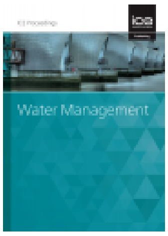

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Optimised multi objective design of low-head diversion structures

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Title: Optimised multi objective design of low-head diversion structures

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Abstract

Diversion head works, also called weirs or barrages, are structures constructed across rivers or canals to store water or raise the water level. Design of diversion structures involves calculating the depth, length and thickness parameters of its horizontal and sloping aprons and cut-off piles. These are set to achieve structural stability against multiple forms of failure such as scour, uplift, sliding, piping and overturning. The components of a diversion structure, which have complex non-linear relationships, are traditionally calculated with empirical recommendations derived from However, currently practiced design approaches such as Khosla's method of independent variable do not explore the trade-offs between the many relevant design objectives, failing to reveal possibly superior designs with less cost. In this article we propose a multi objective optimisation design approach for diversion structures and forward a free and open source code. The method is demonstrated on a stylised design problem. The results show substantial improvement in stability and cost of the structure.

Key words: Modelling; Structural design; Municipal & public service engineering; Environmental engineering; Dams, barrages & reservoirs; Design methods & aids; Buildings, structures & design; Hydrology & water resource; Cut-off walls & barriers; Developing countries

Key Points

1. We propose a design formulation for multi objective optimization of low-head diversion structures
2. Current design approaches for diversion structures on permeable media do not explore the trade-offs between the many relevant design objectives, failing to reveal possibly superior designs
3. Multi objective optimization achieves substantial improvement in stability of the structure and cost.

1. Introduction

Costly expansion of infrastructure is needed to meet increasing water, food and energy demands and to adapt to climate change while ensuring minimal environmental impact (November, 2010; UK government, 2011; United Nations, 2020). Among these, diversion structures, a name commonly used for structures that are used to raise the water level of a river, are ubiquitous in water supply, irrigation and small scale hydropower applications among others (Tschantz, 2014). For example in the United Kingdom there are 13,000 such diversion structures (weirs), a large number compared to the number of large dams (486). Despite their continuous, wider and increasing use, the design methods used in their design has arguably lagged behind in adapting the computation, visualisation and decision making approaches prominent in other water resource fields such as the design of large dams. In this article we propose a multi objective optimisation approach for diversion structures that reveals trade-off between various design objectives.

Design of diversion structures involve calculating the parameters of a diversion structure's components that are set in consideration of surface flow, subsurface flow, nature of foundation soil, structural stability and economy. The parameters of the components of these structures are interrelated.

A range of surface and subsurface flow theories have been forwarded for the safe and economical design of low-head diversion structures on permeable foundation. One of the oldest is Bligh's creep theory (Bligh, 1912). The theory assumed the total head loss up to a point along the base of the structure to be proportional to the distance of the point from the upstream of the foundation. This theory has been found to be defective from actual field observations. Pavlovsky (1922) developed a general theory of the conformal transformation problem to weir-foundation design. Lane (1935) proposed an empirical method in which the creep is weighted to allow for the variation in creep along vertical and horizontal directions based on his experiment on large number of dams. Casagrand (1935) formalized the method of flow nets, a graphical solution of the Laplace equation for steady state flow, first developed by Forcheimer. A graphical solution of the Laplace equation is a trial and error method and arduous. Khosla (1935) used method of independent variables based on Schwarz - Christoffel transformation (Christoffel, 1867). By splitting the complex foundation profile into several elementary forms the Khosla's method achieves an approximate result. According to this widely applied method, the components of a diversion structure are calculated based on rule of thumbs such as basing the downstream pile depth to be at least 150 % of the expected scour depth at high flood. The overall apron length is set based on the downstream pile depth, head difference between upstream and downstream points to keep the safe exit gradient within acceptable limit to prevent progressive erosion commonly called piping failure. The thickness of the aprons is set to balance the uplift pressure due to residual seepage pressure as it is dissipated from upstream to downstream.

Recent works have suggested solving the complex non-linear design problem with optimisation. (Singh, 2011; Hassan and Al-Shukur, 2016) presented an optimization-based procedure that uses genetic algorithm to minimize the overall cost as well as satisfy the safety and functionality requirements. Al-Shukur & Fadhil Hassan, (2015) conducted a parametric analysis to investigate the effect of variation in the design parameters values on the dimensions and on overall cost of the barrage to find optimal hydraulic design of the barrage. Each parameter was taken separately while the others remained constant. Singh (2011) demonstrated the fuzzy based framework for uncertainty characterization in optimal cost for imprecise hydrologic parameter such as seepage head. The nonlinear optimisation formulation is then solved using GA. Garg, Bhagat, & Asthana, (2002) presented method for minimizing the cost of a barrage using an optimization technique along with a parametric analysis to reveal the effects of various parameters on the optimal design barrage. To assess the effect of uncertainty in seepage due to variations in hydraulic conductivity on optimum design using coupled simulation-optimization methodology, Al-Juboori & Datta (2018) trained meta-models on multiple datasets of simulated seepage scenarios. Safety factors and other hydraulic design requirements are imposed as constraints of the optimization model within the simulation model

As reviewed above, the recent literature shows a cost effective design can be achieved with optimisation and that many alternative parameter combinations can lead to acceptable designs. However, all demonstrations are limited to reducing cost through a single objective optimization and do not explore the trade-offs between the many relevant design objectives, failing to reveal possibly superior designs by exploring the full parameter space.

In this article we present a multi objective optimisation design approach for diversion structures that relies on trade-off analysis with visual analytics. The problem formulation transforms the traditional constraints in the design of diversion structures as performance objectives. The approach results in multiple alternative designs from which decision makers can chose one based on the acceptable trade-offs between metrics of stability against piping, sliding, overturning and uplift failure, and construction cost. The proposed approach is demonstrated on a sample design. A free and open source code is provided for as convenient design and decision tool that simultaneously provide cost efficiency and higher factors of safety against multiple modes of failure such as sliding, rotation, uplift and piping.

The following section revises the widely used (traditional) Khosla's method of independent variables. Section 3 presents the proposed reformulation of the diversion structure design problem to a multi objective optimisation one. The simplified design problem with hypothetical hydrologic and soil properties is given in section 4 where the results is also presented. Sections 5 and 6 present discussion and conclusion respectively.

2. Traditional design method for diversion structures on permeable media

The longitudinal profile of the structure is designed by considering the surface and subsurface flow of water and geology of the site. Designing a longitudinal profile of the structure includes setting the depths of the upstream and downstream piles, lengths and thickness at various points along the structure of the upstream and downstream aprons.

Stability against scour

The upstream and downstream piles are designed to guard against anticipated scouring action of surface water. Lacy (1939) found the scour depth (R) depends on soil property and discharge intensity as:

$R = 1.35(\frac{q^2}{f})^{\frac{1}{3}}$ where, R= scour depth, q = discharge intensity, f = Lacy's silt factor

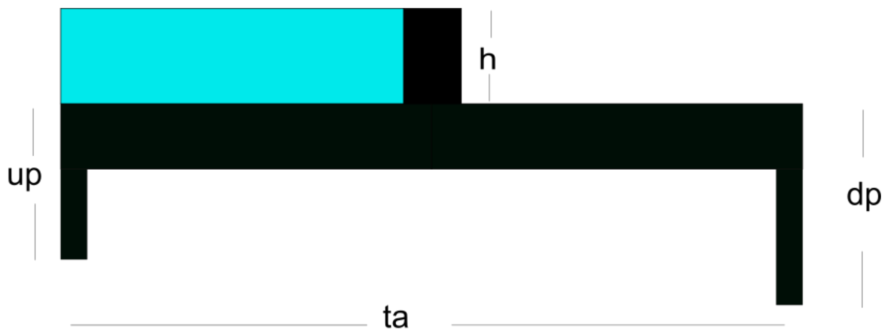

Figure 1 Simplified drawing of a longitudinal cross-section of a low head diversion structure with upstream and downstream piles.

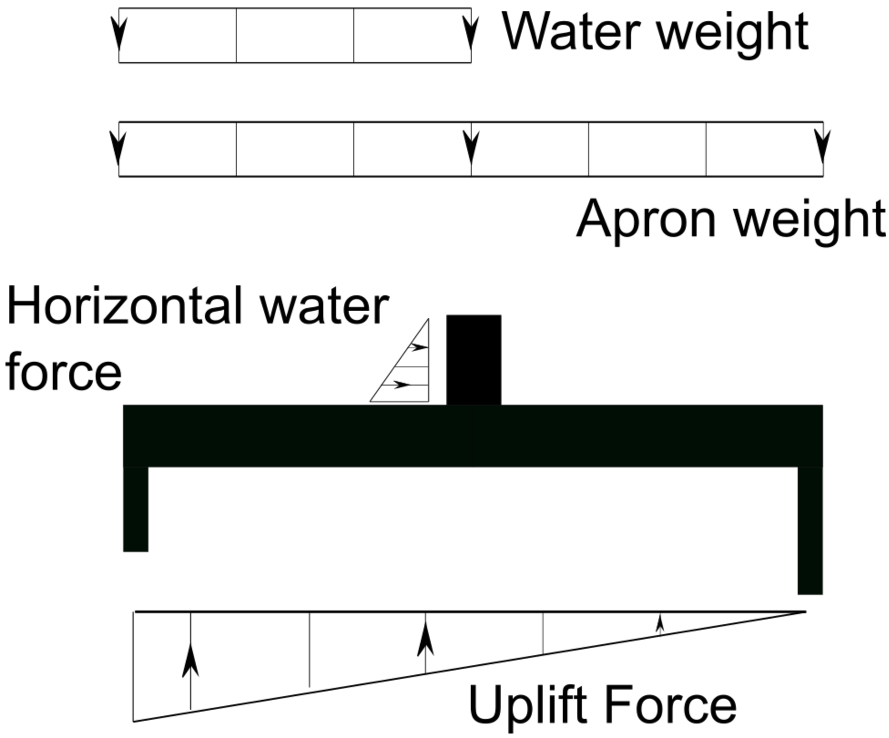

Figure 2 free hand diagram of forces acting on the diversion structure

The downstream pile depth is traditionally set to be more than 1.5 times the scour depth ® below the high flood level (HFL) and the upstream pile depth is set at 1.25 times R below the high flood level.

Stability against piping

The exit gradient is the hydraulic gradient of the seepage flow under the base of the weir floor. The rate of seepage increases with the increase in exit gradient. Such an increase can wash away by the percolating water. This, commonly known as piping, can be minimized by reducing the exit gradient. The total length of apron and the downstream pile depth act together to keep the exit gradient in safe limit. Khosla gives the relation between these parameters as

$G_E = \frac{H}{dp\pi\sqrt{\lambda}}$ where, G_E = the exit gradient; λ = a function of the relation between the total apron length and downstream pile depth; H = is the maximum head difference anticipated from high flood flow, pond level flow and static water cases; dp = downstream pile depth

The value of λ for a permissible exit Gradient G_E and a downstream pile depth d_d is therefore calculated as $\lambda = \left[\frac{H}{dp\pi G_E}\right]^2$. The value of α is calculated as $\alpha = \sqrt{(2\lambda-1)^2-1}$ from which the total apron length is calculated as calculated as $\alpha = \sqrt{(2\lambda - 1)^2 - 1}$ from which $b_T = \alpha d_d$ where b_T = Total apron length, dp = Depth of downstream pile.

The downstream apron length is set to contain the full length of the hydraulic jump for all flow conditions. Viz. high flood flow and pond level flow with and without concentration of flow and retrogression of river with time considered.

Design goals are finding the combination of parameters (shown with letters in the figure) that will achieve stability against multiple forms of failure with the least cost

performance objectives are maximizing stability against uplift, sliding, overturning, and minimizing cost

Constraints are that upstream and downstream piles are deeper than the scour depth

Once the pile depths and the length of the aprons are set based on the surface flow (e.g., scour depth) and subsurface flow (e.g., stability against piping failure) considerations, the structure should be checked for stability.

Stability against uplift

Uplift force exists on the structure because of the subsurface flow of water underneath it. This uplifting pressure head decreases from upstream to downstream. Designed for stability against uplift is achieved by balancing the thickness of aprons at various points along the longitudinal section to the uplift pressure due to the subsurface flow. The forces and moments acting on the corresponding structure are then calculated and the structure is checked for its stability against overturning and sliding.

$t = \frac{h}{G-1}$ where, t= Thickness of apron at a point, h = The unbalanced head between the uplifting pressure head and surface water depth, G = Density of construction material for apron

Stability against Overturning

As with design consideration against uplift, it is important to keep the stabilizing moment more than the destabilizing moments.

Since unpredictable situation are likely to occur and cause the toppling moment to exceed the balancing one, a factor of safety of 1.5-2.0 is usually applied for safety against overturning

(Baban, 1995). In order to avoid lifting up the structure's heel and tension occurrence at the base, the resultant force must pass through the middle third of the structure's base.

$e < \frac{ta}{6}$

$$e < \left|\frac{ta}{2} - X\right| < \frac{ta}{6}$$

Where $X = \frac{\sum M}{\sum Vf}$, 'ta' is the bed width, M is the moment about the toe and 'Vf' the vertical forces

However, if the condition is not satisfied, the tension and compression at the hill of the weir shall be checked as follows:

$\rho_{min} = \frac{\sum F_v}{2} x \, (1 - \frac{6e}{B})$ $\rho_{min} > 0$ and $\rho_{max} = \frac{\sum F_v}{2} x \, (1 + \frac{6e}{B})$ $\rho_{max} <$ 70 tones/m^2 for masonry under stressing or tension is checked as where $e =$ eccentricity, $\sum M =$ summation of all moments about the structures toe, $\sum V_f =$ summation of vertical forces excluding the base reaction, X= distance of the resultant of the forces from the toe, ta = width of the weir base.

Stability against Shear and Sliding

The structure may slide in the flow direction if there is not enough grip between the base and the foundation. To prevent this happening, the vertical forces are checked to be adequate, compared to the horizontal forces, to supply static friction that would keep the structure intact in its place. The US bureau of reclamation, as quoted by Baban (1995) suggests 0.35 for concrete structures on common soils. $\frac{\sum V}{\sum H} > 0.35$ Where, $\sum V =$ Sum of external vertical forces, $\sum H =$ Sum of external horizontal forces

3. Method

Approaches that link simulation models with heuristic global search methods such as evolutionary algorithms (Deb *et al.*, 2002; Coello Coello, Lamont and Veldhuizen, 2007) are well suited to handle non-linearity present in diversion structure design. We develop a computer program that calculates multiple stability performance metrics and cost for a set of input parameters. The simulator is capable of replicating a design with the traditional method (Khosla's method of independent variable) where the component parameters are set empirically. The simulator calculates measures of stability (Table 1).

The simulator, which accepts decision variables that alter the minimum design parameters for the structure as input parameters, is then linked to a multi objective evolutionary algorithm to reveal a set of Pareto-optimal designs that best balance multiple performance objectives. We validate the proposed multi objective optimization approach by comparing design results with those based on the traditional method, and optimization based on parametric grid search. The multi objective design problem is formulated as:

Minimize $\boldsymbol{F} = \boldsymbol{f}(\boldsymbol{fu}, \boldsymbol{fo}, \boldsymbol{fs}, \boldsymbol{fe}, \boldsymbol{fc})$

Where $\boldsymbol{fu}$ = stability against uplift, $\boldsymbol{fo}$ = stability against overturning, $\boldsymbol{fs}$ = stability against sliding, $\boldsymbol{fe}$ = eccentricity, $\boldsymbol{fc}$ = cost. Decision variables are the depths of upstream and downstream cut-off piles, length and thickness of horizontal aprons.

Table 1 Performance consideration in traditional method and metrics used in the suggested method

Design Criteria	Traditional checks	Suggested metric transformation
Stability against Uplift	$\frac{\sum Vg}{\sum Vu} > 1$	Maximize fu = $\frac{\sum Vg}{\sum Vu}$
Stability against Overturning	$\frac{\sum Ms}{\sum Md} > 2$	Maximize $fo = \frac{\sum Ms}{\sum Md}$ Where $\sum Ms$ moments leading to stability $\sum Md$ destabilizing moments
Reduce eccentricity	$e < \left\lfloor \frac{ta}{2} - X \right\rfloor < \frac{ta}{6}$	Minimize $fe = \left\lfloor X - \frac{ta}{2} \right\rfloor$ where $X = \frac{\sum M}{\sum Vf}$

Stability against Shear and Sliding	$\frac{\sum V}{\sum H} > 0.35$	Maximize fs Where $fs = \frac{\sum V}{\sum H}$
Cost	Cost was calculated post design	Minimize fc Where fc is the sum of costs of apron, piles and excavation and depends on the length, thickness and depth of the components

4. Results

For this proof of concept paper, we use a synthetic problem with simplified structure. This is done to ease communication and facilitate the reproducibility of results.

For this example we will assume the following site parameters Head = 7.12, Safe exit gradient = 0.125, Discharge intensity = 2.5, Lacy silt factor = 0.75. Density of concrete material (with which the apron and the cut-off piles will be built) = 2200 kg/m^3 .Density of water = 1000 kg/m3

This section describes results of the proposed approach to the stylized diversion structure design problem. We start by discussing the stopping criteria for the MOEA computations. We then discuss the trade-offs between 2 first, followed by 3 and then all 6 performance objectives and discuss the contribution of various component parameters to the Pareto-optimal designs.

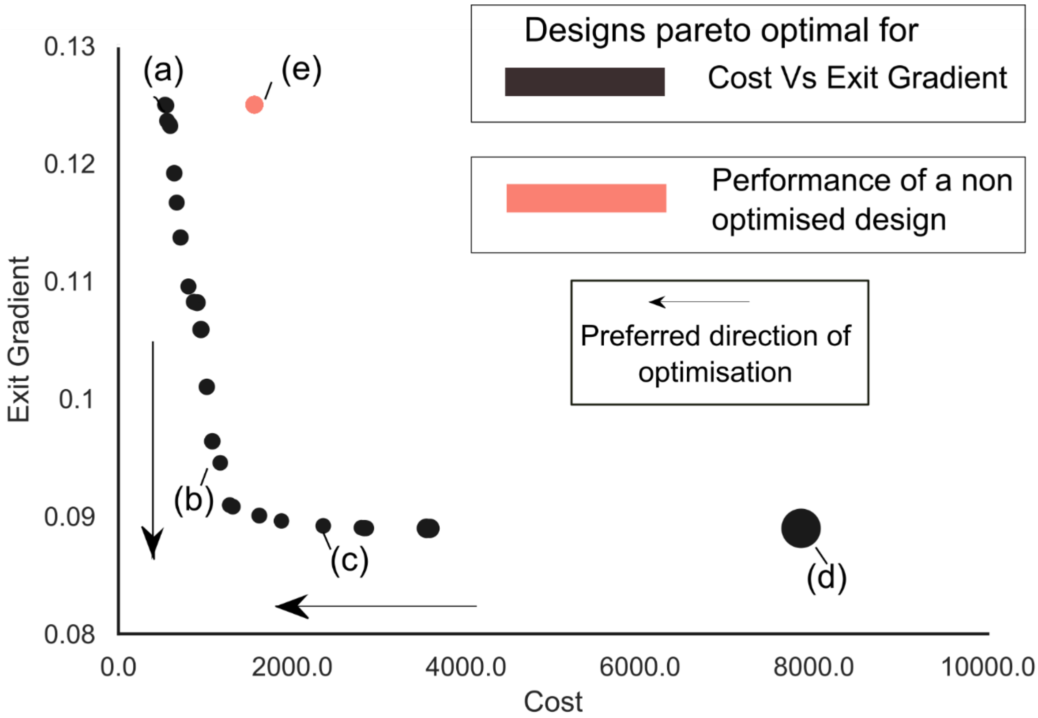

Figure 3 trade-offs between cost and exit gradient. Improving the exit gradient from 0.12 to 0.1 costs around 50% more (shown with label 'b'). However a further improvement of the exit gradient to 0.09 or less can cost from 300 to 600% (shown with labels 'c' and 'd' respectively).

Figure 3 shows the performance of the optimised designs and trade-offs between cost and exit gradient, both of which are preferred to be minimized. Designs labelled 'a' and 'b' show the possible simultaneous gain compared to the traditional design (shown with label 'e') both in reducing cost and increased safety against failure by piping (represented by the exit gradient) when optimisation is applied. Performance comparison of designs 'a' and 'b' show how with a relatively small increase in cost, a large improvement in the exit gradient may be achieve. However, if the exit gradient were to be decreased further from label 'b' say to point 'd' a substantial cost increase will need to be sustained (by more than 6 fold).

The best designs when only cost and exit gradient are considered may not meet other performance criteria such as stability against uplift, overturning and sliding. Blue markers in Figure 4 show designs that are dominated (hence undiscovered) if only cost and exit gradient were the decision criteria but would be relevant when stability against uplift (represented by the size of the markers) is also considered.

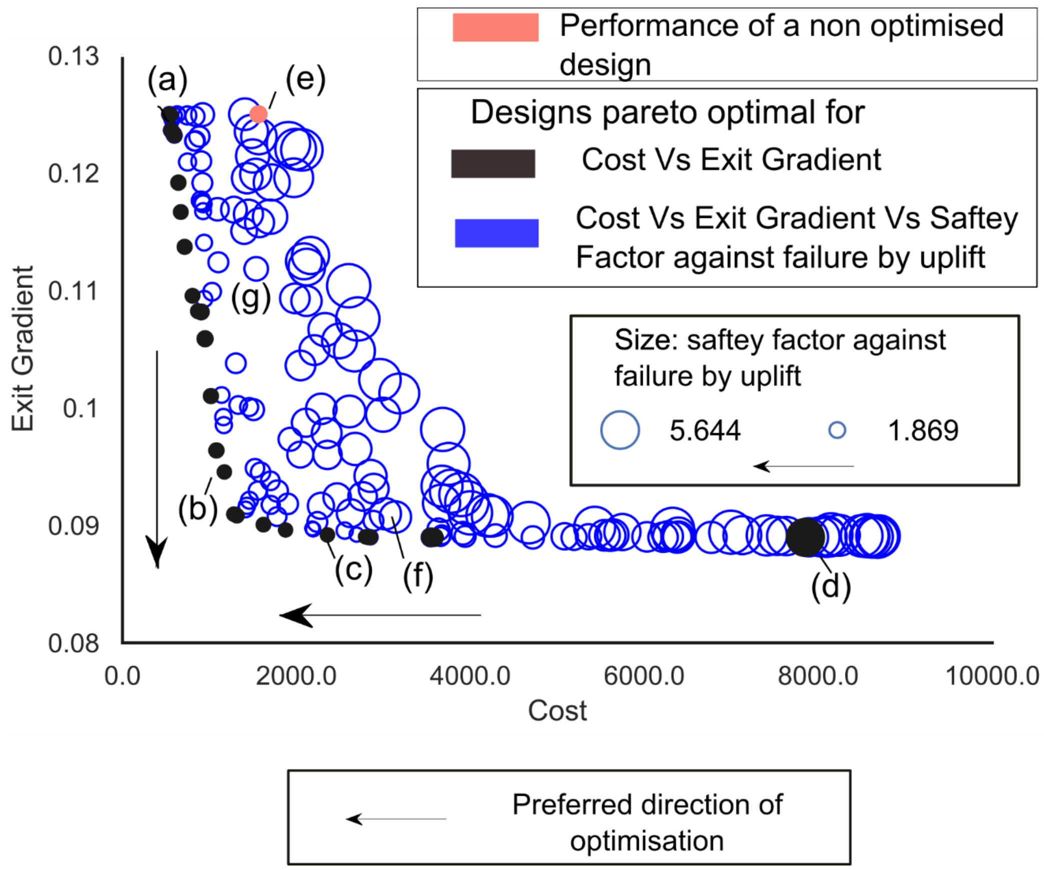

Figure 4 trade-off between cost, exit gradient and stability against uplift failure. Black circles show the same designs shown in Figure 3. Performance on stability against uplift is represented with the size of the circles. Blue circles (in addition to the black circles) show designs that are Pareto optimal when considering safety factor against uplift in addition to the cost and exit gradient.

Figure 4 shows the designs that are Pareto optimal for cost and exit gradient only perform poorly in their stability against uplift (shown with the size of the marker). However, design with higher performance in stability against uplift (e.g., 'f' and 'g') can be found with close performance to those that are Pareto-optimal when considering only cost and exit gradient (e.g., 'b' and 'c'). Although higher cost is associated with more construction material, designs with higher cost do not necessarily perform higher in stability against failure by uplift because the larger portion of the material is going into cut-off pile depths (to reduce the exit gradient) in some of the designs.

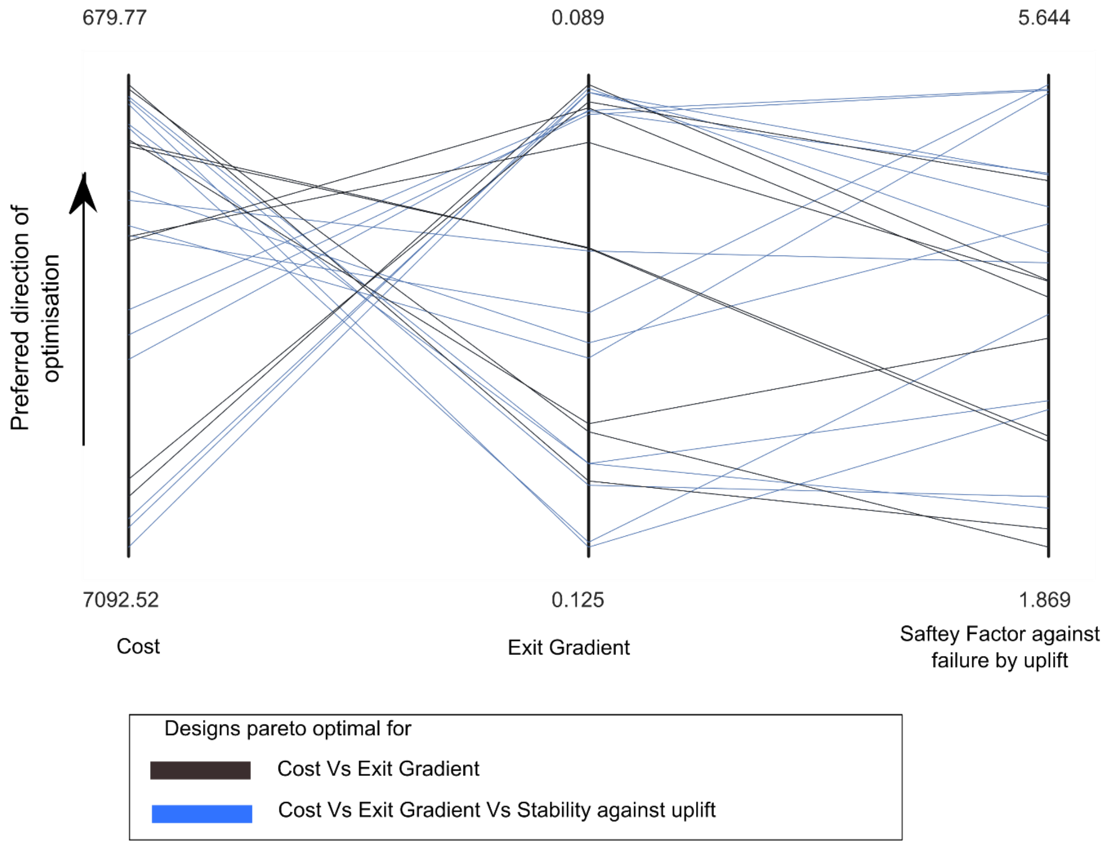

Figure 5 trade-off between cost, exit gradient and safety factor against uplift failure shown with parallel axis plots. This figure shows the same information as Figure 4 and shown here to introduce parallel axis plots for further analysis of the Pareto optimal designs. An ideal design would have been a horizontal line touching the vertical axes at the top. The largest trade-off is shown to be between minimizing cost and minimizing exit gradient objectives (indicated by the steepness of the line crossings).

Figure 5 presents the same information as Figure 4. The values at the top of the parallel axes represent the highest achievable performance if that particular objective were to be prioritized. The non-vertical lines represent efficient (Pareto-optimal) designs. Lines that cross between two adjacent axes signal a trade-off between those measures; the steeper the angle the stronger the trade-off between the two performance indicators.

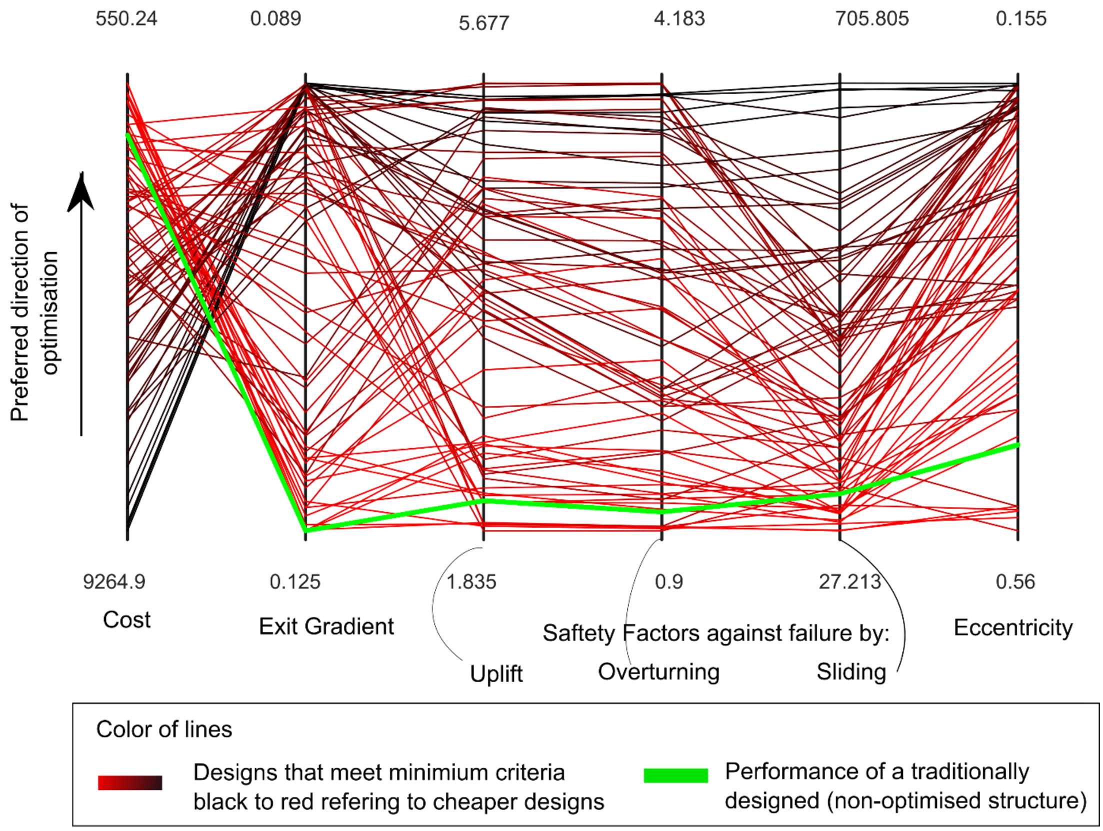

Figure 6 A Parallel axis plot showing designs that are Pareto-optimal when all 6 performance objective are considered. Color of lines show the cost gradient used to visually track how designs performing well in one of the objective does in the rest of the objectives. The designs that are the cheapest (bright red lines) are shown to have the lowest score in all other performance measures.

Figure 6 demonstrate the multi objective optimisation identifies superior designs than with the traditional engineering design approach (all lines that consistently score higher in the six performance objectives than the green line are better). The safety factors against uplift, overturning, sliding and lowering of eccentricity objectives have relatively small trade-off amongst themselves but exhibit strong trade-offs with both cost and exit gradient minimizing objectives.

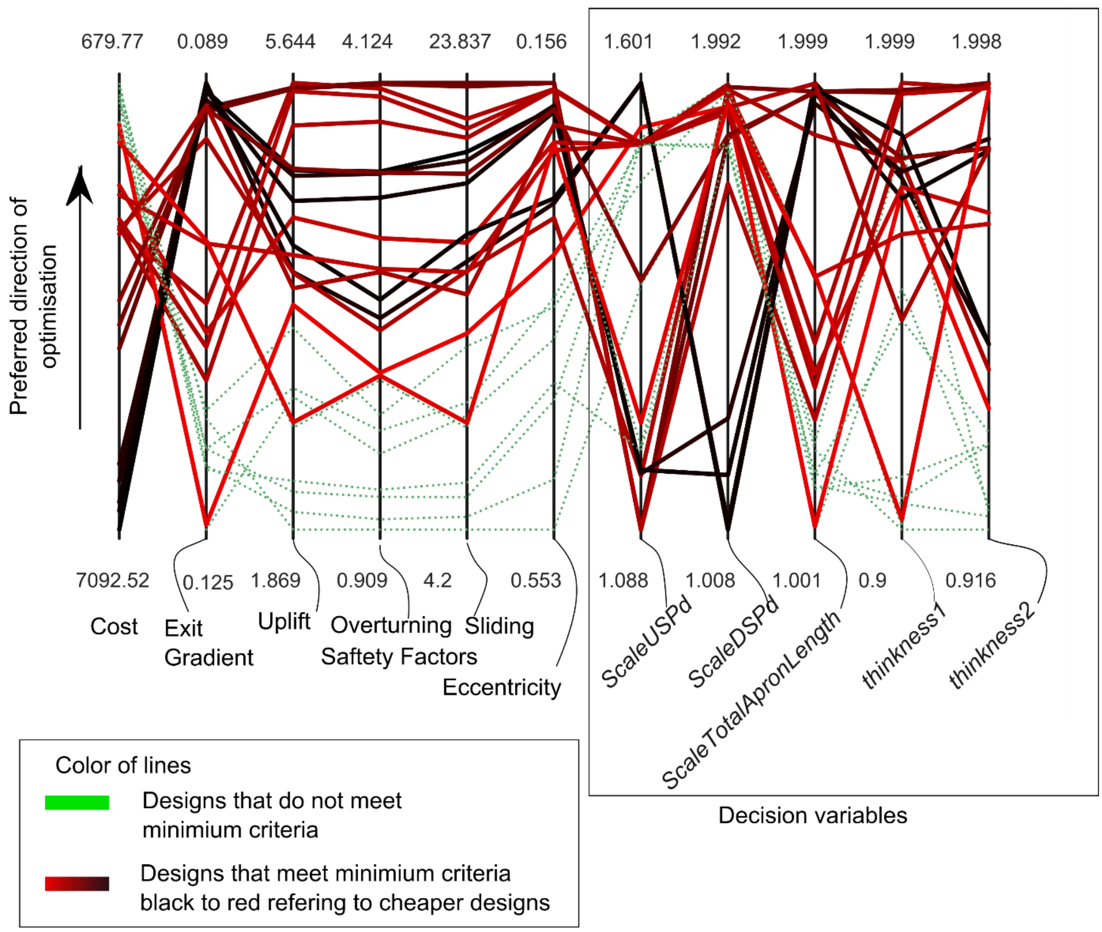

Figure 7 parallel axis plot showing the design parameters corresponding to the different Pareto-optimal designs. The solid lines show designs having a score of more than or equal to 2 in the safety factors against uplift, overturning and sliding and an eccentricity of less than 1/6; the minimum criteria for acceptable designs. The dashed green lines show designs that are Pareto optimal but that do not meet the minimum stability criteria. The 5 axes on the right show the design parameters for the Pareto – optimal designs. Scaling the downstream pile depth is shown to be critical to achieve lower overall cost.

Solid lines in Figure 7 show designs that would be acceptable based on commonly practiced stability criteria. Among those designs cost is most sensitive to downstream pile depth and to a lesser extent the downstream thickness. Various combinations of values can lead to acceptable results. However, there is a strong trade-off between the exit gradient and cost. Some of the least cost design that are cheaper than the designs with the traditional (non-optimised) approach (Shown with green line in *Figure 6*) fail the commonly used minimum stability criteria; showing that low dimensional optimisation (which doesn't include the stability performance criteria) can be misleading.

This figures shows how a decision maker acquainted with traditional design criteria would be able to reduce the choice set. Multiple designs meet the criteria against the 5 failure modes. Line A in the figure is shown for comparing a design made with the traditional method against the optimized ones. And show the multi objective optimization produces designs that are superior in all performance objectives.

5. Discussion

A comparison of the results in Figure 3 and Figure 4 demonstrate how by using the traditional empirical methods or single objective optimization, infrastructure design engineers could inadvertently ignore important decision alternatives and substantial potential to improve performance. The advantage of optimising all perforamnce criteria explcitly, rather than treating them as constraints is that design engineer may not know what is possible before seeing the full set of possibilities. This, that considering many-objectives explicitly and simultaneously can help avoid such cognitive myopia was recognised early on by (Hogarth, 1981). Visual interaction with results allows engineers and stakeholders to introduce minimum performance requirements (by filtering or 'brushing' results) (Reed and Kollat, 2013). The minimum criteria for structural stability or cost can be set post optimisation as shown in Figure 7. Interactive multi-criteria performance plots can help in understanding the implications of choice of balance of sometimes conflicting performance goals on the design parameterization (Reed & Kollat, 2013; Woodruff, Reed, & Simpson, 2013; Geressu & Harou, 2019). By adopting a generate-first-choose-later approach (Herman, Zeff, Reed, & Characklis, 2014; Geressu & Harou, 2015) enabled by many objective optimization and visual analytics, assessments are not restricted by a lone designer's assumptions of acceptable performance tradeoffs and safety factors against failure.

Considering multiple social, economic and environmental metrics simultaneously along with potential impacts of new infrastructure on existing and future use should be preferred to avoid decision biases (Giuliani, Herman, Castelletti, & Reed, 2014; Hogarth, 1981; Geressu et al., 2020). Applying state of the art system design approaches could be crucial both for efficient use of the limited resources (Jeuland *et al.*, 2014) and for creating consensus and cooperation among various stakeholders (Berger *et al.*, 2007; Wu *et al.*, 2016). This requires building human resources and institutional capacity along with a culture of consultative decision making.

A larger number of low head diversion structures are designed and implemented at more local levels by various engineers and government offices. The design of diversion structures is complex; requiring extensive experience along with a number of tests to craft the right design for a specific project. These requirements are lacking in in many developing countries because of limited human, capital and test and design equipment resources (Baban, 1995). Commonly, higher factors of safety are applied resulting in unnecessarily high cost. In economies with high inflation, the cost of material and construction vary with time; making an optimum design at one point in time (while in design stage) to be obsolete at other (during construction). Computer programs developed with this article allows for the optimum design to easily be revised with short notice (including at the construction stage), reducing overall expenses. A wider application of the design optimization code could also help standardize the designs, lower costs by avoiding large often unwarranted safety factors and ensure designs that are robust to various uncertainties (e.g., high flood magnitude, inflation) are considered. Moreover, the design of low head diversion structures, by its nature is multi objective (e.g., minimizing cost, maximizing safety against uplift, overturning , sliding, etc.); making it ideal to introduce the wider practicing engineering community to the use of trade-off analysis in decision making.

This study optimised a simplified diversion structure problem for brevity and as a proof of concept. The design large low-head diversion structures particularly on natural rivers involves extensive analysis of surface flow condition at high floods. We used Khosla's method of independent variable for the calculation of seepage. Other analytical or computational methods such as finite difference method may achieve better accuracy in calculating the seepage head loss and it distribution under the horizontal apron (Al-Juboori and Datta, 2018; Tilaye and Hailu, 2020).

The optimum combination different parameters of the components of a diversion structure is dependent on the cost of construction of the components at a particular site. The optimal design would vary based on the relative cost of piles and apron construction cost. This would depend on specific site condition and availability and choice of material for construction. Hence generalizing the sensitivity of cost to either the pile depths or length and thickness of apron could be misleading.

Unlike many water resources system problems, where the possible performance in energy, irrigation and other water demand supply, the performance trade-offs for the design of low-head diversion structures can be continuous to infinity. This is because there is unlimited safety factors against uplift, and sliding do not have a limit if they are to be maximized. In the current formulation, the possible maximum value are limited only by the range of the decision variables that the optimisation run is allowed to explore. Although the simulation model is small and relatively small enough to be optimised even using widely available personal computer, future studies should explore transforming the performance metrics so that the unnecessarily computations related to the exploration of likely unwanted designs can be avoided. This may be achieved by limiting the cost of any optimised design to be within a limited range relative to the cost of a design with the traditional design procedures.

6. Conclusion

Traditionally, the components of a diversion structure are calculated with empirical recommendations derived from experience such as the downstream pile depth being least 150 % of the expected scour depth at high flood. The overall apron length is set based on the downstream pile depth, head difference between upstream and downstream points to keep the safe exit gradient within acceptable limit to prevent progressive erosion commonly called piping failure. The thickness of the aprons is set to balance the uplift pressure due to residual seepage pressure as it is dissipated from upstream to downstream. These and other parameters have complex non-linear relationship; multiple parameter combination leading to safe designs but with probably higher cost than the minimum necessary. However, currently practiced design approaches such as Khosla's method of independent variable do not explore the trade-offs between the many relevant design objectives, failing to reveal possibly superior designs.

In this article we propose and demonstrate a multi objective optimisation design approach for diversion structures. The problem formulation transforms the traditional constraints in the design of diversion structures, such as safety factor against uplift, overturning and sliding as performance objectives. The simulation-optimisation method explores alternative designs by scaling the parameters of the diversion structure's different component from their minimum recommended values. This generate first choose later approach is used with visual analytics to show the sensitivity of the performance metrics (e.g., cost and exit gradient) to the design parameters (e.g., the depth of cut-off piles and the length and thickness of the horizontal apron). Simultaneously considering the various stability performance objectives reveal the trade-offs between themselves and with cost.

The results show designs optimised for single of few of performance objectives (e.g., to minimize cost and exit gradient) can perform poorly in their stability criteria such as safety again uplift. However, design with higher performance in stability can be found with only small increase to the cost or exit gradient if the stability performance metrics are considered simultaneously in a multi objective optimisation. Multi objective optimisation identifies superior designs than with the traditional engineering design approach. The safety factors against uplift, overturning, sliding and lowering of eccentricity objectives have relatively small trade-off amongst themselves but exhibit strong trade-offs with both cost and exit gradient minimizing objectives.

A larger number of low head diversion structures are designed and implemented at more local levels by various engineers and government offices. The design of diversion structures is complex; requiring extensive experience along with a number of tests to craft the right design for a specific project. These requirements are lacking in in many developing countries because of limited human, capital and test and design equipment resources. Hence the wide application of the freely available and easy to understand design optimization code could help standardize the designs and lower costs by avoiding large often unwarranted safety factors.

7. Appendix: Computational details

We employ a heuristic optimization approach where a search algorithm (Hadka & Reed, 2012; Kollat & Reed, 2006) is coupled with a simulation model of forces on a diversion structure built on permeable foundation. The ε-NSGAII (Deb et al., 2000) generates its initial random population of decision variables by exploiting uniform random sampling within the user-specified ranges. These variables are then passed as input variables to the water resources simulator that evaluates the performance of the system. The performance information is passed back to the ε-NSGAII algorithm, which evaluates the fitness of the decision variables to produce the next generation of decision variables. Over successive generations of the optimization run, the high quality solution are passed into the epsilon-dominance archive and injected into the population at the beginning of the next run and to automatically adjust the search population size (Kollat & Reed, 2006). The ε-dominance archive sorts solutions based on the user specified levels of significant precision (i.e., the minimum change in performance level between solutions for a user to identify them as significantly different).

The ε-NSGAII was chosen for its search effectiveness for its availability (Kollat & Reed, 2007). An Initial population size of 25 is used with a 0.01 epsilon value was used for all the performance metrics in the Platypus framework (Hadka, 2018) on a personal laptop computer. Other recent algorithms such as Borg Hadka & Reed (2013) may lead to better computational savings of using the MOPO formulation.

Performance of many objective evolutionary algorithms is stochastic, with no guarantee that a particular single optimization run will achieve close performance levels as the true (but unknown) Pareto-front. Pareto-sorting of solutions from different random seeded runs (with different initial points) could better approximate the extent of the true-Pareto front [*Salazar et al.*, 2017]. A lack of improvement in the hypervolume score with more evolution (number of generations) is taken as the stopping criteria.

The many objective optimization is counducted with up to 30 runs with different initial points (random seeds) where each is allowed to last for up to 2000 function evaluations. The results from each run are then sorted together to provide the best overall reference set (Kollat, Reed and Kasprzyk, 2008).

8. References

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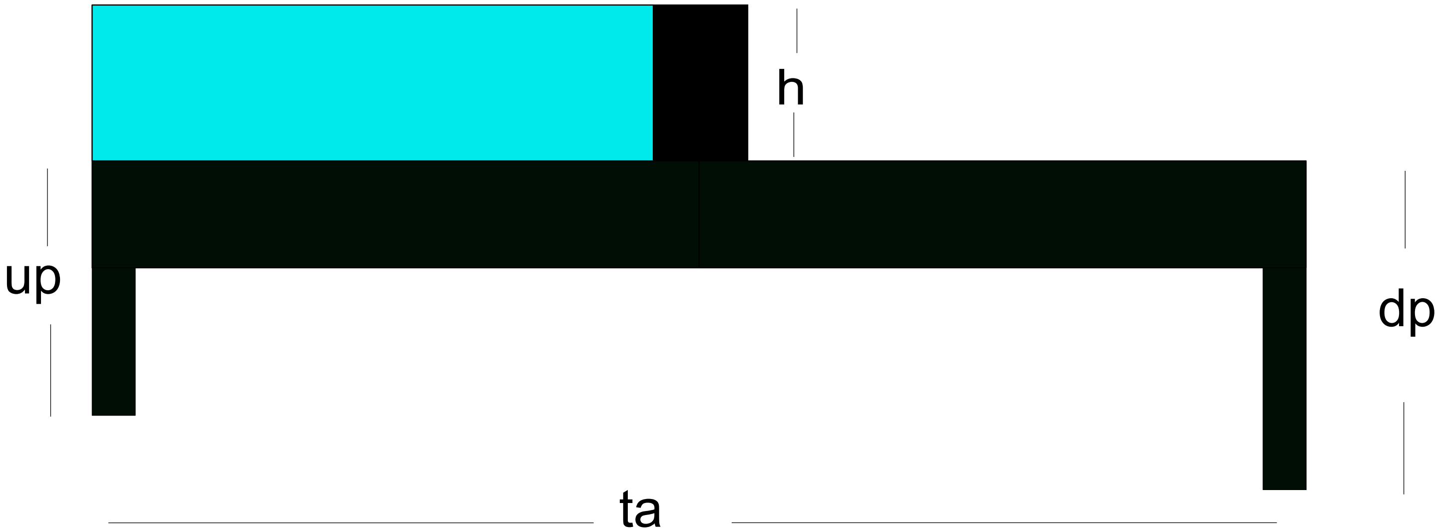


Figure 1.eps $Figure$

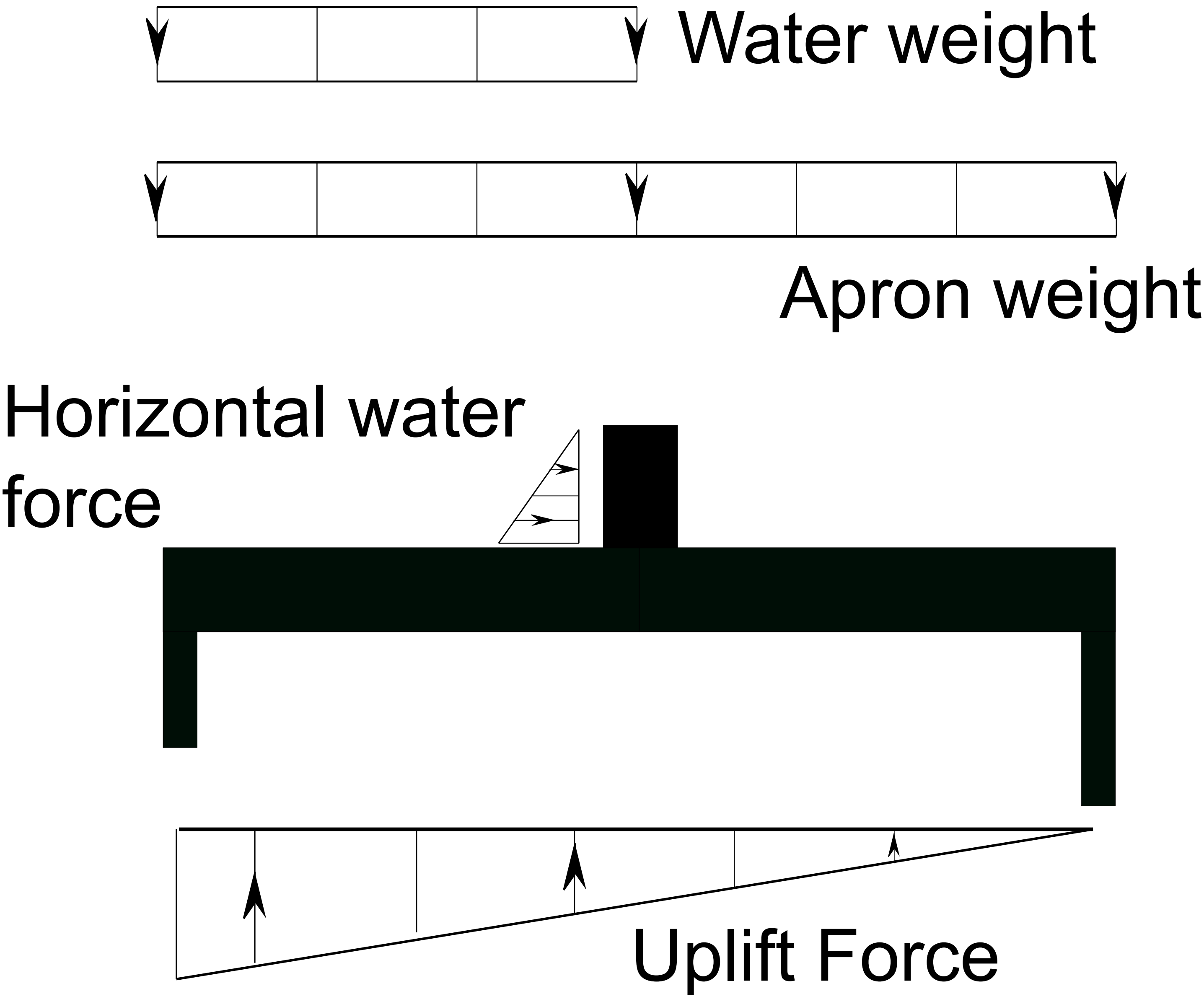
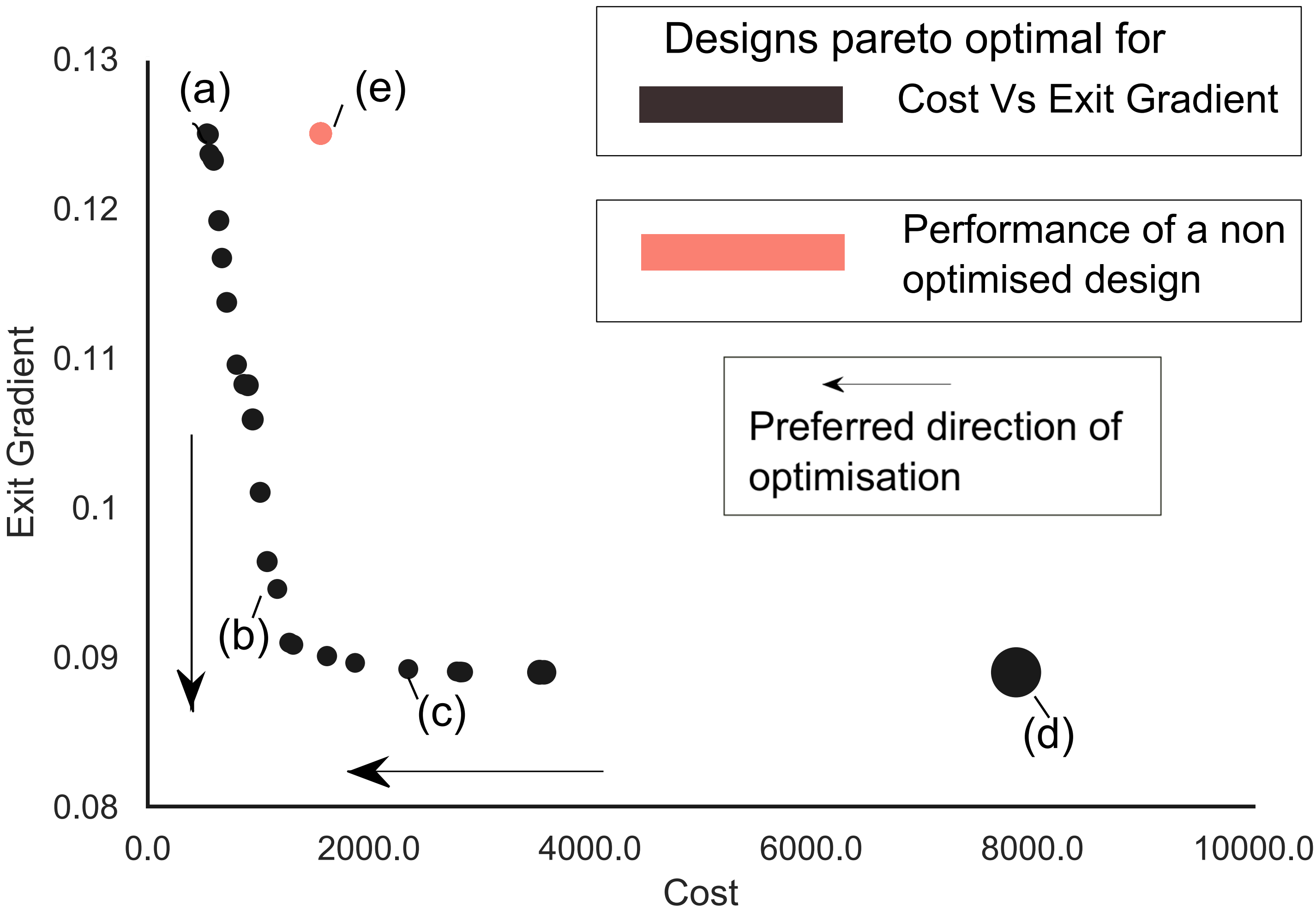


Figure 2.eps $Figure$


Designs pareto optimal for
Cost Vs Exit Gradient
Performance of a non optimised design
Preferred direction of optimisation
0.13
0.12
0.11
0.1
0.09
0.08
Exit Gradient
(a)
(e)
(b)
(c)
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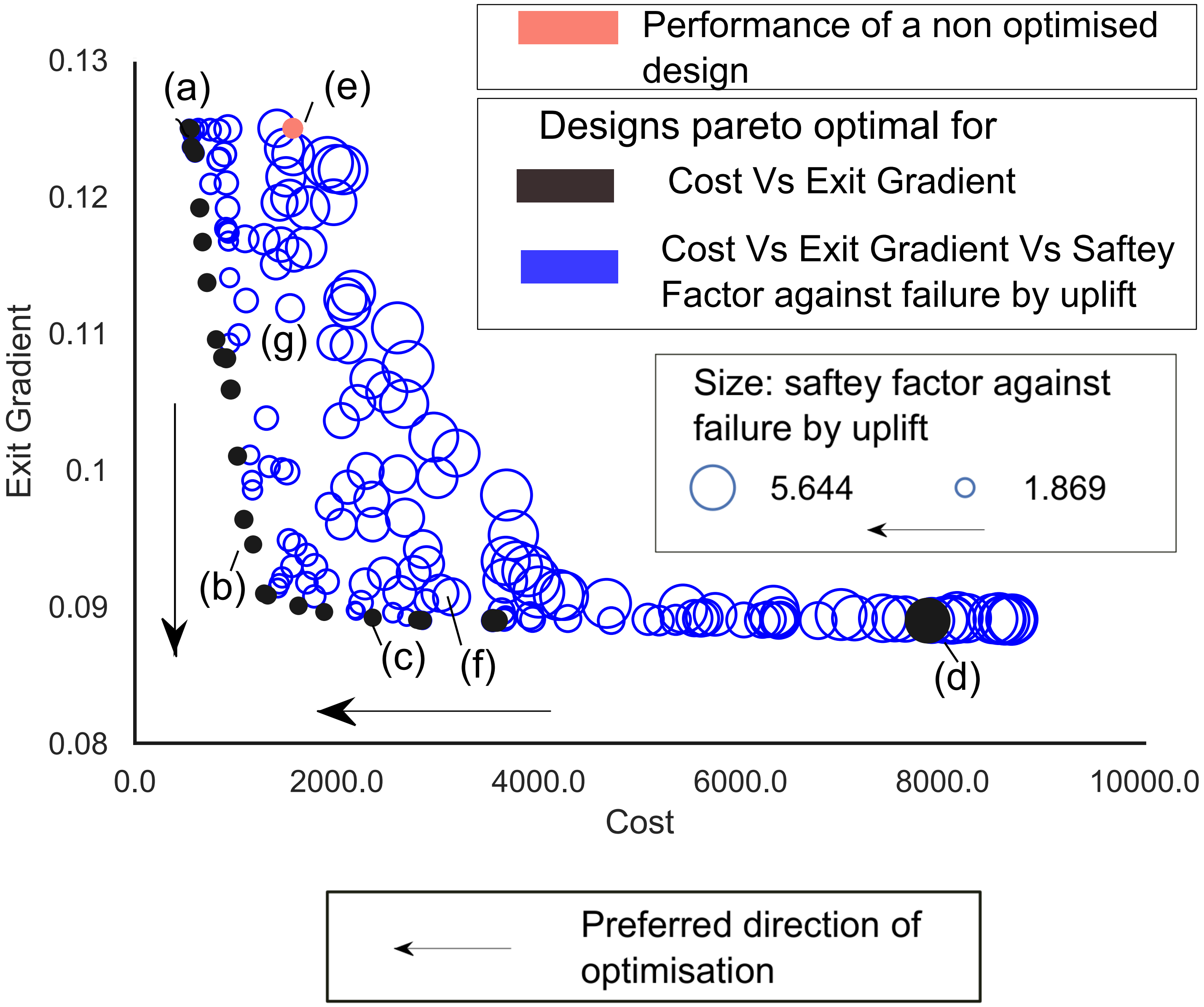
6000.0
8000.0
10000.0
Cost


Performance of a non optimised design
Designs pareto optimal for
Cost Vs Exit Gradient
Cost Vs Exit Gradient Vs Saftey Factor against failure by uplift
Size: saftey factor against failure by uplift
5.644
1.869
Preferred direction of optimisation
Exit Gradient
Cost
0.13
0.12
0.11
0.1
0.09
0.08
0.0
2000.0
4000.0
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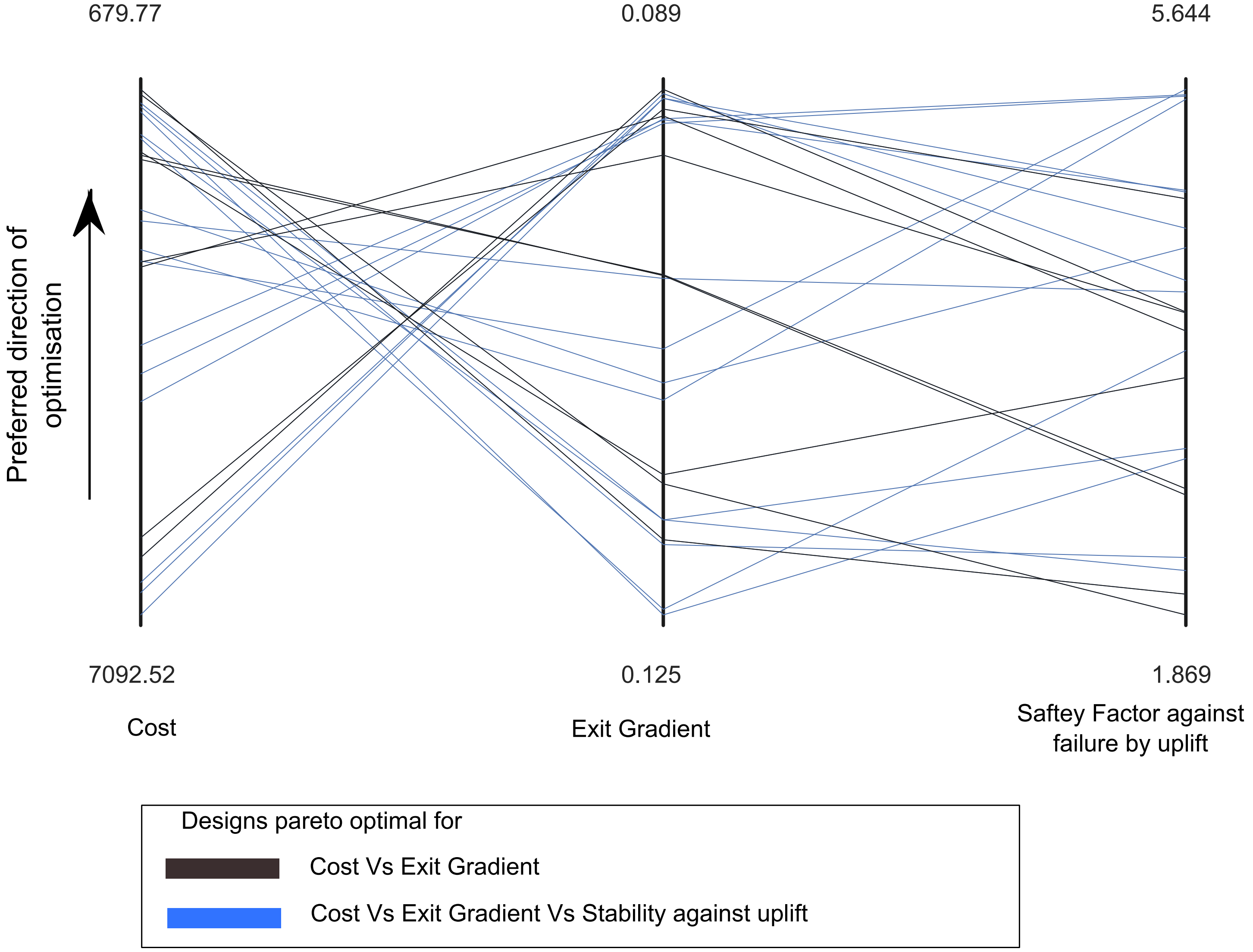
8000.0
10000.0
(a)
(b)
(c)
(d)
(e)
(f)
(g)


679.77
0.089
5.644
Preferred direction of optimisation
7092.52
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Designs pareto optimal for
Cost Vs Exit Gradient
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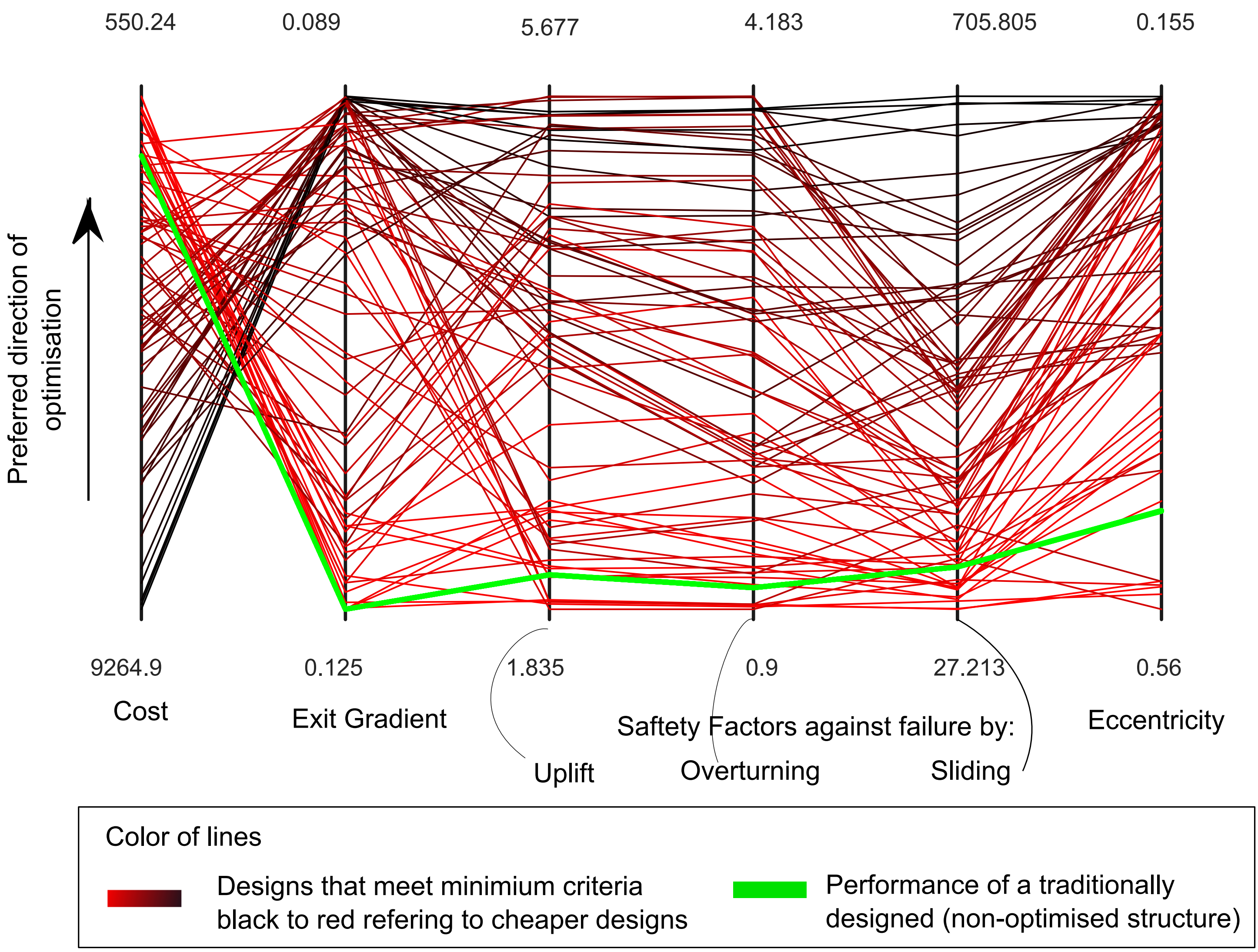
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0.089
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4.183
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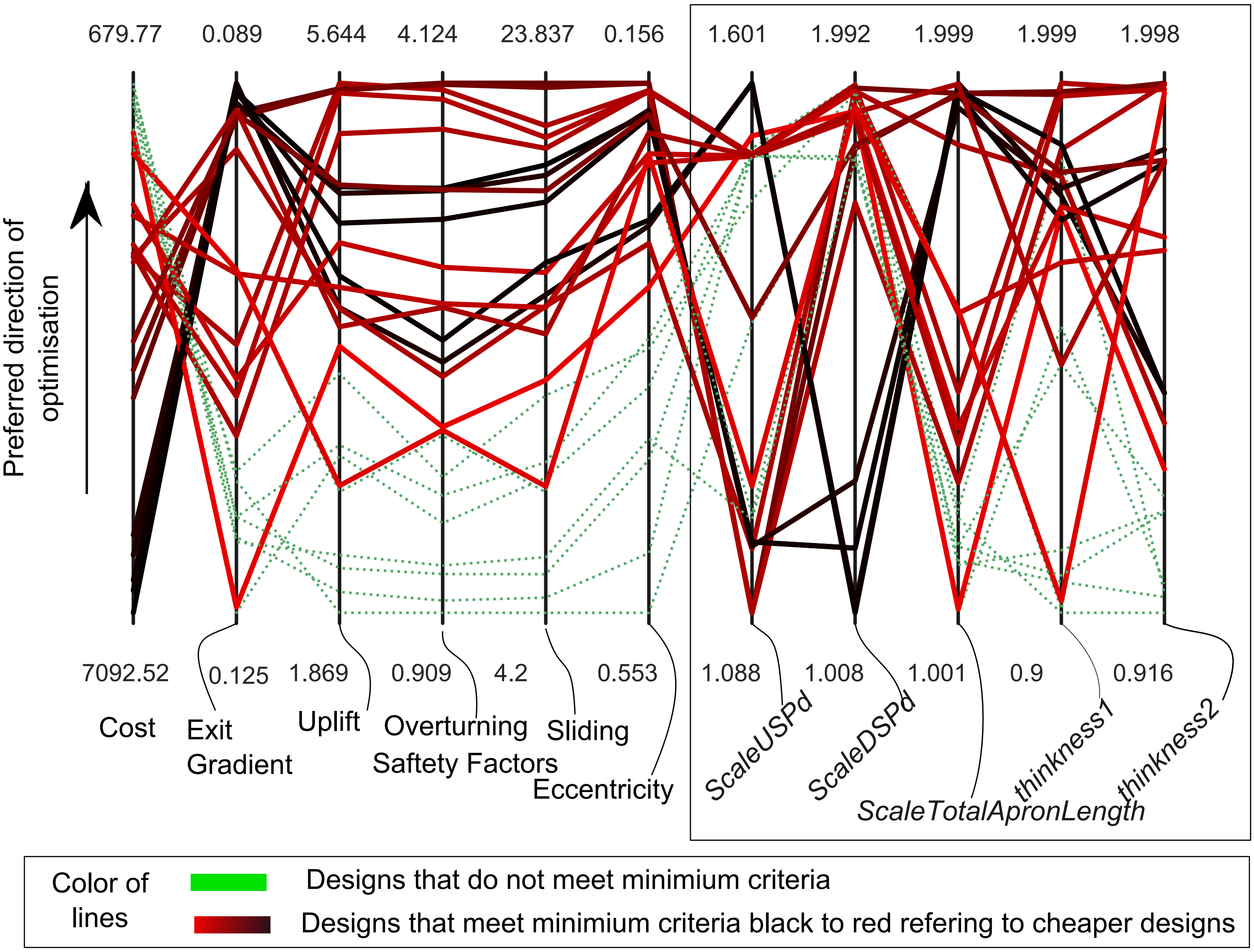
Preferred direction of optimisation
9264.9
0.125
1.835
0.9
27.213
0.56
Cost
Exit Gradient
Saftety Factors against failure by:
Uplift
Overturning
Sliding
Eccentricity
Color of lines
Designs that meet minimium criteria black to red refering to cheaper designs
Performance of a traditionally designed (non-optimised structure)



679.77
0.089
5.644
4.124
23.837
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1.601
1.992
1.999
1.999
1.998
Preferred direction of optimisation
7092.52
0.125
1.869
0.909
4.2
0.553
1.088
1.008
1.001
0.9
0.916
Cost
Exit Gradient
Uplift
Overturning
Sliding
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ScaleUSPd
ScaleDSPd
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thinkness1
thinkness2
Color of lines
Designs that do not meet minimium criteria
Designs that meet minimium criteria black to red refering to cheaper designs

Table 1 Performance consideration in traditional method and metrics used in the suggested method

Design Criteria	Traditional checks	Suggested metric transformation
Stability against Uplift	$\frac{\sum Vg}{\sum Vu} > 1$	Maximize fu = $\frac{\sum Vg}{\sum Vu}$
Stability against Overturning	$\frac{\sum Ms}{\sum Md} > 2$	Minimize $fo = \frac{\sum Ms}{\sum Md}$ Where $\sum Ms$ moments leading to stability $\sum Md$ destabilizing moments
Reduce eccentricity	$e < \left\lfloor \frac{ta}{2} - X \right\rfloor < \frac{ta}{6}$	Minimize $fe = \left\lfloor X - \frac{ta}{2} \right\rfloor$ where $X = \frac{\sum M}{\sum Vf}$
Stability against Shear and Sliding	$\frac{\sum V}{\sum H} > 0.35$	Maximize fs Where $fs = \frac{\sum V}{\sum H}$
Cost	Cost was calculated post design	Minimize fc Where fc is the sum of costs of apron, piles and excavation and depends on the length, thickness and depth of the components