Research Article

Application of the Improved Multipopulation Genetic Algorithm in the TMD Controlled System considering Soil-Structure Interaction

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With the advent of globalization, computing speed has increased tremendously, greatly advancing algorithm research in multiple fields. This paper studies the parameter optimization problem of the improved multipopulation genetic algorithm in the tuned mass damper (TMD) structure considering the soil-structure interaction (SSI) effect. The Newmark time-domain analysis method was used to analyze the dynamic response of a 40-story building under the excitation of EL Centro waves and Tangshan waves in China, respectively. The mass, damping coefficient, and spring stiffness of TMD system are used as the design variables of the controller. To reduce structural damage and obtain better comfort, the displacement response and acceleration response are optimized simultaneously in this paper, achieving multiobjective optimization. The results show that the improved multi-population genetic algorithm method has faster convergence speed and greater accuracy than the traditional genetic algorithm; thus it can be applied to the TMDs parameter optimization of high-rise buildings. Besides, the soil types have a great influence on TMD parameter optimization and structural time history response. If ignoring SSI effect will lead to underestimation of parameter design, the reason is that the soft soil foundations can absorb a lot of seismic energy compared with rigid foundations and then reduce the effect of seismic excitation on the structure. The intention of the research helps researchers to better understand vibration control and provides suggestions for the application of TMD in high-rise buildings.

1. Introduction

With the increase of population, more and more high-rise buildings are coming into view. However, the vibrations caused by dynamic effects such as earthquakes, wind, and traffic may occur at any time, posing a challenge to seismic resistance of buildings. Generally, structural vibration can be reduced by vibration isolation bearings, active control systems (such as active tuned mass dampers (ATMDs)), and passive control systems (such as tuned mass dampers (TMDs)). For earthquakes with different intensities and frequency content, the active and semiactive TMD devices [1–4] can improve the efficiency of TMD system. In contrast to the complexity and high cost of these devices in reducing seismic excitation, the TMD with the advantage of relatively simple and economic construction has become the first choice for structural seismic resistance [5].

Tuned Mass Dampers (TMDs) are one of the passive control systems consisting of mass, stiffness, and damping components. These devices are attached to structures to absorb the energy generated by structural vibration and mitigate structural damage. The Frahm damper, also referred to as a simply TMD, was invented by Frahm in the early 20th century and patented around 1909 [6]; Ormondroyd and Hartog [7] added damping on this basis in 1928, which is the prototype of the initial TMD. With the development of TMD systems, numerous studies have shown that only suitable TMD parameters can achieve optimal control effect [8–12], and the soil parameters under the structure determine the optimal mechanical parameters of the TMD (the optimal tuning frequency and damping and mass ratio). This is because the soil-structure interaction (SSI) effect will significantly change the dynamic characteristics of the structure, such as natural frequency, damping
ratio, and modal damper [13]. Xu and Kwok [14] studied the wind-induced movement of two high-rise structures with TMDs and considered the influence of soil compliance under the foundation. They believed that the soil parameters would affect structural dynamic response and the effectiveness of the TMD. Chen et al. [15, 16] studied the dynamic response of a 6-story frame structure with TMD considering the SSI effect. The results showed that the TMD could reduce the dynamic response of the structure, and the structural response of the soft soil foundation was significantly smaller than that of the rigid foundation. Jia and Liang [17] studied the influence of various parameters on the performance of TMD, such as structural aspect ratio and height, foundation embedment, and soil thickness. By comparing the efficiency of a well-tuned damper and a damper that is misaligned with structural fixed fundamental frequency, the performance degradation of TMD without considering SSI is studied. The dynamic response of high-rise buildings considering SSI is different from that of multistoried buildings. Therefore, it is necessary to study the dynamic response of structure with TMD system considering soil-structure interaction effect.

With the world entering the information age, the speed of computer operations has made great progress. For the coming of the quantum computing era in the future, it is particularly important for scholars in multiple fields to share their research on algorithms. To date, scholars have applied heuristic algorithms to the field of architecture; for example, the heuristic algorithms are used to optimize plane steel frame structures, minimize the weight of the rigid-jointed steel frame structure [18], and optimize reinforced concrete cantilever retaining wall [19]. Besides, the heuristic algorithms are also applied to the problem of damage detection [20] and so on [21–24], among which the parameter design of the TMD is more common. Mohhabbi and Joghataie [25] used a distributed genetic algorithm to solve the problem of the linear TMD design optimized in an eight-story nonlinear shear building. The results show that the method successfully determined the optimal TMD parameters to reduce structural response. In addition, the efficiency of the TMD is affected by the mass ratio of the TMD, the maximum stroke length of the TMD, and the types of seismic waves. Bekdaş et al. [26] used the bat algorithm to optimize the design variables such as the mass, period, and damping ratio of the tuned mass damper, and then the bat optimization method and genetic algorithm were applied for a ten-story civil structure. Compared with other heuristic algorithms, the proposed method is more effective and proves the feasibility of optimizing tuned mass damper through the bat algorithm. The nondominant sorting genetic algorithm (NSGA-II) was used by Pourzeynali et al. [27] to control structural vibration to resist earthquakes; De Domenico et al. [28] also applied the Nondominated Sorting Genetic Algorithm II (NSGA-II) on the optimization of TMD in high-rise buildings. Then, to optimize the maximum displacement, maximum velocity, and maximum acceleration of the floor, the multiobjective optimization design of TMD system is carried out. However, the optimization methods described above assume that the foundation of a building is a fixed foundation, regardless of the effect of soil-structure interaction on the building. Khoshnoudian et al. [29] studied the optimization design of passive tuned mass damper system considering soil-structure interaction. The results show that the performance of damper can be improved considering the influence of soil-structure interaction. In addition, many researches have shown that the genetic algorithm is simple and effective for optimal design of the TMD. Farshidianfar and Soheli [30] used the ant colony optimization algorithm to optimize TMD design of a 40-story structure considering the SSI effect under seismic excitation. Khatibinia et al. [31] used the multiobjective particle swarm optimization algorithm to optimize TMD design considering the SSI effect; then the algorithm is used to optimize and adjust the parameters of TMD, and the numerical results show that the SSI effect has a significant impact on the optimal parameters of TMD. Numerous studies have shown that the SSI effect cannot be ignored if we want to obtain the best parameters of the TMD [32–34]. However, there are few studies on TMD parameter optimization taking the SSI effect into account. The tedious calculation is the main factor that restricts its application. The genetic algorithm has the characteristics of wide applicability, high efficiency, parallelism, and global search. Different from the traditional search method which depends on gradient information and single-point search, genetic algorithm is not subject to the complexity of the problem itself. It can simultaneously deal with multiple individuals in the population and evaluate multiple solutions in the search space at the same time, which make the genetic algorithm have computational parallelism and good global search ability. Therefore, the genetic algorithm has become a hot spot of application and research for complex problems.

This paper attempts to improve the traditional genetic algorithm to obtain faster calculation speed and accuracy and extends the aforementioned research works in the following three main aspects: (1) A mathematical model of the seismic response for high-rise buildings with TMDs considering SSI effect is established by numerical calculation. (2) The Newmark time-domain analysis method was used to analyze the dynamic response of a 40-story building under the excitation of EL Centro wave and Tangshan wave in China, respectively. (3) The improved multipopulation genetic algorithm method is applied to search for the optimal TMD parameters (mass, stiffness, and damping) of the structural model considering the SSI effect. The vibration reduction effect of TMD system with and without soil-structure interaction (SSI effect) is compared and the corresponding dynamic response of the high-rise structure is discussed. The results prove the effectiveness and feasibility of the improved genetic algorithm.

2. Numerical Modeling

Generalizing the specific sketch shown in Figure 1, an n-layer structure with TMD considering the SSI effect is discussed, while a 40-story building model is used in this
paper. Structural stiffness decreases linearly with the increase in height. The mass and moment of inertia of the foundation are expressed as \( M_0 \) and \( I_0 \), and the mass and moment of inertia of each floor are expressed as \( M_i \) and \( I_i \). The TMD parameters including mass, viscous damping, and stiffness are represented by \( M_{TMD} \), \( C_{TMD} \), and \( K_{TMD} \), respectively. The stiffness and damping between the floor slabs are assumed to be \( K_i \) and \( C_i \), respectively. \( C_s \) and \( C_r \) represent the damping of the swaying and the rocking dashpots, while \( K_s \) and \( K_r \) denote corresponding spring stiffness. The foundation displacement and rotation angle are defined as \( X_{0k} \) and \( \theta_{0k} \), the displacement of each floor is \( X_{ik} \), and the TMD displacement is \( X_{TMD} \). The specific parameters are shown in Table 1. Using Lagrange’s equation, the system motion equation as shown in Figure 1 can be expressed as follows:

\[
[M]\ddot{x}(t) + [C]\dot{x}(t) + [K]x(t) = -[m^*]u_p, \tag{1}
\]

where \([M]\), \([C]\), and \([K]\) represent the mass, damping, and stiffness matrices of the structure, respectively; \([x]\), \([\dot{x}]\), \([\ddot{x}]\) are the displacement, velocity, and acceleration vectors of the system. \([m^*]\) is the matrix of acceleration mass for earthquake.

The parameters \( K_s, C_s, K_r, \) and \( C_r \) can be obtained from the soil properties, density \( \rho_s \), Poisson’s ratio \( \nu_s \), shear wave shear modulus \( G_s \), velocity \( V_s \), and foundation radius \( R_0 \) [32], which is given in Table 2. Considering the SSI effect, it is actually a 43 × 43-order matrix, while it is a 41 × 41-order matrix ignoring the SSI effect. The matrices of mass, damping, stiffness, and

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**Table 1: Structural parameters of the building [32].**

<table>
<thead>
<tr>
<th>No. of stories</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Story moment of inertia ((I_i))</td>
<td>1.31 × 10^8 kgm²</td>
</tr>
<tr>
<td>Story mass ((M_i))</td>
<td>9.8 × 10^5 kg</td>
</tr>
<tr>
<td>Story height ((Z_i))</td>
<td>4 m</td>
</tr>
<tr>
<td>Story stiffness ((K_i))</td>
<td>( K_i = 9.98 \times 10^8 \text{N/m} )</td>
</tr>
</tbody>
</table>

**Foundation moment of inertia \((I_0)\) | 1.96 × 10^6 kgm² |
| Foundation mass \((M_0)\) | 1.96 × 10^6 kg |
| Foundation radius \((R_0)\) | 20 m |
physical mass in equation (1) can be expressed as follows, respectively.

\[
[M] = [M_f] + \sum_{i=1}^{N} [M_i] + M_{\text{TMD}} \left( \sum_{i=1}^{N} M_i H_i \right) + M_{\text{TMD}} H_N,
\]

\[
[MH]^T \left( \sum_{i=1}^{N} M_i H_i \right) + M_{\text{TMD}} H_N \left( \sum_{i=1}^{N} \rho_i v_i \right) + M_{\text{TMD}} H_N^2 + I_0 + \sum_{i=1}^{N} I_i
\]

\[
[M_v] = \begin{bmatrix}
M_1 \\
M_2 \\
\vdots \\
M_{N-1} \\
M_N \\
M_{\text{TMD}}
\end{bmatrix},
\]

\[
[MH] = \begin{bmatrix}
M_1 H_1 \\
M_2 H_2 \\
\vdots \\
M_{N-1} H_{N-1} \\
M_N H_N \\
M_{\text{TMD}} H_N
\end{bmatrix},
\]

\[
[C] = \begin{bmatrix}
C_f & 0 & 0 \\
0 & \ldots & 0 & C_s & 0 \\
0 & \ldots & 0 & 0 & C_r
\end{bmatrix},
\]

\[
[K] = \begin{bmatrix}
(K_1 + K_2) & -K_2 & 0 & \ldots & 0 \\
-K_2 & (K_2 + K_3) & -K_3 & \ldots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & \ldots & 0 & -K_N & (K_N + K_{\text{TMD}}) - K_{\text{TMD}} \\
0 & \ldots & 0 & -K_{\text{TMD}} & K_{\text{TMD}}
\end{bmatrix},
\]

Table 2: Soil parameters [32].

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Shear modulus $G_s (N/m^2)$</th>
<th>Shear wave velocity $V_s (m/s)$</th>
<th>Soil density $\rho_s (kg/m^3)$</th>
<th>Poisson’s ratio $\nu_s$</th>
<th>Rocking damping $C_r (Ns/m)$</th>
<th>Swaying damping $C_s (Ns/m)$</th>
<th>Rocking stiffness $K_r (N/m)$</th>
<th>Swaying stiffness $K_s (N/m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft soil</td>
<td>1.80 × 10^7</td>
<td>100.0</td>
<td>1800.0</td>
<td>0.49</td>
<td>2.26 × 10^10</td>
<td>2.18 × 10^8</td>
<td>7.53 × 10^11</td>
<td>1.91 × 10^9</td>
</tr>
<tr>
<td>Medium soil</td>
<td>1.71 × 10^8</td>
<td>300.0</td>
<td>1900.0</td>
<td>0.48</td>
<td>7.02 × 10^10</td>
<td>6.90 × 10^8</td>
<td>7.02 × 10^12</td>
<td>1.80 × 10^10</td>
</tr>
<tr>
<td>Dense soil</td>
<td>6.00 × 10^8</td>
<td>500.0</td>
<td>2400.0</td>
<td>0.33</td>
<td>1.15 × 10^11</td>
<td>1.32 × 10^9</td>
<td>1.91 × 10^13</td>
<td>5.75 × 10^10</td>
</tr>
</tbody>
</table>
\[
[C_f] = 
\begin{pmatrix}
(C_1 + C_2) & -C_2 & & & & -C_N \\
-C_2 & (C_2 + C_3) & -C_3 & & & \\
& \ddots & \ddots & \ddots & \ddots & \\
& & & (C_N + C_{TMD}) & -C_{TMD} & -C_{TMD}
\end{pmatrix},
\]

\[
[m^*] = 
\begin{pmatrix}
M_1 \\
M_2 \\
\vdots \\
M_{N-1} \\
M_N \\
M_{TMD}
\end{pmatrix},
\]

\[
x(t) = 
\begin{pmatrix}
X_{1k} \\
X_{2k} \\
\vdots \\
X_{N-1k} \\
X_{Nk} \\
X_{TMD} \\
X_{0k} \\
\theta_{0k}
\end{pmatrix},
\]

The first three natural frequencies of the structure are 1.09 rad/s, 4.44 rad/s, and 7.40 rad/s in the soft soil and are 1.54 rad/s, 4.58 rad/s, and 7.58 rad/s in the middle soil. Similarly, the frequencies are 1.61 rad/s, 4.59 rad/s, and 7.59 rad/s in the dense soil and are 1.65 rad/s, 4.60 rad/s, and 7.60 rad/s in the fixed base. The maximum mass ratio is about 5% of the mass of the first mode. Therefore, the TMD mass is set to $1 \times 10^5 \leq m_d \leq 2 \times 10^6$ (kg), the TMD spring stiffness of TMD is set to $5 \times 10^5 \leq k_d \leq 5 \times 10^7$ (N/m), and the damping of TMD is set to $100 \leq c_d \leq 2 \times 10^6$ (Ns/m).

Therefore, the optimal parameters of structure with TMD under the excitation of EL Centro wave and the Tangshan wave in China can be obtained, such as mass, stiffness coefficient, and damping coefficient of TMD system. To conveniently compare structural dynamic responses with TMD under the EL Centro wave and the Tangshan wave with the same acceleration peak, the acceleration amplitude is unified, and the value is 5 m/s$^2$. The acceleration time curves and frequency spectra of the two seismic waves are shown in Figure 2.

3. Improved Multipopulation Genetic Algorithm

The genetic algorithm (GA) was first proposed by John Holland in the United States in the 1970s. The algorithm is based on the evolutionary laws of organisms in nature as a prototype and simulates the natural evolution of species through computer simulation of the crossover, mutation, and other processes of chromosomal genes to find the optimal solution. This algorithm can be used to solve various optimization problems that are not suitable for standard optimization algorithms, including discontinuous, non-differentiable, random, or highly nonlinear problems [36]. At the same time, with the deepening of the research, the drawbacks of genetic algorithms are gradually emerging. For example, due to the optimization of a single population, the optimal solution after each iteration cannot be effective after the fitness function is allocated by roulette. The binary operation method means that chromosomes are relatively cumbersome. For large programs, the operation speed is too slow and the result is premature convergence.

The optimization process of traditional genetic algorithms for optimization problems is generally as follows:

1. Set the population number, genetic algebra, variable dimensions, variable range, binary digits, crossover probability, mutation probability, and other parameters.

2. Create the initial population based on the variable range of set and introduce the objective function to
calculate the objective function values of the individuals in the initial population.

(3) Define fitness and select the optimal fitness individual according to the objective function value.

(4) Perform selection, crossover, and mutation operations to generate a new population.

(5) Cycle the above 2–4 processes, update the optimal individual and the objective function value until the genetical algebra meets the requirements, and then the cycle exit. It is worth noting that \( M_{\text{TMD}}, K_{\text{TMD}}, \) and \( C_{\text{TMD}} \) are generally set as three variables in TMD parameter optimization problem. The objective function is set to \( \text{OBJ} = \min(\max(|X_1, X_2, X_3, \ldots, X_n|)) \), where \( X_1, X_2, X_3, \ldots, X_n \) are the maximum displacements of the 1st, 2nd, \ldots nth layers, respectively. The value of the objective function is calculated according to time history analysis of structural dynamic equations.

The ultimate aim of this article is to improve the traditional genetic algorithm in an attempt to rectify the abovementioned shortcomings of the traditional genetic algorithm. The improved multipopulation genetic algorithm based on the traditional genetic algorithm made the following main improvements:

(1) The single population optimization of the traditional genetic algorithm is transformed into an optimization search for multiple different populations at the same time. Different control parameters are assigned to achieve different search purposes. In the traditional genetic algorithm, the values of \( P \) (crossover probability) and \( P_m \) (mutation probability) balance the global and local optimization capabilities of the algorithm. The generation of new individuals is mainly determined by the crossover operator that also determines the global search capability of the genetic algorithm. The mutation operator is just an auxiliary operator for generating new individuals, which determines the local search capability of the genetic algorithm. Relevant literature indicates that it is recommended to choose a larger \( P \) (0.7–0.9) and a smaller \( P_m \) (0.001–0.05) [33]. However, there are countless ways to select \( P \) and \( P_m \) in this range, and different values of \( P \) and \( P_m \) have great differences in optimization results. The improved multipopulation genetic algorithm makes up for the shortcomings of traditional genetic algorithms by considering global search and local search algorithms and through the coevolution of multiple populations with different control parameters. The specific implementation process is shown in Algorithm 1.

(2) Introduce an immigration operator to realize the exchange of optimal individuals among multiple groups and ensure that the acquisition of the optimal solution is the result of the comprehensive exchange of each group. The specific implementation method is to sort the fitness function and replace the worst individual in the target population with the best individual in the source population. The specific implementation process is shown in Algorithm 2. The migration operator is the core of the improved multigroup genetic algorithm, which achieves various intergroup interactions. Compared with traditional genetic algorithms, information exchange improves optimization efficiency. The elite population is very different from other populations. In

\[
\text{Figure 2: Seismic acceleration time history graph and frequency spectrum graph.}
\]
each evolutionary generation, the artificial selection operator will screen out the best individuals in each population and place them in the elite population for preservation to ensure that the best individuals produced by various groups in the evolutionary process can be completely retained. The elite population does not perform genetic operations such as genetic selection, hybridization, and mutation. At the same time, the essential population can be used as a criterion for judging whether the operation is completed. When the optimal individual meets the minimum genetic algebra set for the optimal individual, the operation is immediately exited and the optimal solution is output. This method makes full use of the cumulative operation of the genetic algorithm in the evolutionary process and is more reasonable than the traditional genetic algorithm, which relies on the maximum genetic algebra to determine whether the operation is completed.

(3) Through circular comparison, the optimal individuals in each evolutionary generation of all populations are retained to ensure the optimization efficiency of each generation. Figure 3 is a flowchart of the comparison between the improved multipopulation genetic algorithm and the traditional genetic algorithm.

3.1. Case Verification. Case verification: To verify the correctness of the algorithm used in this paper, reference [35] was taken as an example to compare the TMD optimization results under the excitation of Bam earthquake waves at different site conditions in the literature, and the specific objective function can be found in [35]. As shown in Table 3, the difference of each parameter obtained by using the improved multipopulation genetic algorithm is within 5% compared with the results of reference. Besides, Table 4 show that the improved multipopulation genetic algorithm used in this paper can be accurately applied to the TMD parameters optimization. Compared with the method in [35], the reduction of objective function using the improved multipopulation genetic algorithm is improved under different soil conditions. Therefore, the improved multipopulation genetic algorithm has higher calculation accuracy in TMD parameters optimization and can avoid local optimization of TMD parameters.

To compare the convergence speed of improved multipopulation genetic algorithms with the traditional genetic algorithm, the above optimization problem is taken as an example to compare the optimization process of the objective function under the Bam earthquake wave excitation at soft soil condition. Reducing the displacement and damage of high-rise building structures has been the core concern of designers. Therefore, the displacement and acceleration are optimized simultaneously to improve the safety and comfort of the structure. Since this problem is multiobjective and aims to reduce the maximum displacement and acceleration of buildings, a general objective function containing these two concepts should be used. Since the acceleration result is about 10 times the displacement [30], the objective function is defined as follows:

\[ OBJ = 10 \cdot |d|_{\text{max}} + |a|_{\text{max}}. \]  

Among them, \(|d|_{\text{max}}\) and \(|a|_{\text{max}}\) represent the maximum displacement and maximum acceleration of structural dynamic response, respectively.

Because the minimum search may not converge, the inverse of equation (3) is taken in this manuscript, and then the fitness function of the maximum value is constructed as the objective function as shown in equation (4). The smaller the value calculated by the objective function OBJ, the smaller the dynamic response of the structure, and the larger the fitness values calculated by the fitness function obj.

\[ \text{obj} = -\text{OBJ}. \]  

Detailed structural parameters and soil parameters are shown in Section 2. The parameter settings of the algorithm in this paper are as follows: number of individuals: 40, dimension of variables: 3, binary digits of variables: 10, generation gap: 0.9, number of populations: 4, number of iterations: 100. Besides, the variables of the two methods are the same to facilitate comparison. The two algorithms are each run 4 times (each iteration 100 times). The solution process is shown in Figures 4 and 5.

Figures 4 and 5 show that the improved multipopulation genetic algorithm has achieved the optimal objective function of 20.3342 for 4 times, while the traditional genetic algorithm has a slight deviation from the optimal solution in the 4 times of optimization. In addition, the convergence speed of the improved multipopulation genetic algorithm is obviously better than that of the traditional genetic algorithm. The optimal solution is obtained when iterating to 20 times, while the number of the traditional genetic algorithm is 60. The comparison result shows that the traditional genetic algorithm is unstable in solving complex problems, and the convergence speed is slower than that of the improved multipopulation genetic algorithm. On the contrary, the improved multipopulation genetic algorithm has faster convergence speed and better operational stability, which is suitable for the optimization of complex problems. Therefore, the improved multipopulation genetic algorithm was used to optimize TMD parameters of structure considering soil-structure interaction and the flowchart of multipopulation genetic algorithm in TMD optimization is shown in Figure 6.

4. Optimization Results and Discussions

In this paper, the dynamic time response of fixed foundation and three different soil foundations under the excitation of two different seismic waves (EL Centro wave, Tangshan wave, China) is investigated, and parameter optimization of structure using multiple population genetic algorithm under different site conditions with different TMD performance is discussed.
Whether it meet the stopping criterion
Calculate the fitness value of each individual

\[ \text{GEN} = 0 \]
Generate initial population

\[ i = 0 \]
\[ i := M? \]
Select genetic operations based on probability
Variation
Select an individual
Copy
Select two individuals
Cross
Select an individual
Copy to new population
Perform replication
Copy to new population
Perform hybridization
Insert two offspring into a new population
Performing variation
Insert into new population

\[ i := i + 1 \]
\[ \text{GEN} := \text{GEN} + 1 \]

\[ \text{Y} \]
Specify the result
End
End

(a)

Table 3: The optimized TMD parameters.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Mass [(10^6) kg]</th>
<th>Spring stiffness [N/m]</th>
<th>Damping [(10^6) Ns/m]</th>
<th>(\omega_n) [rad/s]</th>
<th>Mass [(10^6) kg]</th>
<th>Spring stiffness [N/m]</th>
<th>Damping [(10^6) Ns/m]</th>
<th>(\omega_n) [rad/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft soil</td>
<td>2.00</td>
<td>32.735</td>
<td>0.565</td>
<td>4.046</td>
<td>2.00</td>
<td>32.428</td>
<td>0.552</td>
<td>4.027</td>
</tr>
<tr>
<td>Medium soil</td>
<td>2.00</td>
<td>31.377</td>
<td>0.0001</td>
<td>3.961</td>
<td>2.00</td>
<td>31.282</td>
<td>0.0001</td>
<td>3.955</td>
</tr>
<tr>
<td>Dense soil</td>
<td>2.00</td>
<td>30.033</td>
<td>0.0001</td>
<td>3.875</td>
<td>2.00</td>
<td>30.027</td>
<td>0.0001</td>
<td>3.874</td>
</tr>
<tr>
<td>Fixed base</td>
<td>2.00</td>
<td>28.672</td>
<td>0.0001</td>
<td>3.786</td>
<td>2.00</td>
<td>28.785</td>
<td>0.0001</td>
<td>3.794</td>
</tr>
</tbody>
</table>

Table 4: Vibration with and without TMD.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Without TMD</th>
<th>With TMD [34]</th>
<th>With TMD</th>
<th>Reduction (%)</th>
<th>With TMD [34]</th>
<th>With TMD</th>
<th>% reduction for target function</th>
</tr>
</thead>
<tbody>
<tr>
<td>(u_{\text{max}}) (m)</td>
<td>(\bar{u}_{\text{max}}) (m/s)</td>
<td>(u_{\text{max}}) (m)</td>
<td>(\bar{u}_{\text{max}}) (m/s)</td>
<td>(u_{\text{max}}) (m)</td>
<td>(\bar{u}_{\text{max}}) (m/s)</td>
<td>(u_{\text{max}}) (m)</td>
<td>(\bar{u}_{\text{max}}) (m/s)</td>
</tr>
<tr>
<td>Soft soil</td>
<td>0.9588</td>
<td>13.2717</td>
<td>0.7530</td>
<td>12.8784</td>
<td>0.7464</td>
<td>12.8702</td>
<td>21.46</td>
</tr>
<tr>
<td>Dense soil</td>
<td>1.1236</td>
<td>13.1253</td>
<td>1.0231</td>
<td>12.8548</td>
<td>1.0186</td>
<td>12.8501</td>
<td>8.94</td>
</tr>
</tbody>
</table>
Tables 5 and 6 show the parameters of the TMD such as optimized mass, damping coefficient, and spring stiffness obtained by improving the multipopulation genetic algorithm. The results show that there is a close relationship between the soil type and the optimized parameters finally obtained by the TMD. The best quality is the highest mass quantity obtained in the search domain. The reason is that a TMD with a larger mass is more effective in controlling the structural response under seismic oscillations. These results are consistent with other analytical studies, such as [29]. There are obvious differences in the TMD optimization parameters obtained for soft soil and fixed base. The TMD system built on soft soil with low stiffness and damping usually requires high stiffness and damping of the TMDs installed on the structure. Therefore, the SSI effect should be considered when designing the structures with TMDs, especially for the soft soil foundations. The acceleration time history curve and frequency spectrum of Tangshan seismic

```
Step 1: for i = 1: Population number
    Chrom[i] = crtbp (Number of individuals, Dimension of variable * The number of bits of the variable);
end
Step 2: p = 0.7 + (0.9 – 0.7) * rand (Population number, 1);
pm = 0.002 + (0.05–0.002) * rand (Population number, 1);
Step 1 creates a multigroup multivariate population set. Step 2 randomly generates a crossover probability in the range of 0.7, 0.9, and a random probability of variation in the range of 0.002, 0.05.
```

**Algorithm 1:** The implementation process of the improved multipopulation genetic algorithm.

```
Step 1: for i = 1: Population number
    [The best individual of the i population. The line number of the best individual] = min (obj[i]);
Step 2: n = i + 1;
    if n > Population number
        n = mod (n, Population number);
    end
Step 3: [Worst individual value of the nth population, The row number of the worst individual value] = max (obj[n]);
Step 4: Chrom[n](The row number of the worst individual) = Chrom[i](The line number of the best individual);
    obj[n](The row number of the worst individual) = obj[i](The line number of the best individual);
end
Step 1: find the best individual in the i-th population. Step 2: realize the linkage between each population. Step 3: find the worst individual in the n-th population. Step 4: replace the worst individual in the n-th population with the best individual in the i-th population, and cycle by population number until all the worst individuals are replaced by the best individuals.
```

**Algorithm 2:** The implementation process of the exchange of optimal individuals among multiple groups.

```
Step 1: find the best individual in the i-th population.
Step 2: realize the linkage between each population.
Step 3: find the worst individual in the n-th population.
Step 4: replace the worst individual in the n-th population with the best individual in the i-th population, and cycle by population number until all the worst individuals are replaced by the best individuals.
```

**Figure 4:** The evolutionary process diagram of the traditional genetic algorithm running 4 times.
wave in China and EL Centro seismic wave are shown in Figure 2. The frequencies corresponding to the peaks in the frequency spectra of the two seismic waves are 1.099 Hz and 1.458 Hz, respectively, while Tables 5 and 6 show that the optimized value of $\omega_{TMD}$ is near this value, demonstrating Farshidianfar et al.’s [30, 37] point of view that optimized TMD frequencies are obtained near the natural frequency for four soil types.

Taking the Tangshan earthquake in China as an example, Figure 7 compares the maximum displacement of the structure with or without TMD under different ground conditions. Except for the soft soil foundation, the maximum displacement of the other three cases all occurred on the top layer, and the maximum displacement under the soft soil foundation occurred on the 17th floor, so the maximum displacement time history form of Figure 7(d) is different from the other three. Figure 7 shows that the maximum displacement of the structure is decreased due to the existence of the TMD device. By comparing the displacement time histories of the uncontrolled and controlled structure under different soil conditions, the magnitude histories were close to each other at the early stage, which indicates that the response cannot be effectively reduced at the early stage of seismic input by attaching mass dampers. As time goes on, the two dampers show different damping effects. The specific displacement of each floor is shown in Figures 8 and 9.

Tables 7 and 8 show the maximum displacement, maximum interlayer displacement, and peak acceleration of the structure with and without TMD for three different soils and fixed foundations under the excitation of Tangshan wave and EL Centro wave, respectively. Figure 8 shows that the maximum displacements of the uncontrolled structures in soft soil, medium soil, hard soil, and fixed foundation under the excitation of Tangshan earthquake were 0.2421 m, 0.5713 m, 0.7376 m, and 0.9574 m, respectively, while the maximum displacement of the structure with TMD is about 0.17213 m, 0.35818 m, 0.4003 m, and 0.4220 m, respectively. Therefore, the maximum displacement reduction rates are 28.90%, 37.30%, 45.73%, and 55.92%, respectively. The maximum interlayer displacement of uncontrolled structure under the excitation of Tangshan wave in China and EL Centro wave on a fixed foundation is 0.0414 m and 0.0176 m, respectively. Therefore, the maximum interstory drift angles are 1/97 and 1/227, respectively. Correspondingly, the maximum interlayer displacement of controlled structure under the excitation of Tangshan waves in China and EL Centro waves on a fixed foundation is 0.0209 m and 0.0139 m, respectively. Thus, the maximum interlayer displacement reduction rates are 49.52% and 21.02%, respectively, under the excitation of Tangshan wave in China and EL Centro wave, and the maximum interstory drift angle reduced to 1/191 and 1/288. According to the Chinese specification [38], the limitation of elastic interstory drift angle is 1.82% for reinforced concrete structure, while the limitation of elastic-plastic interstory drift ratio for this building is 2% the structure involved in these conditions meet the requirements of code. The results show that TMD can be effectively used in the vibration control of high-rise buildings. On the other hand, it shows that, under the excitation of Tangshan seismic wave, the TMD is more effective on the rigid foundation. Besides, the TMD has achieved good damping effects under the excitation of EL Centro earthquake, but the optimization effect is not as ideal as under the excitation of the Tangshan wave. Combined with the foregoing description, the spectral components of seismic waves greatly affect the damping effect of the TMD. In fact, since the parameters of passive TMDs are constant values, they cannot adequately cope with the changes in load or structural dynamic characteristics caused by earthquakes, so their performance is limited.

As shown in Figures 8–13, the soil type has a significant impact on the dynamic time history response of the structure. The dynamic response of the structure decreases with the decrease of foundation stiffness. This is because the seismic force is transmitted to the structure through the soft soil. Compared with hard soil, it will absorb more
energy, so the dynamic response of the structure on soft soil is generally smaller than that on hard soil. Therefore, ignoring the SSI effect may lead to large errors in the seismic analysis of high-rise structures, which is consistent with the result of [37]. Besides, Figures 8 and 9 show that when high-rise buildings are excited by earthquakes, the maximum drift of floor displacement for the high-rise building is more likely to appear in the middle of the structure with the decrease of foundation stiffness. Figures 10 and 11 show that the displacement between floors increases as the...
Table 6: EL Centro wave optimization TMD parameters.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>$M_{TMD}$ (Kg)</th>
<th>$K_{TMD}$ (N/m)</th>
<th>$C_{TMD}$ (Ns/m)</th>
<th>$\omega_{TMD}$ (rad/s)</th>
<th>Damping ratio $\xi$</th>
<th>Mass ratio $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft soil</td>
<td>1999759</td>
<td>8007722</td>
<td>106692</td>
<td>2.00</td>
<td>0.013</td>
<td>0.051</td>
</tr>
<tr>
<td>Medium soil</td>
<td>1999302</td>
<td>7652570</td>
<td>5209</td>
<td>1.95</td>
<td>6.66 x 10^{-4}</td>
<td>0.051</td>
</tr>
<tr>
<td>Dense soil</td>
<td>1994428</td>
<td>5678396</td>
<td>4010</td>
<td>1.68</td>
<td>5.96 x 10^{-4}</td>
<td>0.051</td>
</tr>
<tr>
<td>Fixed base</td>
<td>1998939</td>
<td>5729029</td>
<td>1660</td>
<td>1.69</td>
<td>2.45 x 10^{-4}</td>
<td>0.051</td>
</tr>
</tbody>
</table>

Figure 7: Comparison chart with or without TMD structure displacement (m) (Tangshan wave, China). (a) Fixed base. (b) Dense soil. (c) Medium soil. (d) Soft soil.
Figure 8: Tangshan earthquake maximum floor displacement comparison chart.

Figure 9: EL Centro earthquake maximum floor displacement comparison chart.

Table 7: Dynamic response to Tangshan wave with or without TMD.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Maximum floor displacement (m)</th>
<th>Maximum drift of floor (m)</th>
<th>Maximum floor acceleration (m/s²)</th>
<th>Maximum floor displacement (m)</th>
<th>Maximum drift of floor (m)</th>
<th>Maximum floor acceleration (m/s²)</th>
<th>Reduction rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft soil</td>
<td>0.2421</td>
<td>0.0226</td>
<td>6.4218</td>
<td>0.0159</td>
<td>5.9960</td>
<td>28.90</td>
<td>29.65</td>
</tr>
<tr>
<td>Medium soil</td>
<td>0.5713</td>
<td>0.0281</td>
<td>7.1687</td>
<td>0.0174</td>
<td>6.9010</td>
<td>37.30</td>
<td>38.08</td>
</tr>
<tr>
<td>Dense soil</td>
<td>0.7376</td>
<td>0.0362</td>
<td>7.5426</td>
<td>0.0240</td>
<td>7.1797</td>
<td>45.73</td>
<td>33.70</td>
</tr>
<tr>
<td>Fixed base</td>
<td>0.9574</td>
<td>0.0414</td>
<td>7.6450</td>
<td>0.0209</td>
<td>7.2360</td>
<td>55.92</td>
<td>49.52</td>
</tr>
</tbody>
</table>
Table 8: Dynamic response to EL Centro wave with or without TMD.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Without TMD</th>
<th>With TMD</th>
<th>Reduction rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum floor displacement (m)</td>
<td>Maximum floor drift of floor (m)</td>
<td>Maximum floor acceleration (m/s²)</td>
</tr>
<tr>
<td>Soft soil</td>
<td>0.3215</td>
<td>0.1427</td>
<td>0.0077</td>
</tr>
</tbody>
</table>

Figure 10: Tangshan earthquake maximum drift of floor comparison chart.

Figure 11: EL Centro earthquake maximum drift of floor comparison chart.
stiffness of the foundation decreases, and the maximum displacement generally occurs in the middle of the high-rise building. Therefore, special attention should be paid to the central location of high-rise buildings in seismic design. Figures 12 and 13 are the peak acceleration comparison diagrams of high-rise building with or without TMD under the excitation of Tangshan seismic wave and the EL Centro seismic wave. It can be seen that the acceleration optimization effect of the TMD on the structure is not obvious and even slightly enlarged. However, compared with the optimization results for Kobe earthquake waves in [30], it is found that this phenomenon is not absolute, which shows that the seismic wave spectrum components greatly affect the optimization effect of the TMD system on displacement and acceleration.

5. Conclusions

This paper has made a series of improvements to the traditional genetic algorithm; the improved multipopulation was utilized to obtain the optimum parameters of TMD; the displacement and acceleration are optimized simultaneously for better comfort for a 40-story building considering soil interaction under earthquake excitations. The conclusions can be listed as follows.

The correctness of the improved multipopulation is tested by case study. It is concluded that the improved
multipopulation has higher convergence speed, operation accuracy, and operation stability than the traditional genetic algorithm, which can provide guidelines for different design purposes. Therefore, the algorithm can be used to calculate the mathematical model to study the optimal solution of TMD parameters under SSI.

The improved multipopulation genetic algorithm was used to adjust and optimize the damping effect of the 40-story building with TMD, and the optimal parameters of TMD under four different foundation conditions (soft, medium, hard soil, and rigid foundation) were obtained. The TMD with optimal parameters can significantly control structural dynamic response. The maximum displacement reduction rates under Tangshan wave and EL Centro wave excitation are in the range of 28%–56% and 16%–56% for different soil conditions, respectively. In general, the optimization effect of TMD on structural displacement response is usually better than that of acceleration.

In addition, ignoring the SSI effect may cause the seismic response and TMD performance of high-rise buildings to deviate from actual estimates under earthquake excitation. For example, the maximum displacement reduction rates for different soil conditions are 28.90%, 37.30%, 45.73%, and 55.92%, respectively, under Tangshan wave excitation. This is because different soil conditions can absorb different seismic energy, leading to great differences in dynamic response of structures. Therefore, in the optimization design process of TMD parameters, TMD usually must have greater mass, damping, and rigidity to obtain better shock absorption effects under soft soil foundation. Besides, the results of the maximum story drift angle indicate that the middle layer of the high-rise structure as a weak layer should also be paid attention to in the design of the structure.

Data Availability


Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References


