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OPTIMIZATION OF GRILLAGES USING GENETIC ALGORITHMS FOR INTEGRATING MATLAB AND FORTRAN ENVIRONMENTS

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Abstract. The purpose of the paper is to present technology applied for the global optimization of grillage-type pile foundations (further *grillages*). The goal of optimization is to obtain the optimal layout of pile placement in the grillages. The problem can be categorized as a topology optimization problem. The objective function is comprised of maximum reactive force emerging in a pile. The reactive force is minimized during the procedure of optimization during which variables enclose the positions of piles beneath connecting beams. Reactive forces in all piles are computed utilizing an original algorithm implemented in the Fortran programming language. The algorithm is integrated into the MatLab environment where the optimization procedure is executed utilizing a genetic algorithm. The article also describes technology enabling the integration of MatLab and Fortran environments. The authors seek to evaluate the quality of a solution to the problem analyzing experimental results obtained applying the proposed technology.

Keywords: global optimization, finite element method, genetic algorithms, optimization of grillages, MatLab, Fortran.

Introduction

The search for a global optimal solution is common and inseparable routine in engineering practice. The paper analyzes a particular civil engineering problem – the optimization of pile positions in grillage-type foundations (further *grillages*). Such foundations are composed of connective beams lying on supporting piles. The grillages are widely recognized as the most popular and efficient foundation design, particularly in the case of unstable soil. All generated load from the structure is distributed through connective beams to piles. The optimum grillage should meet dual criteria: the quantity of piles should be minimum and connective beams should receive minimum possible bending moments resulting in minimum demand of concrete for beams. Thus, two separate optimization problems confront each other: search for a minimum volume of beams and search for a minimum quantity of piles. The first optimization problem is equivalent to the minimization of the maximum bending moment in beams. Since the carrying power of a separate pile is known, the second optimization problem can be rendered as the minimization of the maximum reactive force in piles throughout the entire set of piles. Both problems can be incorporated into one utilizing a compromise objective function. The design parameters for both problems are the location of piles. An algorithm for local search was employed for the optimum location of piles beneath a separate beam of the grillage (Belevičius, Valentinavičius 2001, 2000) and under the whole grillage using an iterative algorithm on the basis of the above mentioned work (Belevičius *et al.* 2002). Experience demonstrates that the objective function possesses many local minima points for practical grillage optimization problems. Consequently, local search is certainly not a proper choice, and therefore global optimization algorithms must be utilized.

This paper also considers the second problem – the minimization of the maximum reactive force in piles. Since the problem may have several tens of design parameters, the only choice for optimization algorithms is to use stochastic optimization algorithms. Simulated annealing (Groenwold, Hindley 2002) and the genetic algorithm (Goldberg 1989) are the most promising algorithms for these problems (Belevičius *et al.* 2011).

Thus, we formulate a problem of pile location searching for proper pile positions beneath connective beams. Identical reactive forces for all piles would be an indicator the ideal pile placement scheme is obtained. This is hardly possible, particularly in case when immovable piles prevail in design. Consequently, such piles always retain their positions and do not participate in the optimization process. Some technological constraints may also make an ideal scheme non-achievable, i.e. the distance between adjacent piles should not be too small due to the specific capacities of a pile-driver. The current paper does not consider immovable piles and allow for a pile to reserve whichever position in the grillage; however, piles are not typically placed at the joints of the grillage.

Bowles (1997); Reese *et al.* (2005) describe exhaustive technical details on grillages.

The following initial data are considered for the problem of grillage optimization:

- cross-section data on all beams (area, moments of inertia);
- loading data – active forces can be applied in the form of concentrated loads and moments at any point on the beam or in the form of distributed trapezoidal loadings at any segment of the beam;
- maximum allowable reactive force at any pile;
- material data of all beams (material in one beam is treated as isotropic);
- minimum possible distance between adjacent piles;
- positions of immovable piles (if any);
- the stiffness of a pile (vertical, rotational);
- geometrical scheme for connecting beams;

The outcome of optimization includes the required number of piles and the location of such piles.

However, only a few works so far deal with the optimization of foundation schemes. Chan *et al.* (2009) combine sizing and topology optimization; however piles are aggregated to special groups. Chamoret *et al.* (2008) analyzed beam optimization problems taking into account the form of the optimal sizing of beams in grillage structures under given boundary and loading conditions.

Mathematical Model of Grillage Optimization

The problem is attractive from a mathematical point of view, because the global solution of the objective function is possible to obtain in advance: it is enough to calculate the ratio of the total active forces and the number of piles. Thus, the quality of the obtained solution is possible to evaluate.

The following single objective optimization problem is formulated as follows:

$$\min_{x \in D} G(x), \tag{1}$$

where G – maximum reactive force in the pile; D – a feasible region of design parameters.; x – design parameters.

In order the value of reactive forces could vary in different piles (in the case the characteristics of piles are different), instead of maximum reactive force, we consider maximum difference between vertical reactive force in the pile and allowable reactive force for the pile:

$$G(x) = \max_{1 \le i \le N_a} \left| P_i - t_i P_a \right|, \tag{2}$$

where P_a – allowable reactive force, o P_i – reactive force for the i-th pile; N_a – number of piles; t_i – multipliers enabling to utilize different allowable reactive forces for different piles.

Since piles may be located only beneath connective beams, obvious restrictions on the location of piles emerge: in the course of the optimization process, piles can move only along connective beams. Hence, a two-dimensional beam structure of the grillage is mathematically "unfolded" to a one-dimensional construct, and piles can freely shift their position through this space. The backward transformation restores the location of piles into the two-dimensional beam structure of the grillage.

The article solves a direct problem of identifying maximum reactive force in piles utilizing the finite element method (FEM) and employing a fast and original program written using the Fortran programming language; the program is incorporated within the MatLab optimization environment applying the "black-box" principle depending on the response of which an appropriate pile placement scheme is defined by the optimization program. One design parameter corresponds to one location of the pile in one-dimensional space. Constraints for design parameters are as follows:

$$0 \le x_i \le L, \; i = 1, 2, ..., N_a, \tag{3}$$

where x_i – the i-th pile coordinate within one-dimensional space; L – the total length of all beams in the grillage.

When investigating the grillage, connective beams are idealized as beam elements, whilst piles are idealized as supports, i.e. finite element mesh nodes with assigned elastic boundary conditions. Beam elements are comprised of 2 nodes with 6 degrees of freedom each (3 displacements along coordinate axes and 3 rotations about these axes). The stiffness matrix $[K]$ for beam element is available in many textbooks (e.g. Spyrakos, Raftoyiannis 1997):

$$[K] = \begin{bmatrix} [K_{11}] & [K_{12}] \\ [K_{12}]^T & [K_{22}] \end{bmatrix}. \tag{4}$$

The main statics equation that secures the stability constraints of the structure is as follows:

$$[K]^a \{u\}^a = \{F\}^a, \tag{5}$$

where index a – the ensemble of elements (not shown in the equation below); $\{u\}$ –nodal displacements and $\{F\}$ – active forces. Since nodal displacements are defined, reactive forces for piles can be computed as follows:

$$R_i = \sum_j \left[K_{ij} \right] u_j . \qquad (6)$$

Technology

Herein the proposed calculation technology is presented analyzing the optimization problem of 10-pile grillage (Fig. 1). The technology is composed of two stages:

1. Investigation into the grillage and a solution to a direct problem of computing reactive forces in piles are performed utilizing FEM. It can be implemented applying an original algorithm created using the Fortran programming language.
2. The "Black-box" principle is utilized to integrate the algorithm within the MatLab environment where the optimization problem is solved employing the genetic algorithm.

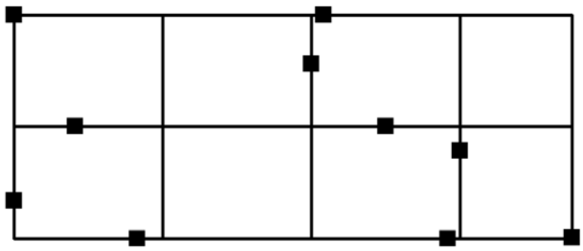

Fig. 1. 10-pile grillage

At the first stage, the objective function (2) is calculated and at the second stage this function is optimized. In such a case, the technological problem emerges, i.e. to call the Fortran function from the MatLab environment.

Further, one of the algorithms is proposed to solve such problem in practice:

1. It is necessary to create a library in the Fortran environment. The subroutine of the objective function (2) should be included within the library. Therefore, two files - $*.dll$ and $*.lib$ are created;
2. File $*.h$ where the objective function (2) is declared within the Fortran library utilizing the syntax of the $C++$ programming language is created;
3. Created files ($*.dll$, $*.lib$ and $*.h$) must be uploaded into the corresponding catalogues:
   3.1.1. file $*.dll$ – into catalogue
   ...\bin\win32;
   3.1.2. file $*.lib$ – into catalogue
   ...\ extern\lib\win32\microsoft;
   3.1.3. *file* $*.h$ – into catalogue *...\extern\include;*
4. Within the MatLab environment, file $*.h$ utilizing command *hfile*, i.e.
   $hfile = [matlabroot' \backslash extern \backslash include \backslash grill.h']$
   should be defined;
5. When utilizing command *loadlibrary*, the library we will use, i.e. $loadlibrary('grillage', hfile)$ should be defined;
6. Following these actions, a possibility of operating all functions of *grillage.dll* libraries appears. These functions are described in the file *grill.h*;
7. Command *calllib* is utilized to call functions from an external library integrated within the MatLab environment and the arguments should be transferred by arrows. Therefore, an additional function (within the MatLab environment) where all these actions will be performed have been created.
   An example of a function:
   function [r]= grill_10(x)
   pX = libpointer('doublePtr', x);
   pR_best = libpointer('doublePtr', 100000.);
   calllib('grillage',
   'OBJECTIVE_FUNCTION', pX,10,pR_best);
   r = get(pR_best, 'Value');

The created library function *'OBJECTIVE_FUNCTION'* contains 3 parameters:

pX – an array of pile coordinates,
10 – the number of piles,
pR_best – maximum reactive force in piles.

8. Next, we are enabled to use function *grill_10(x)* within the MatLab environment – *The genetic algorithm and direct search Toolbox* (Fig. 2).

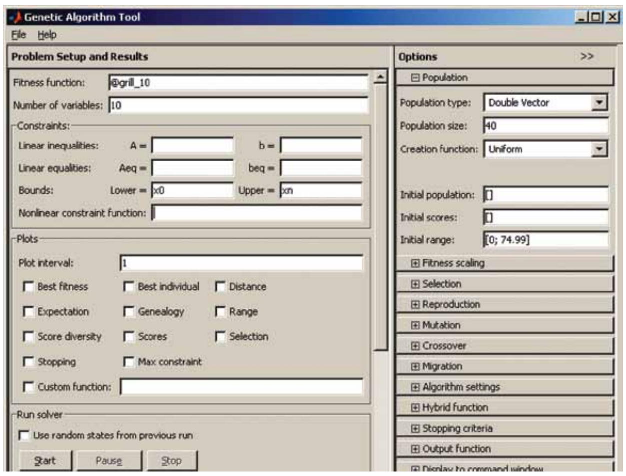

Fig. 2. Optimization toolbox in MatLab

Numerical Experiments

To solve the optimization problem for 10-pile grillage, 30 independent numerical experiments have been performed. The total length of all beams in the grillage is 75, and therefore the following boundary conditions for pile position have been applied:

x0 = [0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0]

xn = [74.99 74.99 74.99 74.99 74.99 74.99 74.99 74.99 74.99 74.99]

Almost all parameters of the genetic algorithm are selected by default, except the parameters shown in Fig. 3.

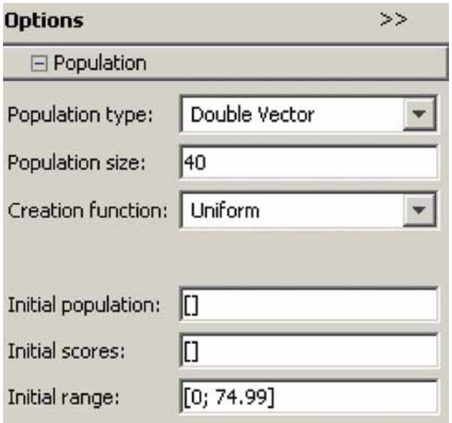

Fig. 3. Parameters of the genetic algorithm

The results of the conducted experiments are presented in Table 1. The average duration of one experiment is 2 min 30 sec (computer *Intel(R) Core(TM)2 Duo CPU T7500 @ 2.20GHz, 984 MB of RAM*). Fig. 4 shows a typical convergence of the objective function (2) average and the best values depending on the number of generation.

Table 1. The results of numerical experiments

No. of a numerical experiment	The best value of an objective function	No. of a numerical experiment	The best value of the objective function
1	223.1701	16	207.5362
2	205.0659	17	208.0543
3	204.2530	18	210.5133
4	210.9061	19	199.6463
5	204.5285	20	201.4831
6	202.5660	21	195.1419
7	221.4256	22	205.5572
8	222.8372	23	216.9473
9	195.8146	24	221.8892
10	202.8087	25	203.1146
11	204.2033	26	211.5554
12	222.0529	27	214.2275
13	246.9790	28	217.9776
14	208.4597	29	205.0124
15	258.9327	30	214.2355

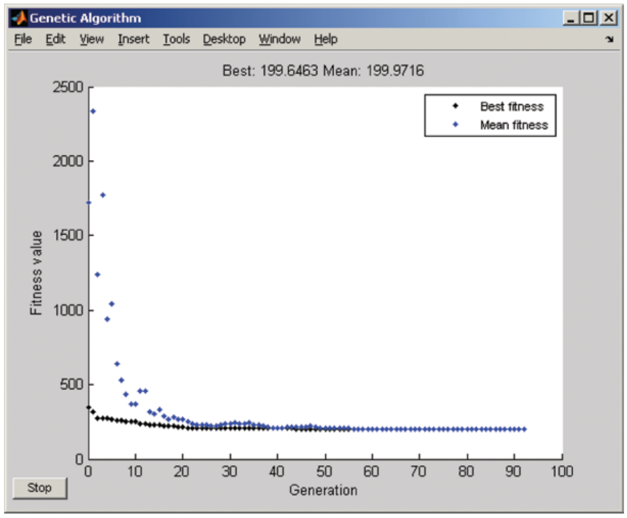

Fig. 4. Typical convergence of the objective function

The results of numerical experiments (Table 1) have revealed the best value of the objective function (2) is 195,1419. A scheme for pile placement that corresponds to the best value of the solution is shown in Fig. 5.

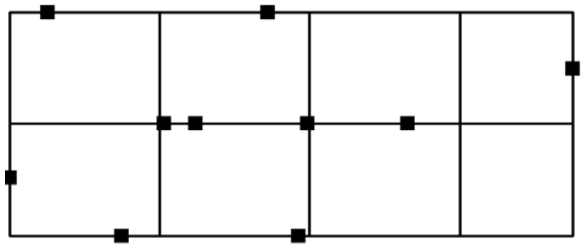

Fig. 5. Scheme for pile placement corresponding to the best solution

The previous works (Belevičius *et al.* 2011) have demonstrated that the global solution of the objective function is possible to be obtained in advance (considering a similar type of problem); however, the locations of piles (corresponding to such global solution) are to be determined during the optimization process. The global solution for 10-pile grillage is 183,7656. Therefore, the difference between the best obtained value of the objective function (195,1419) during optimization and the global solution is approx. 6,2%. Hence, the proposed calculation technology is a perspective tool for optimizing small scale grillages.

Conclusions

The proposed technology enables a researcher to potentiate from MatLab opportunities and optimizes objective functions realized utilizing the Fortran programming language. It seems to be very useful particularly in the case, when objective functions are very complicated and enormous time consumption would be required to create similar functions directly within the MatLab environment. Since the best obtained optimization result is very close to the global solution of the problem, this technology can be successfully applied for optimizing small scale grillages.

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MATLAB IR *FORTRAN* APLINKŲ SUJUNGIMAS ROSTVERKAMS OPTIMIZUOTI GENETINIAIS ALGORITMAIS

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Santrauka

Straipsnyje pateikiama sijynų tipo pamatų (toliau *sijynų*) globalaus optimizavimo technologija. Optimizavimo tikslas – nustatyti optimalų polių išdėstymą sijynuose. Šis uždavinys priskiriamas topologijos optimizavimo uždavinių grupei. Tikslo funkciją sudaro maksimali poliuje kylanti atraminė reakcijos jėga, kuri minimizuojama optimizavimo procese. Šio uždavinio projektavimo kintamieji – polių padėtys po jungiančiosiomis sijyno sijomis. Tiesioginis reakcijų poliuose skaičiavimo uždavinys sprendžiamas originaliu algoritmu, sukurtu *Fortran* programavimo kalba. Šis algoritmas juodosios dėžės principu jungiamas prie *MatLab* aplinkos, kurioje genetiniu algoritmu sprendžiamas optimizavimo uždavinys. Straipsnyje taip pat aprašyta technologija, kuri leidžia sujungti *Matlab* ir *Fortran* aplinkas, t. y. iš *Matlab* aplinkos iškviesti *Fortran* paprogramį. Analizuodami eksperimentinius duomenis autoriai bando įvertinti gaunamų sprendinių kokybę.

Reikšminiai žodžiai: globalusis optimizavimas, genetiniai algoritmai, rostverkų optimizavimas, baigtinių elementų metodas, *MatLab*, *Fortran*.