PHYSICAL PARAMETER IDENTIFICATION FOR A RC FRAME STRUCTURE ON ELASTIC FOUNDATION BY GENETIC SIMULATED ANNEALING ALGORITHM

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Abstract: This study aims to develop a parameter identification method for determining structural parameters of a model RC frame structure built on the soil-foundation. A new method called the genetic simulated annealing algorithm (GSAA) is presented for identification of structural parameters of the frame. In this method the genetic algorithm and the simulated annealing algorithm are syncretized to improve the global searching ability. In the constructing process of the frame model, the experiments were conducted with the increasing of stories of the frame. Based on four cases of modal frequencies and vibration shapes measured from experiments, the elastic modulus of concrete of each story and the dynamic shear modulus of soil-foundation are identified by GSAA. By compared with the results identified by sensitivity method, it is shown that the parameters identified by GSAA agree well with the results obtained from material testing.

1. INTRODUCTION

The measured modal parameters of the buildings or bridges are influenced by their foundations. There are a few researches on the modal characteristics of structures built on the soil-foundations. Whitman et al.(1973) used dynamic moment and horizontal equation to identify the horizontal and vertical impedance of the foundation. The study by Wong et al.(1988) showed significant changes in the natural frequencies identified from the responses of a seven-story reinforced concrete hotel building in Vn Nuys, California during 12 seismic events. Apparent building rocking angles was used in Fourier spectra analysis. Hans et al.(2005) conducted ambient vibrations, harmonic vibration and shock loading test on five decommissioned buildings. After Northridge earthquake Chassiakos et al.(2005) strengthened the Long Beach Public Safety Building by shear wall step by step and measured different modal characters of the building. Luco et al (2005) identified the structure and foundation parameters from forced vibration testing on Hualien containment model in Taiwan.

The genetic algorithm is brought forward by John Holland in 1970's, which is a global searching and optimization method and is simulated the biology evaluation in nature. Darwin's evaluation theory and Mendel's evaluation law is used for reference. It is widely used in different optimization problem. Friswell et al.(1998) used genetic algorithm in damage diagnosis problem and the sensitivity method is combined in searching the local minimum. Yi et al.(2001)developed some improved strategies, for instance, multi-parents crossover and fine-tuning of variables, to detect the damage of a fixed-end beam. Levin et al.(1998) compared simulated annealing algorithm and genetic algorithm in model updating and devoted an improved simulated annealing algorithm to search the effective possible answers. Hao et al. (2002) combined different modal information to detect damage in cantilever beams and frame structures. Lu et al. (2005) used real coding genetic algorithm combining sensitivity method in local climbing hill, conducted damage identification in frame structures.

In this paper, the simulated annealing algorithm and the genetic algorithm are combined in a serial mode, called genetic simulated annealing algorithm (GSAA), and used to identify the physical parameters of model RC frame built on the soil-foundation based on the modal experiments of the frame.

2. GENETIC SIMULATED ANNEALING ALGORITHM

2.1 Genetic algorithm

Genetic algorithm (GA) is different with the other traditional algorithm. GA can search the whole solution space, and can obtain the global optimization solution. In GA the chromosome is defined as the participant solution, fitness is the objective function, the component of chromosomes are called gene. Most of the GA begins as n number chromosomes; the adaptive function $f(x)$ is used in evaluation. The idea of reproduce, fitness is survival, crossover and mutation in Darwin's evaluation theory is used in creating new population, and the process is as following:

(1)Reproduction: reproduction is to select the excellent individual in population, in which the generation has more chances to reproduce the chromosomes in the next generation. The chromosomes are copied in the next generations according to the fitness function, and the ones have higher fitness have the higher survival probability.

(2) Crossover: crossover is to randomly select father generation and change a part of chromosomes in gene to produce two new off-springs. The new generation combined the father individual's characters and it embodied the principle of 'information changes'.

(3) Mutation: mutation is to change the value in the chromosome in some probability and provide the change for new population.

Someone proved that the basic algorithm will not reach the global optimization point. 'Cheating problem' influence the genetic algorithm work well. 'Premature problem' is prior converged in early state. So the basic genetic algorithm should be improved, the scholar devoted the ideal of hybrid genetic algorithm. The simulated annealing algorithm is syncretized in GA in this paper.

2.2 Simulated annealing algorithm

Simulated annealing algorithm (SA) belongs to a nonlinear inversion. The basic idea comes from the thermodynamic cooling process. Many materials have one crystalline low-energy state and multiple glassy high-energy states. Annealing is a method of finding the lowest energy state from all of the possible stable states. Under some initialization temperature, with the decreasing of the temperature, the probabilistic abrupt jumping character is combined to search the objective function's global optimization solution. SA is helpful to overcome the optimization process in local minimum and which depend upon the initial value. The idea of simulated annealing algorithm is based by Metropolis criterion, which according to the solid's heat balance process. The Metropolis criterion is as Eq.(1).

$$p=\begin{cases}1 & (E(x_{new})<E(x_{old})) \\ \exp\left[-\dfrac{E(x_{new})-E(x_{old})}{T}\right] & (E(x_{new})>E(x_{old}))\end{cases} \quad (1)$$

The two energy status are separately E_i and E_j, if $E(x_{new})<E(x_{old})$,the new status is accepted as the current status, otherwise, if the probability of $\exp[-(E(x_{new})-E(x_{old}))/T]$ is large than $[0,1)$,the random numbers in the region accept new status j as the current status, if it is not coming into existence, the status j is preserved, k is Boltzmann constant.

The process repeat for several times and the system will get into equilibrium status. The status' probability will get into some normal distribution. At the beginning the value of T is large; the deteriorated solution will be accepted. With the decreasing of the value of T, the better deteriorated solution will be accepted. At last the value of T tends to be zero, any deteriorated solution will not be accepted. SA will jump from local optimization trap.

2.3 Genetic simulated annealing algorithm

GA and SA can be synchronized together and GSAA is formed, this article GA and SA can be combined into serial mode as in Figure 1. SA in GSAA adopts serial mode, the process is endued with time-variety probable abrupt jumping character, the local limit is prevented and the global optimization is achieved. GA in GSAA adopted population parallel search, it based on the idea of 'fitness is survival' to get into optimization. GA and SA depend on the selection of parameter. When the two methods are combined, the dependence of the initial parameter is decreased and the global searching ability is developed.

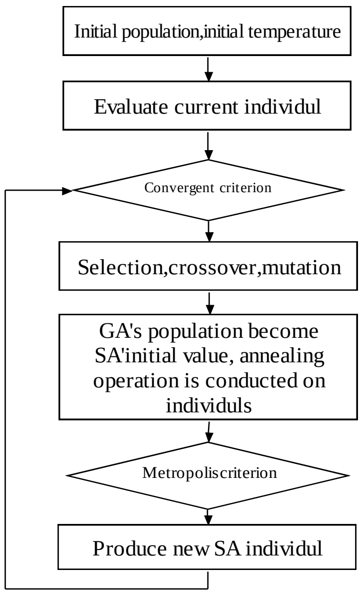


Figure1. Sketch of genetic simulated annealing algorithm

In this serial mode, the initial values of SA come from GA's evolution results, and by Metropolis criterion and annealing process of SA, it become to be initial population of GA. SA in high temperature is helpful to status's transfer in large-scale. The mutation in GA and SA in low temperature is helpful to local range inclined movement in optimization (Wong, 2001). In this article GSAA will be used to conduct physical parameter identification on the frame structure on the elastic foundation.

3. MODAL EXPERIMENTS ON FRAME STRUCTURE ON ELASTIC FOUNDATION

3.1 Introduction of the experiment model

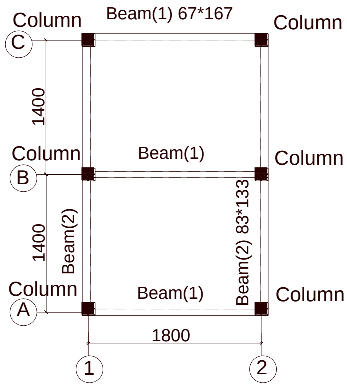
The model structure studied is a four-story reinforced concrete frame as shown in Fig.2, under each column there is an embedded footing with plane dimension of 0.6 m thick, the designed yielding strength of the steel bars in frame structure is 235 MPa and the designed strength of concrete is 25 MPa.

The experiment is done on the soil groove in the structural laboratory in Hunan University in China. Before the construction of the RC frame model, a groove with a depth of 1.20 m is excavated. The lower 1.10 m depth is filled with powder clay to simulate soft soil, which is hammered at every 20 cm~30 cm height. The density of the filled power clay is 1,965 kg/m^3. Bearing plate experiments of ten points indicate the static elastic modulus of the filled power is 48.1 MPa. Three dimensional soil pressure system TSZ-30B (made in China, which is three axis pressure experiment system controlled by strain. The shear force resist intensity can be used for fine soil and sand sample with diameter 3.91 cm under around pressure σ_3) was used to measure the shear force strength. From four sample of soil column under different around pressure, the index of soil characteristics are C=55.81 kPa, φ =8.519° according to Moore-Coulomb criterion by outer side curve fitting.

The dynamic character of soil is adopted by the impulse exciting method, the damping ratio of the soil is set as 0.3, the dynamic character is listed as Table 1 (Wong.2001).

Table 1.Index of the dynamic character of the soil

Index of the dynamic character	Value
Rayleigh wave velocity v_R	145.54 m/s
Shear wave velocity v_s	156.88 m/s
Dynamic shear modulus G_d	4.837e7 N/m^2
Dynamic elastic modulus E_d	1.258e8 N/m^2



(a) (b)

Figure2.The frame on the foundation and the dimension: (a) Photo of the frame structure; (b) Plane view and dimension of the frame structure

In this study, experiment is carried out respectively after the concrete of the first, the second, the third and the fourth story has been cast. Therefore, four groups of modal experiments corresponding to different construction stages are named as Case I, Case II, Case III and Case IV. Concrete strength is synthetically evaluated by resilience technique and concrete cube compression testing. According to the Chinese Code for Design of Concrete Structures, the concrete elastic modulus E_s can be estimated in Eq.(2), and four groups of elastic modulus are listed in Table 2 which providing the reference value for the following physical parameter identification.

$$E_c = \frac{100}{2.2 + 34.7 / \bar{f}_{cu}} \tag{2}$$

Table 2.Elastic modulus of the concrete(×e10 N/m^2)

Finish casting	First story	Second story	Third story	Fourth story
Case I	2.526	/	/	/
Case II	2.979	2.161	/	/
Case III	3.020	2.881	2.132	/
Case IV	3.456	3.329	3.364	3.085

3.2 Calculating model of the frame structure on elastic foundation

The dynamic impedance function of embedded square slab proposed by Pais et al. (1988) is used in the analytical model of the foundation [10]. Generally the foundation dynamic impedance function of the model is the function of frequency and can be expressed by $a_0 = \omega B/V_s$. The horizontal, rocking, horizontal-rocking coupling dynamic impedance functions of embedded square slab are as

$$K_{Hx}^d = K_{Hx}^s(G,B,v,L,e)(1.0 + ia_0c) \tag{3}$$

$$K_{Rx}^d = K_{Rx}^s(G,B,v,L,e,a_0)(k + ia_0c) \tag{4}$$

$$\bar{K}_{HR}^d = (e/B)\bar{K}_{Hx}^d/3 \tag{5}$$

Where K^s is defined as static stiffness of the foundation, ω is natural circle frequency, L and B denote half of the length and width of the foundation respectively. G is dynamic shear modulus of the soil. e is embedded depth of the slab. V_s is the shear wave velocity, k and c are dynamic stiffness and damping coefficient of the foundation respectively. The stiffness item in impedance function is the function of dynamic shear modulus, which is set as quantity in physical parameter identification.

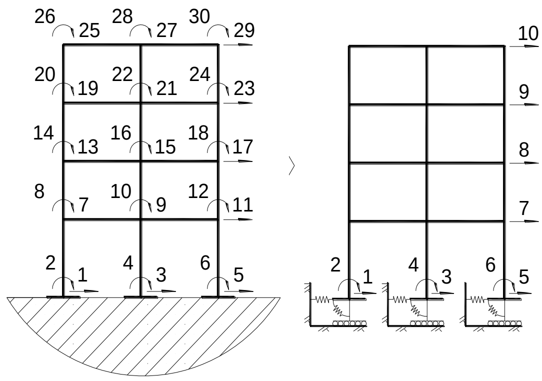


Figure3.Calculating model of the frame structure on elastic foundation

By trial and error calculation process, the numerical modal analysis results by bending shear model is close to the measured results, so bending shear model is used as the calculating baseline model, the members of the super-structure are modelled as beam elements and the effects of axial force in each member are neglected. The original 24 degree of freedoms (DOFs) of the whole frame structure are then further reduced to 4 by static condensation as shown in Fig.3. There are 6 boundary degrees of freedom which account for the contribution of each foundation. Therefore, the whole soil-structure coupled structure is modelled as 10-DOFs system as shown in Fig.3. There are seven unknown parameters including elastic modulus of each story, E_1, E_2, E_3 and E_4 and the dynamic shear modulus of the isolated foundation, G_1, G_2 and G_3. The mass matrix is used as assembled mass matrix.

4. PHYSICAL PARAMETER IDENTIFICATION BASED ON GSAA METHOD

4.1 Objective criterion and initial parameter selection

The parameters needed identification are four elastic modulus and three independent dynamic shear modulus, firstly the search range is defined as:

$$E_1, E_2, E_3, E_4 \in [2e10, 5e10] \tag{6}$$

$$G_1, G_2, G_3 \in [2e7, 8e7] \tag{7}$$

The objective function is selected according to the following criterion (Levin.1998)

$$J_\omega = \sum_{i=1}^{N_f} W_{ai} \left(\frac{\omega_{mi} - \omega_{ai}}{\omega_{mi}}\right)^2 \tag{8}$$

$$J_\phi = \frac{1}{N_f}\sum_{i=1}^{N_f} W_{\phi i}(\phi_{mi} - \phi_{ai})^T(\phi_{mi} - \phi_{ai}) \tag{9}$$

Among in it, ω_{mi} and $\omega_{\phi i}$ are the ith measured frequency and numerical frequency in theory, ϕ_{mi} and ϕ_{ai} are the ith measured modal shapes and numerical modal shapes in theory, N_m is the number of selected modes. $W_{\omega i}$ and $W_{\phi i}$ is the ith mode's weighting factor. $W_{\phi i}$ can be chosen by reciprocal of the discrete errors of mode shapes by several time's measurement. The optimization criterion considering frequencies and modal shapes are defined as following

$$J_{\omega\phi} = W_1 J_\omega + W_2 J_\phi \tag{10}$$

W_1 and W_2 are frequencies and modal shapes assembled participant factor.

Table 3 The weighting factor of different vibration shapes

Weighting factor	$W_{\phi 1}$	$W_{\phi 2}$	$W_{\phi 3}$	$W_{\phi 4}$
Value	0.2553	0.3058	0.2267	0.2121

In GA of GSAA, Gray Code is used for encoding, initial population is set as 100, the generation evolution is 100, the generation gap is 0.9, random sample criterion is used as selection method, shuffle cards crossing is used as crossing method, the crossing probability is set as 0.7, mutation probability is set as 0.003.

In SA of GSAA, initial temperature is set as $T = 50$℃, based on the real coding method, The parallel searching method is used in chromosome calculated by GA, the optimization method of status function IS set as $x(k+1) = x(k) + \eta \cdot x(k) \cdot \xi$, among in it η is the disturbance parameter, which adopt the normal distribution mechanism, the probability density function is set as

$$f(\xi) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(\frac{-\xi^2}{2\sigma}\right) \quad (11)$$

σ is standard deviation. In normal distribution, the chance of the little adjacent region function has larger disturbance, and has little chance of large disturbance. The annealing parameter is set as $T = T_0(0.95^{g-1})$. Among in it, GA may get into local optimization, and SA easily has large disturbance, so it may get into the entire optimization. Due to the GA and SA are serial mode, it has the cost of wasting time.

4.2 Selection parameter in SA

In GA of GSAA, the selection of the parameter has been researched extensively, there are experiential value range can be selected, but in SA of GSAA, two important parameters influence the operation velocity of the program and the astringency of the result. The selection of annealing parameter g is influenced by the annealing process is sufficient or not, when the temperature control parameter is small enough, the high quality solution can be obtained; the value has the relation with the time cost. The value is selected as 20, 40 and 60 respectively.

Another parameter is the disturbance parameter η in optimization, if the parameter is too large, it will cause large range disturbance and cause random search, if the value is too small, it will has no disturbance effect. The value is selected as 0.05, 0.03 and 0.01 respectively.

As Case IV for example, three groups of numerical experiments are conducted, as Fig. 4 for example, when the value of g is unchanged, the program is convergent fast when η value is 0.01. As Fig.5 for example, when the value of η is unchanged, the program is convergent fast when g value is 20. So in the following analysis, η is set as 0.01 and g is set as 20.

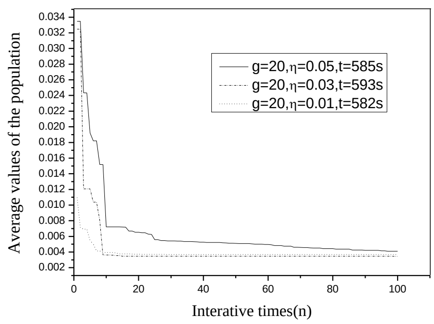


Figure4.The average value of population with the varies of η

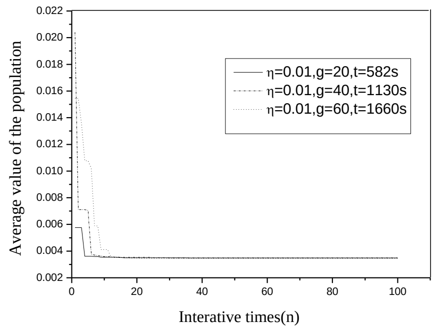


Figure 5.The average value of population with the varies of g

4.3 Physical parameter identification with increasing of the story

Four cases of physical parameter identification are conducted. It is helpful to know the change of elastic modulus of the concrete and dynamic shear modulus of the soil. It has important significance to long time health monitoring of the structure, there scarcely has people do the same research.

GSAA is used in the identification. The elastic modulus and dynamic shear modulus are identified with the increasing of the story are listed in Table 4. Each story's elastic modulus are increased with the increasing of the story, it has the relation with the concrete intensity increasing with the age. The dynamic shear modulus of the foundation are increased with the increasing of the story, it has the relation with the dynamic shear modulus increased with the increasing of the upright pressure. Three dynamic shear modulus are close to each other, which is according with the reality.

Table 4 The physical parameter identified by GSAA

Modulus	Case I	Case II	Case III	Case IV
E_1	2.7845	3.2685	3.7520	3.7994
E_2	/	3.3956	3.6673	3.7984
E_3	/	/	3.5835	3.7246
E_4	/	/	/	3.6969
G_1	4.8752	5.3358	6.1928	6.2752
G_2	3.5271	5.3421	6.2921	6.9955
G_3	4.8246	5.4245	6.4383	6.1712

Note: Elastic modulus × e10 N/m^2
Dynamic shear modulus × e7 N/m^2

Table 5 The physical parameter identified by SM

Modulus	Case I	Case II	Case III	Case IV
E_1	2.5415	3.0159	3.6519	3.9886
E_2	/	3.4983	4.9146	4.6607
E_3	/	/	2.6850	4.0833
E_4	/	/	/	3.3983
G_1	6.9608	7.5252	7.6464	7.7155
G_2	6.9608	7.3175	7.5553	7.5553
G_3	6.9608	7.5252	7.6160	7.6848

Note: Elastic modulus × e10 N/m^2
Dynamic shear modulus × e7 N/m^2

Table 6 The comparison of calculating and measuring modes

Case	Order	Test /Hz	GASA /Hz	SM /Hz
Case I	1st	20.1	20.1	20.1
Case II	1st	13.4	13.5	13.4
	2nd	51.2	50.9	51.2
Case III	1st	9.9	10.4	10.7
	2nd	34.1	35.4	34.8
	3rd	69.3	68.2	68.7
Case IV	1st	7.7	8.2	8.7
	2nd	26.1	26.9	27.8
	3rd	50.6	50.8	52.2
	4th	79.3	77.0	80.3

The dynamic shear modulus by identification in Case I are close to the field experiment results. The identified elastic modulus of the concrete is generally larger than by resilience technique and concrete cube compression testing, it may has the relation with the difference of the dynamic modulus and static modulus. The dynamic modulus is larger than static modulus, Ren et al.(2002) regarded that the dynamic modulus is 12% larger than static modulus in beam structure. Due to the limitation of the experiment instrument, the dynamic elastic modulus of the concrete have not be tested.

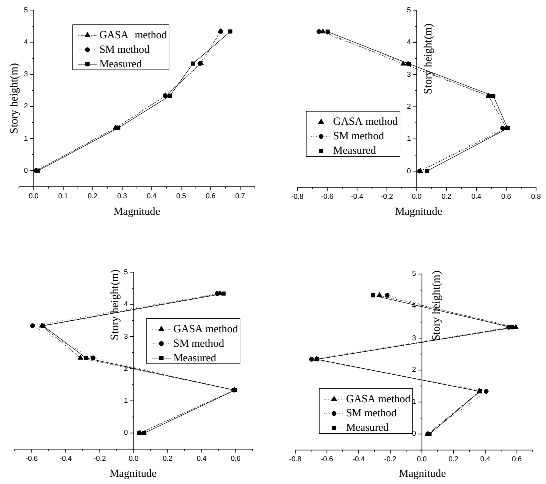


Figure .6 Comparison of measured and calculated modal shapes (Case IV)

In order to compare with GSAA, the traditional sensitivity method (SM) is also used in the identification; the identification results are shown as in Table 5, the regulation of the parameter identified by SM are worse than by GSAA.

The calculating frequencies by using modulus inversed by SM and GSAA are listed in Fig.6, The measured mode results and the other two methods are compared in Fig.6. By comparison with SM, GSAA can be used successfully in identification of elastic modulus and foundation’s dynamic shear modulus, it has robust global searching ability, the calculated modal results inversed by GSAA are close to the measured results.

5. CONCLUSION

In this paper, GSAA is used in physical parameter identification of frame structure on elastic foundation with independent base with increasing of the story. The main conclusions are listed as follows:

(1) Traditional basic genetic algorithm has globe searching ability, but 'premature problem' and 'cheating problem' are easily occurred in it. SA is combined in GA, the two searching mechanisms are combined skilfully, the global searching ability is greatly developed.

(2) Four cases of modal tests were done on frame structure on elastic foundation with increasing of the story, and four cases of modal tested results are obtained.

(3) When GSAA is used in calculation, in SA of GSAA, the annealing parameter g and disturbance parameter η have important influences on the searching efficiency and global searching ability.

(4) The parameter identification research is done on four cases of modal experiment results by GSAA, traditional SA is compared with it, the results identified by GSAA is better than SM. With increasing of the story, the elastic modulus and foundation dynamic shear modulus are increased. The dynamic shear modulus by identification in Case I are close to the field experiment results. The identified elastic modulus of the concrete is generally larger than by resilience technique and concrete cube compression testing, They may have the relations with the differences of the dynamic modulus and static modulus.

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