m^2)
Edge of base depth	0.75 m
Middle base depth	0.5 m
Number of columns	50
Column spacing	5.0 m *X* direction; 5.1 m *Y* direction
Spine wall thickness	0.4 m
External walls thickness	0.6 m base 0.4 top (tapered)
Roof slab thickness	0.25 m

rowing its options. The second is that the steel reinforcement is particularly high on the wall corners horizontal steel and the centre of the walls vertical steel which could be reduced if the wall section width were increased. Construction of this nature design may be possible but perhaps not practical on site without additional engineering geometrical input. For example the engineer may make small revisions to some parameters to improve buildability.

However the results show that improvements can be applied to; the base slab and walls which could have had a reduced section thickness for similar steel reinforcement results; the walls which can be shorter; and the whole reservoir which can be more square in plan to be able to realise potential savings of over £170,000. These results have shown that real cost savings that can be made in design of reservoirs using optimisation techniques.

8. Discussion

8.1. Size and shape

The aspect-ratio optimised from the simulations was between 1.1 and 1.4, which was lower than the ratio found in good practice of 1.5. This figure will vary according to volume anyhow, and may not influence the design as much if the external earth pressure is insignificant in the design or other such factors.

8.2. Steel reinforcement

The design of the steel reinforcement was carried out using Eurocode 2 Part 1 to a lower yield strength of steel, at 200 N/mm^2, in order to increase the area of steel reinforcement to a value closer to liquid retaining quantities. The actual yield strength currently used in construction is 500 N/mm^2. Scia Engineer did not incorporate Eurocode 2 Part 3 (Design of liquid retaining and containment structures) at the time of writing. Also two factors were included to allow for lap lengths and the application of practical steel sizes. The factor of practical steel sizes may have to be increased in future to allow for practical reinforcement detailing. There was a large cost difference between the constructed and the model reservoir. The amount of steel in the reinforcement schedule of the constructed reservoir was double that of the model. However this included stairs, parapets, sumps and a valve chamber. Also the cost of detailing steel reinforcement to satisfy good construction practice was probably more expensive than first realised. In order to lay out steel at equal centres and specify practical reinforcement the factor of steel could be increased from 1.2 to 1.5. This would mean a 50% increase in the average steel area calculated from Scia Engineer. Good detailing practice could improve this figure but more should be done to justify this factor.

8.3. Concrete section thickness

The section thickness of different structural elements is an important cost factor which is closely linked with reinforcement area. A thicker section can usually decrease the amount of reinforcement required in the section although the dead weight will increase. The section thicknesses observed were usually thinner than those used in practice, and this can increase the reinforcement area and may make such solutions impractical for construction. However ResOp can limit such solutions to a certain extent by restricting the genes which specify section thicknesses.

8.4. Intelligent design

Although a certain section can be quite thin over the majority of the wall, there are some very localised areas (usually at the connections to other structural elements) that may have impractical steel area requirements. ResOp has little intelligence with regard to these problems. The steel reinforcement requirements found from ResOp are currently averaged over a whole structural element (such as the North wall or roof). In order to make these results more realistic the results may need to be skewed more to the side of higher reinforcement to request greater section thicknesses. However further trials will have to be done to determine the amount of skew.

8.5. Depth into soil

It was observed that the depth into soil was 500 mm deeper than the total depth of the reservoir. This is possibly due to the increased soil stiffness found at this depth. This depth into soil

Table 4
Material and cost output comparison summary for 13Ml reservoirs.

Double celled reservoir	Material	Quantity (approx. m^3)	Cost (approx. £)	Total cost (approx. £)
Cornwall service reservoir	Concrete	2440 m^3	£292,800	
Actual	Steel	83 m^3	£801,083	£1,000,883
Cornwall service reservoir	Concrete	2398 m^3	£287,783	
Model	Steel	41 m^3	£394,182	£681,965
ResOp reservoir	Concrete	1862 m^3	£223,442	
Model	Steel	29.7 m^3	£284,916	£508,358

has been taken into account for the external walls but has not increased the load directly onto the roof. This has been thought to insubstantially increase the total cost. In practice this may be a design requirement of the site and can be considered further at detailed design.

9. Conclusion

Economies to a rectangular reinforced reservoir have been found through a Genetic Algorithm based on a combination of commercially available software. The cost savings could vastly outweigh the cost of the program and its components, particularly as most are readily available to many companies. The program ResOp does not eliminate the need for a structural engineer but can be used as a tool to contribute to the design process, particularly at an earlier stage in design. Some solutions produced may not be viable in terms of cost or buildability, therefore an experienced structural engineer will be required at detailed design stage or earlier. The process to use ResOp requires both project managers and civil and structural engineers, as before, but provides them with a deeper understanding of construction costs when considering a design. To produce a least cost solution at the touch of a button is no longer a future technology and this should be harnessed more in civil engineering, not just as mechanical and electrical, aerospace and naval engineering. The construction industry is undergoing an advancement with the use of BIM that should make tools used by ResOp more available due improvements in software and better site investigations and topographical surveys.

Currently the length of time to calculate a solution using ResOp is excessive but this will improve with more efficient coding and using more powerful computers. Also the population and number of generations are low for this type of analysis and should be increased with more efficient finite element analysis and algorithm software. Further resources could create parallel solutions and may reach an optimised solution faster.

The emerging technologies used in ResOp are increasing in popularity and the tool was programmed using well founded computer languages. Design in structural engineering should combine both human and computer intelligence; and replicating previous designs without considering site parameters should no longer be practiced. A deeper understanding of cost during preliminary design and detailed design will enable savings to be made throughout the design and construction phases of a project.

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