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Determination of natural periods of vibration using genetic programming

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Abstract. Many building codes use the empirical equation to determine fundamental period of vibration where in effect of length, width and the stiffness of the building is not explicitly accounted for. Also the equation, estimates the fundamental period of vibration with large safety margin beyond certain height of the building. An attempt is made to arrive at the simple empirical equations for fundamental period of vibration with adequate safety margin, using soft computing technique of Genetic Programming (GP). In the present study, GP models are developed in four categories, varying the number of input parameters in each category. Input parameters are chosen to represent mass, stiffness and geometry of the buildings directly or indirectly. Total numbers of 206 buildings are analyzed out of which, data set of 142 buildings is used to develop these models. It is observed that GP models developed under B and C category yield the same equation for fundamental period of vibration along X direction as well as along Y direction whereas the equation of fundamental period of vibration along X direction and along Y direction is of the same form for category D. The equations obtained as an output of GP models clearly indicate the influence of mass, geometry and stiffness of the building over fundamental period of vibration. These equations are then compared with the equation recommended by other researcher.

Keywords: genetic programming; natural periods of vibrations; data driven tools

1. Introduction

The fundamental period has a primary role in seismic design and assessment as it is the main feature of the structure that allows one to determine the elastic demand, and indirectly, the required inelastic performance in static procedures. In the majority of cases, the assessment of the period is considered as a function of the structural system classification and number of storeys or height (Verderame *et al.* 2010). Structural dynamics principles indicate that the fundamental period plays a prominent role in anticipating the forces to which a structure will be subjected during earthquake ground motions (Gilles and McClure 2008). The seismic response of a structural building system depends on several factors including its configuration, dynamic characteristics and the characteristics of the applied ground motion. It is imperative to simulate these factors as close to reality as possible in order to correctly predict seismic performance or vulnerability of a given

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structural system using experimental and/or analytical techniques (Annan *et al.* 2009). The dynamic analysis of structures for earthquake induced loads is very expensive in term of the computational burden and is a time consuming process (Ahamadi *et al.* 2008). Seismic responses of reinforced concrete structures have been investigated using different methodologies which involve a great complexity particularly in the analysis of real building due to lack of complete data related to excitation, creation of an idealized model, modeling the dynamic loads, performing an analysis and extrapolating the predictions to the real system (Caglar *et al.* 2008). The fundamental vibration period of a building appears in the equation specified in building codes to calculate the design base shear and lateral forces. It is seen that although the code formulas provide periods that are generally shorter than the measured periods, these formulas can be improved to provide better correlation with the measured data. An improved empirical formula is obtained for RC moment resisting frames based on available dataset of 27 RC moment resisting buildings. The dataset is actual recorded observations taken during several California earthquakes (Goel and Chopra 1997). Mehanny (2011) quantified the error in the calculated period of single-mode dominant structures due to the error propagated through variation and uncertainty in the values of both mass and stiffness parameters. According to achieved results, a relative error in the period of vibration in the order of 19% for new designs / constructions and of about 25% for existing structures for assessment purposes is acknowledged. Verderame *et al.* (2010) determined relationships of elastic period of sub-standard reinforced concrete moment resisting frame buildings for the three populations (with seismic coefficient 0.05g, 0.07g and 0.1g) of seismic building. The authors have analyzed 700 structures to investigate the elastic period in two principal directions of the building. The variation in the length and width of the buildings is considered between 15 m to 30 m and 8 m to 12 m respectively. The height of the building is considered between 6 m to 24 m. The result of the study has suggested that height of the building seem inadequate to predict period variability and a global parameter such as plan area should be added in simplified relationship for rapid period evaluation. Pinho and Crowley (2006) proposed simplified equation to relate the yield period of vibration of existing buildings to their height for use in large-scale vulnerability assessment applications.

Over many years, research has been conducted to verify and improve the empirical equation for the fundamental period of the building. The formulae are calibrated to give shorter periods than measured to produce conservative design forces. In view of this, it felt necessary to apply recent data driven technique in the form of Genetic Programming (GP) for estimating natural periods of vibration of reinforced concrete building. Even analytical methods are also based on certain assumptions which may introduce the errors in the actual value and analytical value. Also conducting on site testing of actual buildings requires sophisticated instrumentation and heavy cost. The data driven techniques extract the information from the data presented to them. Even though the GP models are developed from the analytical values, it is seen that GP technique has given the empirical equation closer to the equation obtained from the experimental observations. Moreover, since GP evolves an equation or formula relating the input and output variables, a major advantage of the GP approach is its automatic ability to select the programs which perform better discarding the ones having less accuracy. GP can thus reduce substantially the dimensionality of the input variables. In the present work emphases is on the development of GP models with minimum possible number of input parameters. Although many researchers have used data driven technique in the form of Artificial Neural Network (ANN) and Wave nets in the dynamic analysis of building frames either to reduce the computational efforts or the computational time, an attempt is made to arrive at the empirical equation for fundamental period of vibration using GP technique. The other type of application of ANN found in the field of earthquake engineering is in forecasting tsunami water levels (Charhate and Deo 2006). The tsunami water level data belonging to the Alaska–Aletutian region is used to develop the ANN model. The results are found satisfactory.

Article 2 of this paper describes the theory of Genetic Programming along with its application in Civil Engineering. The few of basic concepts of Genetic Programming are illustrated in Appendix A. The generation of data required for the development of GP models, methodology and details of model formulation are discussed in article 3. The results obtained through these models are shown in article 4 and finally the conclusions are discussed in article 5.

2. Genetic programming

The concept of genetic programming (GP) is borrowed from the process of evolution occurring in nature, where the species survive according to the principle of 'survival of the fittest'. The GP is similar to genetic algorithms (GA) but unlike the latter its solution is a computer program or an equation as against a set of numbers in the GA (Gaur and Deo 2008). Although research on GP techniques dates back to the 1960s and 1970s, GP emerged as a distinct discipline presented by Koza (Johari *et al*. 2006).

2.1 The primitives of genetic programming

Every solution evolved by GP is assembled from two sets of primitives nodes; terminals and functions. The terminal set contains nodes that provide an input to the GP system while the function set contains nodes that process values already in the system. Constants can be used in GP by including them in the terminal set. Once the evolutionary process is started, the GP system randomly selects nodes from either set and thus may not utilize all of the available nodes. However increasing the size of each node set enlarges the search space. Therefore only a relatively simple node set is initially provided and nodes are usually added only if required (David *et al.* 2004).

2.2 Tree based genetic programming

The primitives of GP, the function and terminal nodes, must be assembled into a structure before they may be executed. Three main types of structure exist: tree, linear and graph. Within this work, the input (the structure to be optimized or designed) actually forms a graph network. However by the duplication of joint data i.e. the same 'joint node' can exist in the same tree on more than one occasion, this graph network is converted into a tree structure (David *et al.* 2004).

2.3 Algorithm of genetic programming

The genetic programming paradigm breeds computer programs to solve problems by executing the following three steps:

(1) Generate an initial population of random compositions of the functions and terminals of the problem (computer programs).

(2) Iteratively perform the following sub steps until the termination criterion has been satisfied:

(a) Execute each program in the population and assign it a fitness value according to how well it solves the problem.

(b) Create a new population of computer programs by applying the following two primary operations. The operations are applied to computer program(s) in the population chosen with a probability based on fitness.

(i) Copy existing computer programs to the new population.

(ii) Create new computer programs by genetically recombining randomly chosen parts of two existing programs.

(3) The best computer program that appeared in any generation (i.e., the best-so-far individual) is designated as the result of genetic programming. This result may be a solution (or an approximate solution) to the problem (Koza 1992).

2.4 Advantages of genetic programming

A key advantage of GP as compared to traditional modelling approaches is that it does not assume any a priori functional form of the solution. For instance, in a typical regression method, the model structure is specified in advance (which is in general difficult to do) and the model coefficients are determined. For neural networks, the time consuming task of initially defining the network structure has to be undertaken and then the coefficients (weights) are found by the learning algorithm. On the other hand, in GP, the building blocks (the input and target variables and the function set) are defined initially, and the learning method subsequently finds both the optimal structure of the model and its coefficients. However common drawback of GP is the difficulty to handle constants.

In GP, as in any data-driven prediction model, the selection of appropriate model inputs is extremely important. This is especially so when lagged input variables are also used. Inclusion of irrelevant inputs leads to poor model accuracy and creation of complex models, which are more difficult to interpret as compared to simpler ones.

2.5 Applications of genetic programming in civil engineering

Applications of Genetic Programming in Civil Engineering are sparse and few. Majority of them can be found in Hydraulic Engineering including wave hydrodynamics, Hydrology and Hydraulics. Londhe and Dixit (2012) have taken a comprehensive review of these applications along with theory of GP. Amongst other applications in Civil Engineering, Heshmati *et al.* (2008), proposed new formulations for soil classification by means of linear genetic programming (LGP). It was observed that LGP models were able to predict the target values to high degree of accuracy and the equations obtained through GP models were quite short, more simple and more practical as compared with then existing models found in the literature. Johari (2006) employed GP to predict the soil water characteristic curve (SWCC) of soils. GP simulations were compared with the experimental results as well as the models proposed by other investigators. This comparison indicated superior performance of the proposed model for predicting the SWCC. Shaw *et al.* (2004) have discussed some basics of genetic programming and its applications in civil engineering and structural engineering. As mentioned in introduction no applications of GP were found particularly in the field of Earthquake Engineering by the authors. Perhaps the present work is a first ever application of GP to predict natural periods of vibration.

Use of GP in Civil Engineering field is a very recent development. No references are noticed by the author in the field of application of Genetic Programming for seismic analysis of RC building although some applications are found in Hydraulic Engineering (Londhe and Dixit 2012).

3. Data generation, methodology and analysis

3.1 Geometry and material properties

The buildings are assumed to be fixed at the base without soil structure interaction and the floors as rigid diaphragm. The sections of the structural elements are rectangular and square for the beams as well as the columns. The thickness of slab is 150 mm and the height of the floor as 3m or 3.5m. The beam sections are considered in the size range of 230 mm x 450 mm to 450mm x 750mm. The column sections for square shapes are assumed in the size range of 300 mm x 300 mm to 750 mm x 750 mm and that for rectangular shapes are considered in the range of 230 mm x 300 mm to 230 mm x 600 mm. The modulus of elasticity is considered as $5000\sqrt{f_{ck}}$ and the mass density as 25 KN/m^3. Three grades of concrete assumed in the analysis are M20, M25 and M30. Live load intensity is considered as either 2 KN/m^2 or 3 KN/m^2. A typical floor plan of building is shown in Fig. 1.

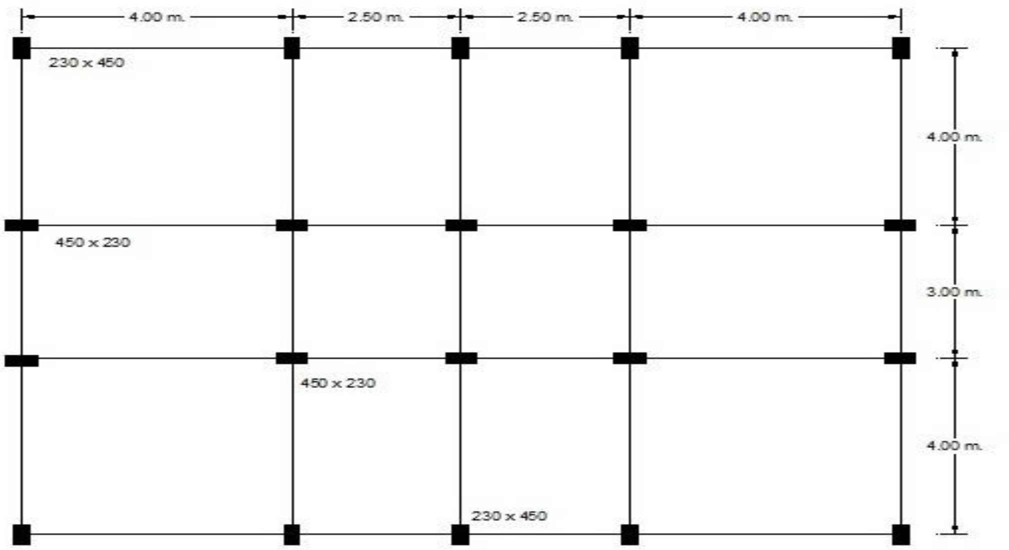

Fig. 1 Typical floor plan of building

3.2 Generation of data

Total number of 206 buildings with height range between 4 storeys to 15 storeys is analyzed for natural periods of vibration along X as well as Y directions. The structures are assumed to be located in the seismic zone number III on the medium soil. Importance Factor (I) as 1 and Response Reduction factor (R) as 5 are considered for all buildings. Authors have developed MATLAB codes to perform the analysis. Effect of first three modes is considered for the dynamic analysis.

3.3 Methodology

Out of the data for 206 buildings, the data set of 142 buildings is used to train the model and that of remaining 64 buildings is used to test the model. This division of the data is arrived at after the several trials. So the division of the data is approximately 70 % for training and remaining 30% for testing the model. An attempt is made to arrive at the minimum possible input parameters to develop all GP models without sacrificing much of the accuracy. Effect of first three modes is considered in the estimation of natural periods of vibration of reinforced concrete building frames. The statistic measures used to assess the accuracy of the developed models are Root Mean Squared Error (RMSE), Correlation Coefficient (R) and Coefficient of Efficiency (CE). A tree based GP has been employed to develop these models using GPKernel Software developed by Babovic and Keijzer (2000).

3.4 Model formulation

In the present study, Genetic Programming models are developed under four categories to predict the structural response in terms of natural periods of vibration along X and Y directions. Each category mentioned here consists of two subcategories GP1 and GP2. GP1 category models estimates the natural period of vibrations for first three modes along X direction. GP2 category models estimates the natural period of vibrations for first three modes along Y direction.

Category A comprises all GP models developed with 9 input parameters. These input parameters are chosen considering the effect of geometry, mass distribution and the stiffness characteristics of the building frames in the dynamic analysis. Effect of geometry is incorporated in terms of L, W and H whereas the effect of the mass of the building is incorporated in terms of N_c, N_B, W_{cmin}, W_{cmax}, D_{cmin}, D_{cmax} and n. The stiffness characteristic of the building frames is assumed in terms of W_{cmin}, W_{cmax}, D_{cmin}, D_{cmax} and h.

Category B comprises all GP models developed with eight input parameters. Effect of asymmetry of the building frames in the plan may be incorporated by introducing one more input that is perimeter of the building (P) as a substitute for two input parameters viz. Length and Width of building. New set of GP models are developed using eight input parameters instead of nine and three output parameters.

Category C comprises all GP models developed with five input parameters. With an aim of minimizing the number of input parameters to avoid duplication of inputs to the model, an attempt is made to develop these models using only five input parameters. As the mass, stiffness and geometry of the building are significant parameters in the dynamic analysis; it is decided to develop the models with five input parameters as a trial. Perimeter (P) and height of the building (H) can represent the geometry to the model, sizes of the columns and height of the storey (W_{cmin}, W_{cmax}, D_{cmin}, D_{cmax} and h) can be referred for the stiffness calculations and the effect of the other input parameters like number of beams and columns per floor and number of floors (N_c, N_B and n) may be taken indirectly into account through the perimeter of the building, height of the building and other input parameters chosen. So five input parameters becomes: Perimeter of the building

(P), Minimum Width of the Column (W_{cmin}), maximum width of Column (W_{cmax}), Height of the building (H) and Height of the storey (h) along X direction and Perimeter of the building (P), Minimum depth of the column (D_{cmin}), and maximum depth of column (D_{cmax}), Height of the building (H) and height of the storey (h) along Y direction.

Table 1 Input parameters for X direction

Sr. No.	Parameter	Notation Used
1	Length of building	L
2	Width of Building	W
3	Number of Columns	N_c
4	Number of Beams	N_B
5	Minimum dimension of column along X direction	W_{cmin}
6	Maximum dimension of column along X direction	W_{cmax}
7	Height of the Building	H
8	Height of the storey	h
9	Number of Floors	n

Table 2 Input parameters for Y direction

Sr. No.	Parameter	Notation Used
1	Length of building	L
2	Width of Building	W
3	Number of Columns	N_c
4	Number of Beams	N_B
5	Minimum dimension of column along Y direction	D_{cmin}
6	Maximum dimension of column along Y direction	D_{cmax}
7	Height of the Building	H
8	Height of the storey	h
9	Number of Floors	n

Table 3 Details of GP models

Category of GP Model	Subcategories	Number of Input Parameters	Number of Output parameters
A	GP1	9	3
	GP2	9	3
B	GP1	8	3
	GP2	8	3
C	GP1	5	3
	GP2	5	3
D	GP1	6	3
	GP2	6	3

Category D comprises all GP models developed with six input parameters. An attempt is made to develop GP models using six input parameters viz. seismic weight of the building (*W*), stiffness of the building per floor (*K*) , number of floors (*n*), length (*L*), width (*W*) and height (*H*) of the building. Geometry of the building is given in terms of the length, width and height of the building. Unlike remaining all GP models, the seismic weight and stiffness values are directly given as inputs.

All these input parameters are easy to obtain from the drawings. Table 1 and 2 given below shows the input parameters used along X and Y directions respectively. Table number 3 shows the details of categories of these GP models. Output parameters of the subcategories of GP models are shown in table number 4.

Table 4 Output parameters of subcategories of GP models

Model	Direction of Analysis	Output parameters		
		Output 1	Output 2	Output 3
GP 1	X	Natural Period of Vibration for first mode (T_1)	Natural Period of Vibration for second mode (T_2)	Natural Period of Vibration for third mode (T_3)
GP 2	Y	Natural Period of Vibration for first mode (T_1)	Natural Period of Vibration for second mode (T_2)	Natural Period of Vibration for third mode (T_3)

4. Results and discussions

As per the discussions in previous paragraphs, four categories of GP models are developed and comparison of the results is discussed here in this article.

4.1 Results of Category A model

The results are shown in Table 5.

Table 5 Results of GP models (Category A)

Model	Performance Parameters	T_1	T_2	T_3
GP1	R	0.97	0.97	0.97
	RMSE	0.059	0.022	0.013
	CE	0.93	0.93	0.94
GP2	R	0.98	0.97	0.98
	RMSE	0.075	0.029	0.013
	CE	0.95	0.94	0.97

4.2 Results of Category B model

The results of these models are shown in Table 6.

Table 6 Results of GP models (Category B)

Model	Performance Parameters	T_1	T_2	T_3
GP1	R	0.96	0.97	0.97
	RMSE	0.064	0.024	0.014
	CE	0.91	0.90	0.93
GP2	R	0.97	0.97	0.97
	RMSE	0.079	0.028	0.026
	CE	0.94	0.94	0.88

4.3 Results of Category C model

The results of these models are shown in Table 7.

Table 7 Results of GP models (Category C)

Model	Performance Parameters	T_1	T_2	T_3
GP1	R	0.96	0.97	0.97
	RMSE	0.065	0.023	0.014
	CE	0.91	0.91	0.93
GP2	R	0.97	0.97	0.96
	RMSE	0.072	0.028	0.021
	CE	0.94	0.94	0.91

4.4 Results of Category D model

The results of these models are shown in Table 8.

Table 8 Results of GP models (Category D)

Model	Performance Parameters	T_1	T_2	T_3
GP1	R	0.99	0.99	0.99
	RMSE	0.010	0.010	0.012
	CE	0.99	0.98	0.95
GP2	R	0.99	0.99	0.99
	RMSE	0.010	0.018	0.014
	CE	0.99	0.97	0.96

Table 9 shown below shows the hypothesis, obtained from the developed GP models in all the four categories, for the fundamental period of vibration.

Table 9 Hypothesis of GP models

Category	Model	Hypothesis
A	GP1	T_{1x} =0.00602 $h \quad H^{3/4}/(W_{cmin}^{0.5} W_{cmax})$
A	GP2	$T_{1y} = W^{0.25} h \quad H/(1268.54\, D_{cmin} D_{cmax})$
B	GP1	$T_{1x} = 0.00188\, h \quad H/ (W_{cmin}^{0.5} W_{cmax}^{1.5})$
B	GP2	$T_{1y} = 0.00164\, h \quad H/ (D_{cmin} D_{cmax})$
C	GP1	$T_{1x} = 0.00188\, h \quad H/ (W_{cmin}^{0.5} W_{cmax}^{1.5})$
C	GP2	$T_{1y} = 0.00164\, h \quad H/ (D_{cmin} D_{cmax})$
D	GP1	$T_{1x} = n \quad \sqrt{1.7\, m/K_x}$
D	GP2	$T_{1y} = n \quad \sqrt{1.7\, m/K_y}$

However these equations are obtained for the range of input parameters as shown in the Table 10.

Table 10 Range of the values of input parameters

Input Parameter	Range of the values
Length of the building	9.75 m – 36 m
Width of the building	8 m – 32 m
Dimensions of the column	0.23 m – 0.75 m
Height of the building	12 m -52.5 m
Height of the storey	3 m – 3.5 m
Number of floors	4 - 15

4.5 Discussions

From the theory of structural dynamics, for single degree of freedom systems, natural frequency (ω) may be obtained as under

$$\omega = (k/m)^{1/2} \tag{1}$$

Where k = stiffness of the system having mass m.

Fundamental period of vibration (T) is then found out as

$$T = 2\pi / \omega \tag{2}$$

$$T= 2\pi / (k/m)^{1/2} \tag{3}$$

$$T= 2\pi\ (m/k)^{1/2} \tag{4}$$

$$k = Nc\ (12\ E\ I\ /\ h^3) \tag{5}$$

$$k = Nc\ [12\ E\ (w\ D^3/12)\ /\ h^3] \tag{6}$$

Where *w* is width of column, *D* is the depth of column, *E* is Modulus of Elasticity, *I* is moment of Inertia, *Nc* is number of columns and *h* is height of storey.

$$T = 2\pi\ (m\ h^3/Nc\ E\ w\ D^3)^{1/2} \tag{7}$$

Further mass (*m*) of the system may be worked out using perimeter (*P*) and height of the building (*H*). Thus it can be seen from Eq. (7) that height of the building, height of the storey and column sizes have influence on fundamental period of vibration. GP technique has shown similar results which is discussed in following paragraphs:

It is clear from the above tables, that is, Table number 5, 6, 7 and 8 that the GP models developed under category D gives better results as compared with GP models under category GP-A, GP-B and GP-C. The reason may be due to fact that the direct values of seismic weight and stiffness of the building are used as input parameters in developing these models. The equations obtained from this category are of the same form.

As the details of mass of the building, stiffness of the building and geometry of the building are very well given to the models in all above cases, the values of R are obtained more than 0.95 in every case.

GP models developed under Category GP-A gives the fairly good results when compared with GP models developed under Category GP-B and GP-C. In all these models the seismic weight and the stiffness values are given indirectly as input parameters.

In all GP1 models developed under all the four categories, the hypothesis do not show effect of the length and width of building or the perimeter of the building on fundamental period of vibration. It seems that effect of stiffness of the building has been shown in terms of *h*, W_{cmin} and W_{cmax}.

GP2 model developed under category GP-A, show the effect of width of the building on fundamental period of vibration. However the effect is not much dominant as it is seen from one forth power of width of the building in the expression for fundamental period of vibration. In all other categories of the GP2 model effect of perimeter or width of the building has not been shown.

In category GP-D wherein seismic weight and stiffness are used as input parameters, effect of geometry of the buildings is not seen over the values of fundamental period. However GP technique has given the hypothesis which is very similar to one used for single degree of freedom (SDOF) system. Thus it can be observed that GP technique understands the basic theory of vibration analysis. This may be further supported by the exactly similar equations obtained under category GP-B and GP-C.

The equation obtained under category GP-B and GP-C for GP2 models is used to derive relation between height of the building and the fundamental period of vibration. The equation is reduced to the form recommended by Goel and Chopra (1997). The GP technique has given following equation:

$$T_{1y}= 0.0459\ H^{0.9} \tag{8}$$

Whereas the equation (lower bound) suggested by Goel and Chopra (1997) is

$$T = 0.0475\, H^{0.9} \quad (9)$$

In category GP-A, GP-B and GP-C, all the models are showing influence of height of the storey (*h*) and height of the building (*H*) over the fundamental period of vibration along *X* and *Y* directions.

From the database used to develop the models and the GP equations stated above, following equations are suggested for the fundamental period of vibration along *X* direction.

$$T_{1X} = 0.013\, hH \qquad \text{Up to 20 m height of the building} \quad (10)$$

$$T_{1X} = 0.0114\, hH \qquad \text{More than 20 m and up to 25 m height} \quad (11)$$

$$T_{1X} = 0.0109\, hH \qquad \text{More than 25 m and up to 30 m height} \quad (12)$$

$$T_{1X} = 0.00922\, hH \qquad \text{More than 30 m and up to 35 m height} \quad (13)$$

$$T_{1X} = 0.008\, hH \qquad \text{More than 35 m and up to 50 m height} \quad (14)$$

5. Conclusions

The present study shows that genetic programming technique can be implemented for estimating natural periods of vibration and the results are obtained with reasonable and acceptable accuracy. The GP equations show that the fundamental period of vibration depends on sizes of the columns, height of the storey and height of the building. The GP equations obtained are simple, short and meaningful. The fundamental period of vibration may be expressed in terms of height of the storey and height of the building. The equations suggested above may be verified with the experimental investigation.

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Appendix A

Koza (1992) developed a special genetic algorithm known as "genetic programming (GP)" which its population is represented by the "parse tree" (computer programs). A population member in GP is a structured computer program consisting of functions and terminals. The functions and terminals are picked out from a set of functions and a set of terminals. A function set could contain functions such as basic mathematical operators (+, -, *, /, etc.), Boolean logic functions (AND, OR, NOT, etc.), or any other user defined function. The terminal set contains the arguments for the function and can consist of numerical constants, etc. The functions and terminals are selected randomly and put together to form a computer model in a tree-like structure with a root point with branches extending from each function and ending in a terminal. An example of a simple tree representation of a GP model is shown in Fig. A1 (Kermani *et al.* 2009).

Genetic operators

Model structures evolve through the action of three basic genetic operators: reproduction, crossover and mutation.

Reproduction: In the reproduction stage, a strategy must be adopted as to which programs should die. In this implementation, a small percentage of trees with worst fitness are killed. The population is then filled with the surviving trees according to a binary tournament selection. The best program is copied as it is as per the fitness criterion and included in the new population. Individuals are increased by 1.

Reproduction rate = 100 - mutation rate - (crossover rate * [1-mutation rate]) (Londhe 2008).

Cross Over: The crossover operator is responsible for combining good information from two strings and for testing new points in the search space. The two off springs are composed entirely of the genetic material from their two parents. By recombining randomly certain effective parts of a character string, there is a good chance of obtaining an even more fit string and making progress towards solving the optimization problem. Several ways of performing crossover can be used. The simplest but very effective is the one-point crossover. Two individual strings are selected at random from the population. Next, a crossover point is selected at random along the string length, and two new strings are generated by exchanging the substrings that come after the crossover point in both parents. Cross-over operator produces two new individuals for new generation by choosing two individuals of current population and randomly changing one's branch with another (Kermani *et al.*). The mechanism is illustrated in Fig. A2 (Kermani *et al.* 2009).

Mutation: Mutation prevents the population from premature convergence or from having multiple copies of the same string. This feature refers to the phenomenon in which the algorithm loses population diversity because an individual that does not represent the global optimum becomes dominant. In such cases the algorithm would be unable to explore the possibility of a better solution. Mutation operator produces one new individual for new generation by randomly changing a node of one of the trees in current population (Fig. A3) (Kermani *et al.* 2009).

An additional operator, elite transfer, is used to allow a relatively small number of the fittest programs, called the elite, to be transferred unchanged to a next generation, in order to keep the best solutions found so far. As a result, a new population of trees of the same size as the original one is created, but it has a higher average fitness value. Fig. A4 is a flowchart for the genetic programming paradigm (Koza 1992).

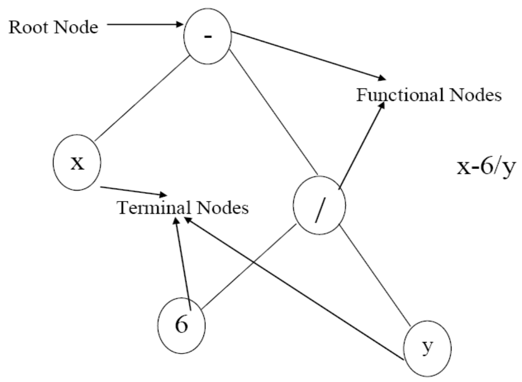

Fig. A1 Typical GP tree representations

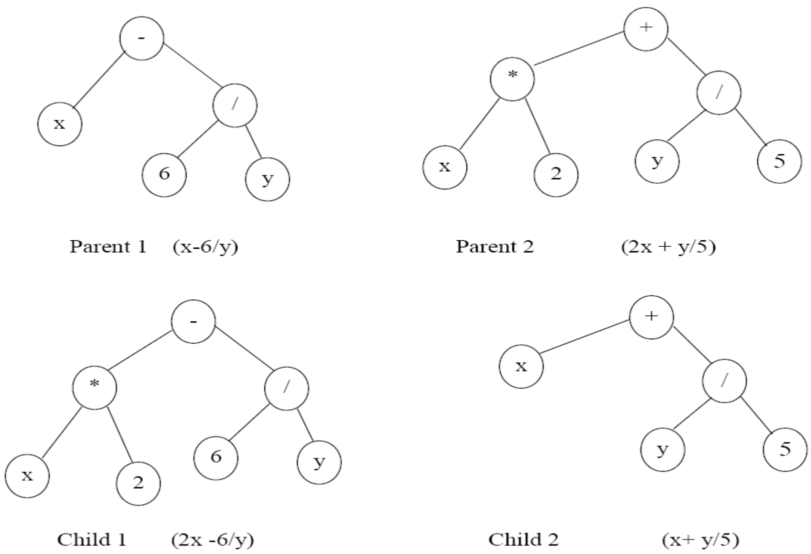

Fig. A2 Typical cross over operation in GP

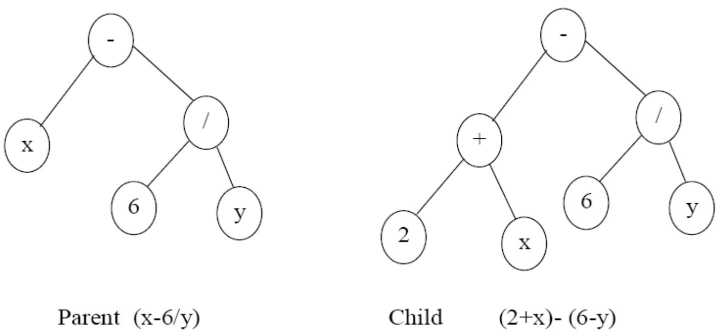

Fig. A3 Typical mutation operation in GP

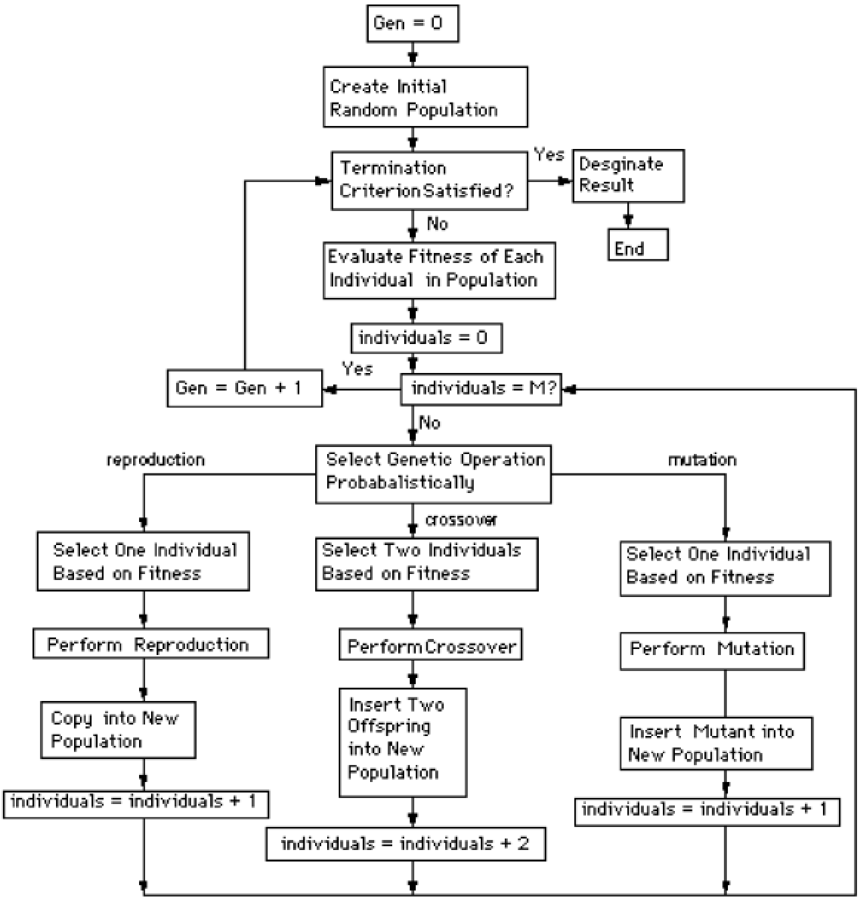

Fig. A4 Flow chart of genetic programming