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

Liming Wu[1*], Zijian Wang[2, 3]

[1] *Chongqing Technology and Business Institute, Chongqing, China, 400052*

[2] *Chongqing University of Science&Technology, Chongqing, China, 401331*

[3] *T.Y.Lin International Engineering Consulting (China) Co., Ltd, Chongqing 401121*

Received 21 October 2014, www.cmnt.lv

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 antijamming 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.

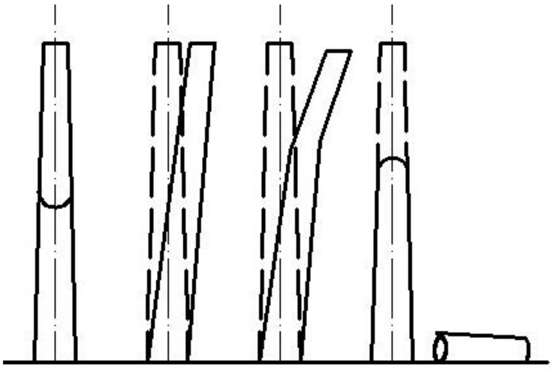
Keywords: Seismic Excitation, Chimney Structure, Physical Parameter, Damage Identification

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.

* ***Corresponding author*** e-mail: 58432053@qq.com



a. Cracking b. Inclining c. Bending d. Crashing

FIGURE 1 Seismic damage diagram of reinforced concrete chimney

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:

$$M\ddot{u} + C\dot{u} + Ku = F(t)\,. \tag{1}$$

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

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

$$C\dot{u} + Ku = F(t) - M\ddot{u} = P\,, \tag{2}$$

$$F(t) = \left[F_u(t) \quad \alpha \cdot F_u(t) \right]'\,, \tag{3}$$

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

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

$$H\theta = P\,\cdot \tag{4}$$

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

$$\tilde{P}_0 = \left[\tilde{P}_{ui} \quad \tilde{P}_{u(i+1)} \right]'\,. \tag{5}$$

$\tilde{P}_{ui}$ 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:

$$\tilde{P}_0 = H\hat{\theta}_0\,\cdot \tag{6}$$

$\tilde{P}_0$ could be expressed as:

$$\tilde{P}_0 = \left[\tilde{P}_{ui} \quad \tilde{P}_{u(i+1)} \right]'\,\cdot \tag{7}$$

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

$$\bar{F}_u(t_i) = \frac{1}{N}\sum_{l}^{N} \tilde{F}_{u.l}(t_i) \quad i = 1, 2, ..., M;\, l = 1, 2, ..., N\,\cdot \tag{8}$$

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

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

Judge whether newly calculated $\hat{\theta}_1$ and original $\hat{\theta}_0$ cater for convergence condition of given accuracy ε . Suppose that $\hat{\theta}_1^i$ is identification value of i structural parameter. If all parameters cater for Formula (9):

$$\left| \frac{\hat{\theta}_1^i - \hat{\theta}_0^i}{\hat{\theta}_0^i} \right| \le \varepsilon\,\cdot \tag{9}$$

Then choose parameter estimated value $\hat{\theta}_1$ 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 $3.25\times10^4\,Mpa$. 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 1 Physical Parameter Llist

Node Number	Weight (kg)	Damping (kg/m.s)	Stiffness (N/m)
1	188.0E+04	3.76E+05	4156E+10
2	126.0E+04	2.52E+05	2567E+10
3	88.40E+04	1.77E+05	1449E+10
4	62.04E+04	1.24E+05	714E+10
5	41.36E+04	0.827E+05	283E+10
6	18.80E+04	0.376E+05	75E+10

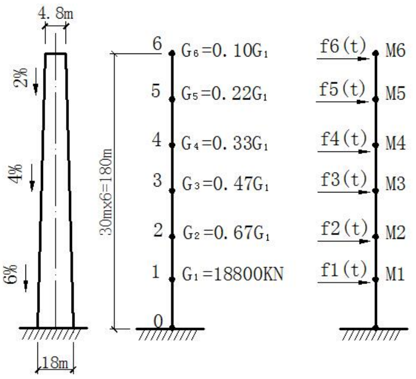


FIGURE 2 Diagram of chimney and simplified model

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):

$$K=\begin{bmatrix} k_1+k_2 & -k_2 & 0 & 0 & 0 & 0 \\ -k_2 & k_2+k_3 & -k_3 & 0 & 0 & 0 \\ 0 & -k_3 & k_3+k_4 & -k_4 & 0 & 0 \\ 0 & 0 & -k_4 & k_4+k_5 & -k_5 & 0 \\ 0 & 0 & 0 & -k_5 & k_5+k_6 & -k_6 \\ 0 & 0 & 0 & 0 & -k_6 & k_6 \end{bmatrix}, \quad (10)$$

$$C=\begin{bmatrix} c_1+c_2 & -c_2 & 0 & 0 & 0 & 0 \\ -c_2 & c_2+c_3 & -c_3 & 0 & 0 & 0 \\ 0 & -c_3 & c_3+c_4 & -c_4 & 0 & 0 \\ 0 & 0 & -c_4 & c_4+c_5 & -c_5 & 0 \\ 0 & 0 & 0 & -c_5 & c_5+c_6 & -c_6 \\ 0 & 0 & 0 & 0 & -c_6 & c_6 \end{bmatrix}. \quad (11)$$

According to Formula (2), specific matrix expressions of H,θ and Pcould be derived:

$$H(t)=\left[H(t_1),H(t_2),H(t_3),H(t_4),H(t_5),H(t_6)\right], \quad (12)$$

$$H(t_i)=\begin{bmatrix} x_1(t_i) & x_1(t_i)-x_2(t_i) & 0 & 0 & 0 & 0 & \dot{x}_1(t_i) & \dot{x}_1(t_i)-\dot{x}_2(t_i) & 0 & 0 & 0 & 0 \\ 0 & x_2(t_i)-x_1(t_i) & x_2(t_i)-x_3(t_i) & 0 & 0 & 0 & 0 & \dot{x}_2(t_i)-\dot{x}_1(t_i) & \dot{x}_2(t_i)-\dot{x}_3(t_i) & 0 & 0 & 0 \\ 0 & 0 & x_3(t_i)-x_2(t_i) & x_3(t_i)-x_4(t_i) & 0 & 0 & 0 & 0 & \dot{x}_3(t_i)-\dot{x}_2(t_i) & \dot{x}_3(t_i)-\dot{x}_4(t_i) & 0 & 0 \\ 0 & 0 & 0 & x_4(t_i)-x_3(t_i) & x_4(t_i)-x_5(t_i) & 0 & 0 & 0 & 0 & \dot{x}_4(t_i)-\dot{x}_3(t_i) & \dot{x}_4(t_i)-\dot{x}_5(t_i) & 0 \\ 0 & 0 & 0 & 0 & x_5(t_i)-x_4(t_i) & x_5(t_i)-x_6(t_i) & 0 & 0 & 0 & 0 & \dot{x}_5(t_i)-\dot{x}_4(t_i) & \dot{x}_5(t_i)-\dot{x}_6(t_i) \\ 0 & 0 & 0 & 0 & 0 & x_6(t_i)-x_5(t_i) & 0 & 0 & 0 & 0 & 0 & \dot{x}_6(t_i)-\dot{x}_5(t_i) \end{bmatrix}, \quad (13)$$

$$P(t)=\left[P(t_1) \quad P(t_2) \quad P(t_3) \quad P(t_4) \quad P(t_5) \quad P(t_6)\right], \quad (14)$$

$$P(t_i)=\begin{bmatrix} f_1(t_i)-m_1\ddot{x}_1(t_i) \\ f_2(t_i)-m_2\ddot{x}_2(t_i) \\ f_3(t_i)-m_3\ddot{x}_3(t_i) \\ f_4(t_i)-m_4\ddot{x}_4(t_i) \\ f_5(t_i)-m_5\ddot{x}_5(t_i) \\ f_6(t_i)-m_6\ddot{x}_6(t_i) \end{bmatrix}, \quad (15)$$

$$\theta=\left[k_1 \quad k_2 \quad k_3 \quad k_4 \quad k_5 \quad k_6 \quad c_1 \quad c_2 \quad c_3 \quad c_4 \quad c_5 \quad c_6\right]. \quad (16)$$

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

$$\alpha_j=\frac{F_{j+1}(t)}{F_j(t)}=\frac{\cosh(kz_{j+1})}{\cosh(kz_j)}. \quad (17)$$

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 EI, sampling point number M is 2000 and sampling time interval $dt=0.02$ s. Weight parameters of each node of chimney are known during calculation process. Initial values of each parameter are seen in Table 1. Error is defined as: *error= | identification value - original value | / original value×100%.*

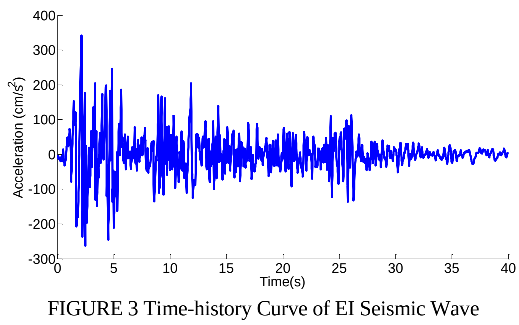


FIGURE 3 Time-history Curve of EI Seismic Wave

3.3.1 Identification results without noise

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

TABLE 2 Parameter list of each node of bridge pier

Node number	Stiffness (1010kg/m.s)	Stiffness error (%)	Damping (105kg/m.s)	Damping error (%)
1	4155.995	0.00012	3.76154	0.04096
2	2566.997	0.00012	2.52067	0.02659
3	1448.998	0.00014	1.77024	0.01356
4	713.9992	0.00011	1.24006	0.00484
5	282.9997	0.00011	0.82701	0.00121

6	74.99992	0.00011	0.37601	0.00266

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 inversion. 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 3 Physical Parameter Identification Results with 0.10% Noise

Node number	Stiffness (1010kg/m.s)	Stiffness error (%)	Damping (105kg/m.s)	Damping error (%)
1	4156.891	0.02144	3.576810	4.87207
2	2568.035	0.04032	2.444738	2.98659
3	1447.654	0.09289	1.620514	8.44554
4	715.3162	0.18434	1.327346	7.04403
5	282.6758	0.11456	0.827778	0.09407
6	74.95855	0.05527	0.385610	2.55585

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 4 Physical Parameter Identification Results with 0.20% Noise

Node number	Stiffness (1010kg/m.s)	Stiffness error (%)	Damping (105kg/m.s)	Damping error (%)
1	4159.233	0.07779	3.367932	10.42734
2	2561.837	0.20113	2.110434	16.25262
3	1452.262	0.22512	1.965439	11.04175
4	714.4945	0.06926	1.317176	6.22387
5	282.3177	0.24110	0.812379	1.76796
6	74.99953	0.00063	0.381750	1.52926

TABLE 5 Physical Parameter Identification Results with 0.30% Noise

Node number	Stiffness (1010kg/m.s)	Stiffness error (%)	Damping (105kg/m.s)	Damping error (%)
1	4154.1740	0.04394	3.105489	17.40721
2	2568.3285	0.05175	2.432373	3.47726
3	1448.3197	0.04695	1.994150	12.66384
4	714.91799	0.12857	1.291334	4.13984
5	282.41363	0.20720	0.801193	3.12056
6	74.87551	0.16599	0.362354	3.62926

TABLE 6 Physical Parameter Identification Results with 0.5% Noise

Node number	Stiffness (1010kg/m.s)	Stiffness error (%)	Damping (105kg/m.s)	Damping error (%)
1	4159.6157	0.08700	4.53599	20.63803
2	2557.81635	0.35776	2.44865	2.83135
3	1446.20886	0.19263	1.76812	0.10621
4	712.426854	0.22033	1.10300	11.04839
5	283.343440	0.12136	0.83913	1.46675
6	74.902921	0.08700	0.351013	2.55585

It is known from identification results in Table 4 to Table 8 that stiffness keeps low sensitivity to noise and its identification precision is high. When noise is 1%, its maximum error is just 1.14084%. In terms of stiffness, identification method in this paper keeps high stability and reliability. While damping is sensitive to noise. With the increasing of noise level, damping error rapidly increases. When noise level is 1.14084, maximum error of damping reaches 63.56106%. Anti-noise stability of this identification method is poor.

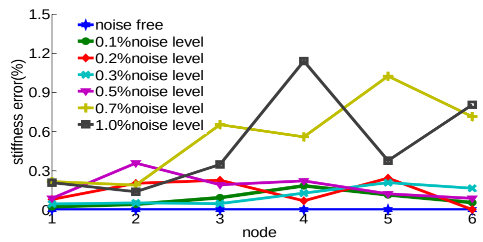
TABLE 7 Physical Parameter Identification Results with 0.7% Noise

Node number	Stiffness (1010kg/m.s)	Stiffness error (%)	Damping (105kg/m.s)	Damping error (%)
1	4164.9417	0.21515	5.50492	46.40745
2	2571.8211	0.18781	3.14236	24.69683
3	1439.5563	0.65174	1.08204	38.86780
4	717.99208	0.55911	1.30570	5.29839
5	280.09672	1.02589	0.55302	33.12938
6	75.536197	0.71493	0.31464	16.31915

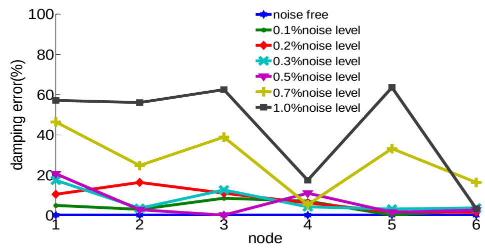
TABLE 8 Physical Parameter Identification Results with 1% Noise

Node number	Stiffness (1010kg/m.s)	Stiffness error (%)	Damping (105kg/m.s)	Damping error (%)
1	4164.593	0.20676	1.61414	57.07074
2	257.0562	0.13876	392934	55.92619
3	1443.966	0.34741	2.87374	62.35819
4	705.8544	1.14084	1.45586	17.40806
5	284.0664	0.37682	0.30135	63.56106
6	74.39705	0.80393	0.38809	3.21543

3.3.4 Comparative analysis on identification error and seismic force inversion



a. Absolute errors of stiffness identification under different noises



b. Absolute errors of damping identification under different noises

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.

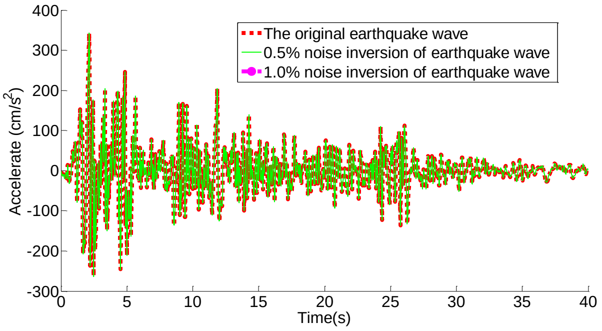


FIGURE 5 Comparison curves of seismic inversion results under noise interference

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

[1] Ren Yaohui.2008 The Seismic Behavior of Chimney.University of Architecture and Technology Master's degree paper

[2] *Deleted by CMNT Editor*

[3] Xiao Shengxie.2008 Bridge bearing capacity theory of evolution and its application technology. Science press

[4] Wu Liming, Wang Zijian. 2013 Physical Parameter Identification and Seismic Inversion Study of Frame Structure under Unknown Vertex Input.Science Technology and Engineering **13**(22) 6370-6375

[5] *Deleted by CMNT Editor*

[6] Kozin F 1985 Estimation of Parameters for System Driven by White Noise Exciton,Proc.of IUTAM Symp.on Random Vibrations and Reliability,Frankfurt Ioder.Gemany, Henning Klaus Ed. 163-173

[7] *Deleted by CMNT Editor*

[8] Wang Zijian 2013 Inverse Analysis and Protection Countermeasure Study of Bridge Pier Under Wave Excitation Response.Chongqing Jiaotong University, Ph.D.Thesis

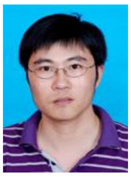
[9] Yu Shuqing, Liang Bingchen.2013 Wave Mechanics for Ocean Engineering. China Ocean Press

[10] Guo Jinxin 2014 Physical Parameter Identification and Load Inversion Analysis of Bridge Pier Structure under Strong Earthquake Action. Science Technology and Engineering **14**(8):260 -264

Authors

Liming Wu, 1981.12, Chongqing City, P.R. China

Current position, grades: the Lecturer of School of Liming Wu, Chongqing Technology and Business Institute,China.
University studies: received his B.E. in Civil Engineering from Shenyang University in China.
Scientific interest: His research interest fields include Civil Engineering, Geotechnical Engineering
Publications: more than 12 papers published in various journals.
Experience: He has teaching experience of 5 years, has completed Three scientific research projects.



Zijian Wang, 1979.11, Chongqing City, P.R. China

Current position, grades: the Lecturer of School of Zi-Jian Wang, Chongqing University of Science&Technology,China.
University studies: received his B.E. in Civil Engineering from Shenyang University in China. He received his M.E&D.E. In Civil Engineering from Chongqing Jiaotong University in China.
Scientific interest: His research interest fields include Civil Engineering,Numerical Simulation
Publications: more than 15 papers published in various journals.
Experience: He has teaching experience of 2 years, has completed Two scientific research projects.