Research on physical parameter damage identification of chimney structure under excitation response of earthquake

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Abstract

When seismic load affects structure height direction, it presents time domain correlation feature. According to this feature and on the basis of utilizing total compensation composite inversion algorithm, establish physical parameter damage identification method combining with probability average method in which seismic excitation response is unknown. Taking one typical chimney as engineering background, input stability and accuracy of analysis algorithm under the action of unknown EI seismic wave and do discussion on anti-jamming capability under low-level noise. Research results show that parameter damage identification of structure without noise jamming keeps high accuracy and stability. Damping has sensitive response on noise jamming in which error amplitude of damping identification obviously enlarges with the increasing of noise level. Meanwhile its accuracy and stability reduce. Response of stiffness on the change of noise level is relatively low and its stability and accuracy are higher. Therefore, research results would provide references for seismic damage and health monitoring method of chimney structure.

Keywords: Seismic Excitation, Chimney Structure, Physical Parameter, Damage Identification

1 Introduction

As a type of important high-rising structure, chimney plays a key role in national industry. Chimneys which are dozens or hundreds of meters in height are generally built in some large coal-fired power plants, steel companies and chemical factories. Even chimneys which are more than 200 meters in height are also built. Their structural seismic safety performance not only directly concerns safety of architectural structures nearby but also concerns the function of disaster reduction lifeline in the city [1]. Especially violent earthquakes constantly happen in recent years. The existing chimneys also keep material, design and construction disadvantages. Therefore, earthquakes necessarily lead using function and bearing capacity of chimneys to degenerate, damage fracture and even collapse. Seismic damage investigation shows that except for several reinforced concrete chimneys at zones of 6.0 and 7.0 anti-cracking degrees presenting to be slight cracking, the others are in good condition when violent earthquakes happen to them. While at seismic zones more than 8 degrees, they also present different levels of damages. Seismic damage form of reinforced concrete chimney mainly includes cracking, inclining, bending, fracturing, crashing, etc (as seen in Figure 1). The main cracking damage sections generally tend to be in the middle and lower parts of chimneys. The fracturing and crashing damage sections are mainly in upper parts of chimneys. Its regularity is not so obvious like that of brick chimney. Both turning and collapsing parts of both brick and reinforced concrete chimneys scatter within the range of 8 to 10 meters away from chimney shaft. Few of them collapses so far [2]. Seismic damage or loss brought to both brick chimney and reinforced concrete chimney keeps high randomness and unpredictability which leads safety pre-warning to be difficult. Therefore it is necessary to detect current situation of architectural structures on-duty, judge their damage and structural health conditions and protect them [3].

Correctness of health inspection result of chimney structure mainly depends on whether identification algorithm could accurately and effectively identify the true form of structure among practically recorded signals. At present most identification algorithms are established on the basis of recorded information being complete which is actually not suitable for damage identification of structural physical parameter. In practical test, environment excitation often serves as vibrating load whose acting positions are undefined keeping measuring difficulties [4]. Therefore, completeness of input information cannot be guaranteed. According to this situation, physical parameter time domain identification method and probability average method are utilized to do damage identification research on chimney structure under seismic excitation response as earthquake keeps the feature of time domain along height direction. Taking one 180m typical reinforced concrete chimney structure for example, verify physical parameter damage identification accuracy of chimney structure under seismic excitation response on the basis of EI seismic wave being input. Also discuss its anti-noise-interference ability. Analysis and verification show that physical parameter damage identification on chimney structure under seismic excitation response keeps high identification accuracy and certain anti-interference ability. The research achievements would provide references for health monitoring and safety assessment of existing chimney structure in earthquake regions.

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2 Structural damage identification method under seismic excitation response

2.1 NUMERICAL SIMULATION OF IRREGULAR WAVE OF LINEAR SUPERPOSITION METHOD

Dynamic equation of multiple-degree-of-freedom system is:

\[ M \ddot{u} + C \dot{u} + K u = F(t) . \]  

(1)

In this formula, M, C and K are respectively weight, damping and stiffness matrix. \( F(t) \) is external excitation vector. \( \dot{u} \), \( \ddot{u} \) and \( u \) are structural displacement, velocity and acceleration response vector.

Suppose that M is the known diagonal matrix. Do transposition on Formula (1) to obtain that:

\[ C \dot{u} + K u = F(t) - M \ddot{u} = P , \]  

(2)

\[ F(t) = [ F_s(t) \quad \alpha \cdot F_u(t) ] , \]  

(3)

Here \( F_s(t) \) is wave force of unknown input unit and \( \alpha \cdot F_u(t) \) is wave force of neighboring unknown unit input. \( \alpha \) is ratio of the two neighboring units affected by wave force and seismic time-domain correlation \( \alpha \) equals to 1.0.

According to Literature [5, 6], convert Formula (2) to be:

\[ H \Theta = P . \]  

(4)

Then acquire system input vector based on Formula (2):

\[ \tilde{P}_0 = \begin{bmatrix} \tilde{P}_w & \tilde{P}_{u(i+1)} \end{bmatrix} . \]  

(5)

\( \tilde{P}_w \) and \( \tilde{P}_{u(i+1)} \) are unknown input vectors of \( i \) and \( i+1 \) degree of freedom or units.

The main steps of its identification are:

Artificially set that initial value of random structural parameter vector is \( \hat{\Theta}_0 \).

Put the set initial value \( \hat{\Theta}_0 \) into Formula 4 to calculate that:

\[ \tilde{P}_0 = H \hat{\Theta}_0 . \]  

(6)

\( \tilde{P}_0 \) could be expressed as:

\[ \tilde{P}_0 = \begin{bmatrix} \tilde{P}_w & \tilde{P}_{u(i+1)} \end{bmatrix} . \]  

(7)

After \( \tilde{P}_0 \) is calculated, \( F(t) \) in Formula (2) becomes known. Therefore estimated values of \( \tilde{F}_s(t) \) and \( \alpha \tilde{F}_u(t) \) are acquired through Formula (3) which are generally unequal. Then do processing on \( \tilde{F}_s(t) \) utilizing statistical average method [5]. Use the averaged \( \tilde{F}_s(t) \) to calculate new estimated input force \( \tilde{P} \) processes of each unit.

\[ \tilde{F}_s(t) = \frac{1}{N} \sum_{i=1}^{N} \tilde{F}_s(t) \]  

(8)

In this formula, N is degree of freedom or unit number and M is sampling point number.

Utilize new \( \tilde{F}_s(t) \) to acquire the corrected vector \( \hat{\Theta}_0 \) and use Formula (3) calculate new parameter estimated value under least square method [7].

Judge whether newly calculated \( \hat{\Theta}_0 \) and original \( \hat{\Theta}_0 \) cater for convergence condition of given accuracy \( \varepsilon \). Suppose that \( \hat{\Theta}_i \) is identification value of \( i \) structural parameter. If all parameters cater for Formula (9):

\[ \left| \hat{\Theta}_i - \hat{\Theta}_0 \right| \leq \varepsilon . \]  

(9)

Then choose parameter estimated value \( \hat{\Theta}_i \) in this step to be the final calculation result. Otherwise it would serve as new parameter initial value to repeat Step 2 to Step 5 until convergence.

3 Precision verification of engineering project

3.1 ENGINEERING SITUATION

Electrical Reinforced concrete chimney in one area is shown in Figure 2. Its height is 180m and anti-cracking degree is set to be 8. Seismic design group is 2nd Group. II Type of site is built [2]. Gravity load representative values of simplified particle of chimney are seen in Figure 2. Suppose that bridge pier and the foundation are fully consolidated in which damping ratio of each order is 3% and elastic modulus of reinforced concrete is \( 3.25 \times 10^4 \text{ Mpa} \). Chimney structure model and load representative values of each particle are in Figure 2 [2]. Utilize EI seismic wave to input. Time-history curves of seismic wave are shown in Figure 3. Without considering shear deformation, damping between each particle utilizes Rayleigh Damping [8]. Assume that original physical parameter indexes of chimney are seen in Table 1.

<table>
<thead>
<tr>
<th>Node Number</th>
<th>Weight (kg)</th>
<th>Damping (kg/m.s)</th>
<th>Stiffness (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>188.0E+04</td>
<td>3.76E+05</td>
<td>4156E+10</td>
</tr>
<tr>
<td>2</td>
<td>126.0E+04</td>
<td>2.52E+05</td>
<td>2567E+10</td>
</tr>
<tr>
<td>3</td>
<td>88.40E+04</td>
<td>1.77E+05</td>
<td>1449E+10</td>
</tr>
<tr>
<td>4</td>
<td>62.04E+04</td>
<td>1.24E+05</td>
<td>714E+10</td>
</tr>
<tr>
<td>5</td>
<td>41.36E+04</td>
<td>0.827E+05</td>
<td>283E+10</td>
</tr>
<tr>
<td>6</td>
<td>18.80E+04</td>
<td>0.376E+05</td>
<td>755E+10</td>
</tr>
</tbody>
</table>
3.2 DYNAMIC PARAMETER MATRIX OF CHIMNEY STRUCTURE

Matrixes of damping $C$, stiffness $K$, response $H$ and excitation $P$ of chimney structure are shown as Formula (10) and (11):

$$H(t) = \begin{bmatrix}
    x_1(t) & x_2(t) & 0 & 0 & 0 & 0 & 0 \\
    \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
    x_i(t) & x_{i-1}(t) & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix} \begin{bmatrix}
    \dot{x}_1(t) \\
    \vdots \\
    \dot{x}_i(t) \\
    \vdots \\
    \dot{x}_{i-1}(t) \\
    0 \\
    0 \\
    0 \\
    0 \\
\end{bmatrix} \begin{bmatrix}
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix} = \begin{bmatrix}
    x_i(t) \\
    \vdots \\
    x_{i-1}(t) \\
    0 \\
    0 \\
    0 \\
    0 \\
    0 \\
\end{bmatrix}
$$

(10)

According to Formula (2), specific matrix expressions of $H, \theta$ and $P$ could be derived:

$$H(t) = \left[ H(t_1), H(t_2), H(t_3), H(t_4), H(t_5) \right],$$

(12)

3.3 PHYSICAL PARAMETER IDENTIFICATION OF CHIMNEY UNDER SEISMIC EXCITATION RESPONSE

Suppose that displacement, velocity and acceleration responses of each node under seismic excitation are known. Utilized method in 2nd section to identify damping and stiffness physical parameters of each node. Apply Newark – $\beta$ method [9, 10] to calculate dynamic response of chimney under seismic excitation in which the input seismic wave is

$$P(t) = \begin{bmatrix}
    P(t_1) & P(t_2) & P(t_3) & P(t_4) & P(t_5) \\
\end{bmatrix}.$$

(14)

$$P(t) = \begin{bmatrix}
    f_1(t_1) - m_1 \ddot{x}_1(t_1) \\
    f_2(t_2) - m_2 \ddot{x}_2(t_2) \\
    \vdots \\
    f_i(t_i) - m_i \ddot{x}_i(t_i) \\
    \vdots \\
    f_n(t_n) - m_n \ddot{x}_n(t_n) \\
\end{bmatrix}.$$

(15)

$$\theta = \begin{bmatrix}
    k_1 & k_2 & 0 & 0 & 0 & 0 & 0 \\
    k_3 & k_4 & 0 & 0 & 0 & 0 & 0 \\
    \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
    k_{i-1} & k_i & 0 & 0 & 0 & 0 & 0 \\
    \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
    k_{n-1} & k_n & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}.$$

(16)

It is deduced from the simplified Formula (10) that wave force ratio affected on any adjacent unit is determined only by $\cosh(kz_j)$.

$$\alpha_j = \frac{F_{j+1}(t)}{F_j(t)} = \cosh(kz_{j+1}) \cosh(kz_j).$$

(17)

3.3.1 Identification results without noise

Physical parameter identification results without noise are expressed in Table 2.

<table>
<thead>
<tr>
<th>Node number</th>
<th>Stiffness (1010kg/m.s)</th>
<th>Stiffness error (%)</th>
<th>Damping (105kg/m.s)</th>
<th>Damping error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4155.995</td>
<td>0.00012</td>
<td>3.76154</td>
<td>0.04096</td>
</tr>
<tr>
<td>2</td>
<td>2566.997</td>
<td>0.00012</td>
<td>2.52067</td>
<td>0.02659</td>
</tr>
<tr>
<td>3</td>
<td>1448.998</td>
<td>0.00014</td>
<td>1.77024</td>
<td>0.01356</td>
</tr>
<tr>
<td>4</td>
<td>713.9992</td>
<td>0.00011</td>
<td>1.24806</td>
<td>0.00484</td>
</tr>
<tr>
<td>5</td>
<td>282.9997</td>
<td>0.00011</td>
<td>0.82701</td>
<td>0.00121</td>
</tr>
</tbody>
</table>
It is seen from Table 2 and Figure 5 that utilize probability average statistical method to do physical parameter damage identification on chimney structure according to time domain correlation feature of earthquake and on the basis of total compensation composite inverse. Then acquire the maximum value of stiffness error which is only 0.00014% and that of damping error is 0.04096%. Identification results keep high precision.

3.3.2 Identification results under working conditions with different noises

In order to further discuss the reliability of identification method under noise interference, this section does damage identification research on working conditions with 6 kinds of different noises. They are 0.1%, 0.2%, 0.3%, 0.5%, 0.5% and 1.0%.

Table 3 shows physical parameter identification results of chimney structure when noise interference is 0.1%.

<table>
<thead>
<tr>
<th>Node number</th>
<th>Stiffness (1010kg/m.s)</th>
<th>Stiffness error (%)</th>
<th>Damping (105kg/m.s)</th>
<th>Damping error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4156.891</td>
<td>0.02144</td>
<td>3.57630</td>
<td>4.87207</td>
</tr>
<tr>
<td>2</td>
<td>2568.035</td>
<td>0.04032</td>
<td>2.44478</td>
<td>2.98659</td>
</tr>
<tr>
<td>3</td>
<td>1447.654</td>
<td>0.09289</td>
<td>1.620514</td>
<td>8.44554</td>
</tr>
<tr>
<td>4</td>
<td>715.3162</td>
<td>0.18434</td>
<td>1.327346</td>
<td>7.04403</td>
</tr>
<tr>
<td>5</td>
<td>282.6758</td>
<td>0.11456</td>
<td>0.827778</td>
<td>0.09407</td>
</tr>
<tr>
<td>6</td>
<td>74.95855</td>
<td>0.05527</td>
<td>0.85610</td>
<td>2.35585</td>
</tr>
</tbody>
</table>

It is presented from Table 3 that precision of identification on stiffness keeps high whose maximum error is just 0.18434% when structural response affords 0.1% noise interference. While damping is sensitive to noise whose maximum error is 8.44554%. Identification results tell us that it could basically cater for engineering error requirements.

3.3.3 Identification results under different noise

Do seismic excitation response damage identification on physical parameter of chimney structure under different noise levels. The results are shown in Table 4 to Table 8.

<table>
<thead>
<tr>
<th>Node number</th>
<th>Stiffness (1010kg/m.s)</th>
<th>Stiffness error (%)</th>
<th>Damping (105kg/m.s)</th>
<th>Damping error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4159.233</td>
<td>0.07779</td>
<td>3.367932</td>
<td>10.42734</td>
</tr>
<tr>
<td>2</td>
<td>2561.837</td>
<td>0.20113</td>
<td>2.110434</td>
<td>16.25262</td>
</tr>
<tr>
<td>3</td>
<td>1452.262</td>
<td>0.22512</td>
<td>1.965439</td>
<td>11.04175</td>
</tr>
<tr>
<td>4</td>
<td>714.4945</td>
<td>0.09626</td>
<td>1.317176</td>
<td>6.22387</td>
</tr>
<tr>
<td>5</td>
<td>282.3177</td>
<td>0.24110</td>
<td>0.812379</td>
<td>1.76796</td>
</tr>
<tr>
<td>6</td>
<td>74.99953</td>
<td>0.00063</td>
<td>0.381750</td>
<td>1.52926</td>
</tr>
</tbody>
</table>

3.3.4 Comparative analysis on identification error and seismic force inversion

- FIGURE 4 Influence comparison curves of different noises on physical parameter identification results of chimney
Draw absolute errors of stiffness and damping under each working condition into curves changing with nodes. The drawn curves are in Figure 4. Meanwhile Figure 5 presents time-history curves of seismic load inversion results under 0.5% and 1.0% noise interference.

It is known from Figure 4 and Figure 5 that identification errors of stiffness and damping increase with increasing of noise level whose increasing amplitude also becomes higher and higher. Here stiffness error presents slow response to the increasing of noise level. While damping error is sensitive to it. Precision of seismic load time-history affected by identification inversion under different noises is high. It is to say that noise has low influence on seismic load inversion which keeps high reliability.

5 Conclusions

Under According to time domain correlation feature of earthquake action, physical parameter identification of chimney structure and seismic inversion method without knowing seismic input is established combining with probability statistical average method on the basis of total compensation composite inversion algorithm. Do precision and stability analysis through one typical engineering project. Conclusions and suggestions are below:

Structural physical parameter damage identification without noise interference keeps high precision and stability. Damping identification is highly sensitive to noise in which identification error rapidly increases with the increasing of noise level. In terms of structural analysis controlled by damping, influences of noise should be fully considered.

Noise has low influences on stiffness. Although error also increases with the increasing of noise level, its precision is high and stability is good under low noise leve.

Comparative analysis on seismic load inversion under different low noise levels shows that precision of inversion results is high and its reliability is good.

In order to lead identification method to keep better anti-noise ability, further improvement is needed. Stability and reliability of damping identification especially need further progress.

References

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[2] Deleted by CMNT Editor
[5] Deleted by CMNT Editor
[7] Deleted by CMNT Editor

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