

基于陈列柜边界条件的馆藏文物地震滑移响应试验

周 乾^{1,2}, 闫维明², 纪金豹²

(1. 故宫博物院, 北京 100009; 2. 北京工业大学 工程抗震与结构诊治北京市重点实验室, 北京 100124)

摘 要:为保护馆藏浮放文物,采用振动台试验方法研究了地震作用下基于不同陈列柜边界条件下的文物滑移响应。根据展柜原型制作了 1:1 比例模型,分别考虑陈列柜底部浮放及固定于振动台面,进行了振动台试验。通过白噪声激励获得了两种边界条件下陈列柜的基频;通过对模型分别输入不同类型及不同强度的地震波,研究了地震作用下陈列柜及文物的震害形式,对比分析了两种边界条件下典型节点位移、加速度响应及动力放大系数。结果表明:无论陈列柜处于固定还是浮放状态,其基频远大于地震波卓越频率,因此震害较轻;对浮放文物而言,当地震波强度较小时,不同条件下文物的滑移响应为陈列柜浮放>陈列柜固定条件;当地震波强度较大时,由于陈列柜与振动台面的摩擦减震作用,文物的滑移响应为陈列柜浮放<陈列柜固定条件。为减小文物的滑移响应,陈列柜宜以浮放形式为主,并保持适当的间距。

关键词: 陈列柜; 边界条件; 浮放文物; 地震滑移响应; 振动台试验

中图分类号: G266; P315.924

文献标志码: A

文章编号: 1000-0844(2013)02-0220-06

DOI: 10.3969/j.issn.1000-0844.2013.02.0220

Experiments on Slide Response of Museum Cultural Relics under Earthquakes Considering Various Showcase Boundary Conditions

ZHOU Qian^{1,2}, YAN Wei-ming², JI Jin-bao²

(1. Palace Museum, Beijing 100009, China; 2. Beijing Key Laboratory of Earthquake Engineering and Structural Retrofit, Beijing University of Technology, Beijing 100124, China)

Abstract: Many museum pieces are of cultural heritage and worthy of protection for their historical and artistic values. Because such relics are usually free-standing, they are easily damaged during earthquakes. For example, the 2008 Wenchuan earthquake in China led to substantial losses of property such that at least 216 museums were affected, and more than 3169 cultural relics were damaged. Slide motion is a typical seismic response mode of museum cultural relics; large slide sizes may cause relics to drop from their display stands and incur damage. Thus, it is important to study slide response of free-standing cultural relics under earthquake conditions and adopt aseismic measures for protection. In previous works, theoretical analyses were mainly used to study the slide responses of free-standing relics. Experimental studies were insufficient, and boundary conditions of showcases were seldom considered. To determine protection measures for movable cultural relics, slide responses of free-standing cultural museum relics under earthquake conditions are studied by considering various showcase boundary conditions. 1:1 scale models were created on the basis of actual of a museum showcase sizes. A glass cultural relic was placed

收稿日期: 2012-06-30

基金项目: 文化部科技创新项目(17-2009)

作者简介: 周 乾(1975-), 男(汉族), 湖南株洲人, 博士, 高级工程师, 主要从事文物建筑抗震加固与振动控制研究。

E-mail: zy_7225@yahoo.com.cn

通讯作者: 闫维明, 教授, 博士生导师, 主要从事建筑结构振动控制与工程振动研究。E-mail: Yanwm@bjut.edu.cn

in the showcase by free-standing mode. The static friction coefficient between the relic bottom and its base was determined to be $\mu = 0.15$ and the barycenter height values of the showcase and relic were calculated as 556 mm and 65 mm, respectively. To study seismic responses of the relic, acceleration sensors were set on the showcase bottom and relic top. In addition, a video measuring apparatus was used to capture displacement response values of the relic. Shaking table tests were conducted that considered two boundary conditions of the showcase bottom including fixed and free-standing status. Frequency distributions of the showcase under both boundary conditions were obtained by white noise excitation. Three different types of earthquake waves including those of El-Centro in 1940 and Taft and Artificial of II site classification were applied to the models in east-west direction with intensities of $PGA = 0.1g, 0.2g, 0.4g, \text{ and } 0.7g$; time duration of 30 s; and time space of 0.02 s. Aseismic parameters such as displacement, acceleration, and dynamic magnification coefficients for both relic and showcase under the various boundary conditions were compared. Results show that under both showcase boundary conditions, relic sliding was minimal under small-intensity earthquake conditions, while the sliding was obvious under those of high intensity. For the duration of the tests, the relic slid under both showcase boundary conditions, and the showcase slid only under free-standing showcase boundary conditions. When earthquake intensity increased to certain degree, slide motion of the relic under fixed showcase boundary condition increased to a more significant degree than that under free-standing showcase boundary conditions. Regardless of showcase status, the prominent frequency factors were far greater than those of the input earthquake waves; thus, the showcase was not damaged significantly. The slide response for the relic under the free-standing showcase boundary condition was more significant under low-intensity earthquakes than that under fixed conditions and was significantly less when earthquake intensity increased, obviously due to friction between the showcase and shaking table. Thus, free-standing museum showcases are helpful for mitigating the slide response of cultural relic contained in them, provided that the distance between each showcase is sufficient to guarantee sliding motion during strong earthquakes.

Key words: Showcase; Boundary condition; Free-standing cultural relics; Slide response in earthquake; Shaking table test

0 引言

博物馆文物属宝贵的历史文化遗产,保护意义重大。在通常情况下以浮放形式为主,因而在地震作用下很容易产生各种震害。如 2004 年 10 月日本新潟县 6.8 级地震造成许多馆藏文物破坏且难以修复^[1];2007 年 3 月在希腊 Kefalonia 地区发生的 5.9 级地震造成大量博物馆文物受损^[2];而 2008 年中国汶川地震中,仅四川省就有 216 家文物收藏单位的 3 169 件可移动文物受到不同程度破坏,造成了巨大的损失^[3-4]。馆藏文物的典型震害形式之一为滑移。在地震作用下文物滑移量过大时将导致从陈列台掉落,从而产生破坏。因此研究浮放文物在地震作用下的滑移响应具有重要意义,国内外很多学者也开展了相关研究^[5-10]。

对结构进行抗震性能评估,可采取理论或试验

方法^[11-13],其中振动台试验方法可通过设备对结构直接施加地震荷载,进而有效评估结构动力特性和抗震性能,因而是一种广受欢迎的评估方法。文献[14]采用振动台试验方法,探讨了不同陈列柜边界条件下(固定或浮放地面)文物的摇晃响应。地震作用下文物产生的滑移响应也与陈列柜不同的边界条件密切相关。为探讨陈列柜边界条件对文物滑移响应的影响,本文采取振动台试验为主的方法进行分析,结果将为馆藏文物抗震加固提供理论依据与技术参考。

1 试验概况

试验选取与文献[14]相同的陈列柜模型,尺寸见图 1(a)。文物(仿品)的尺寸为:45 mm×2 mm×150 mm(底部半径×壁厚×高度),材料为玻璃(图

1(b))。经计算,陈列柜的重心高度为 556 mm,文物的重心高度为 65 mm。模型中不同构件的具体布置方式为:文物浮放在陈列台座上,陈列台座固定在陈列柜上,陈列柜则根据试验情况考虑底部固定及浮放在振动台面上。

为研究陈列柜的地震响应情况,在陈列柜底部(节点 1)及顶部(节点 2)布置了加速度传感器;为研究文物的滑移响应情况,在文物上部(节点 3)布置了微型加速度传感器以测定文物的加速度响应,并采用探地雷达及视频测量仪捕捉该节点相对陈列台座的位移响应。测点的位置见图 1(a)所示。

试验在北京工业大学工程抗震与结构诊治北京市重点试验室进行。试验时首先对模型施加 $PGA=0.07\text{ g}$ 、 0.14 g 、 0.28 g 、 0.56 g 及 0.7 g ($1\text{ g}=9.8\text{ m}\cdot\text{s}^{-2}$) 的白噪声激励,研究陈列柜的振动频率;然后分别选取 3 种类型的地震波:EL-centro 波(1940 年)、Taft 波以及 II 类场地人工波作用于模型,输入强度分别为: $PGA=0.1\text{ g}$ 、 0.2 g 、 0.4 g 、 0.7 g ,作用方向为东西向,持时为 30 s,时间间隔为 0.02 s。基于振动台试验,分析选定节点的加速度与位移响应情况,研究文物及陈列柜的地震响应^[11]。

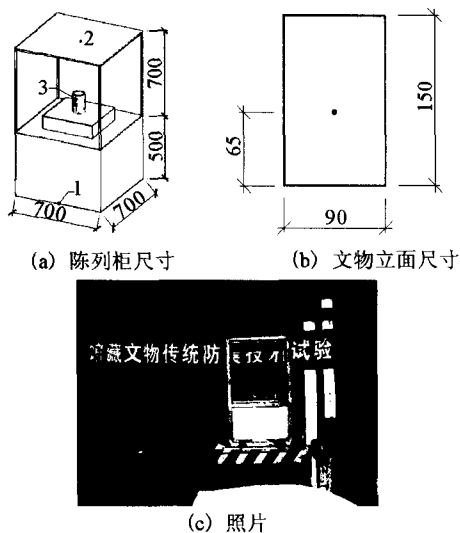


图 1 试验模型(单位:mm)

Fig. 1 Test model.

根据文献[9-10,15-16]提供资料,浮放文物产生滑移的条件为: $\mu < \alpha_{\max}$ 及 $\mu < B/H$;产生摇晃的条件为: $B/H < \mu$ 及 $B/H < \alpha_{\max}$ 。这里 μ 指文物与陈列台顶部之间的静摩擦系数,测得 $\mu=0.15$; α_{\max} 为水平地震力最大值与重力加速度比值,本分析中取值为 0.1、0.2、0.4 及 0.7; B 为文物底部半径,为 45

mm; H 为文物重心高度,为 65 mm。易知 $PGA > 0.1\text{ g}$ 时,文物将产生滑移为主的震害。下面将通过试验进行具体分析。

2 试验结果及分析

地震波作用下,不同陈列柜边界条件下文物的滑移响应表现为如下特点:(1)相同点: $PGA \leq 0.2\text{ g}$ 时文物无明显滑动,陈列柜几乎保持相对静止状态; $PGA > 0.2\text{ g}$ 时地震波强度增大,文物在陈列台面开始有明显滑移,且随着地震波增强,滑移量增大。此外,整个试验过程中,文物只产生滑移,不产生摇晃,且即使在地震波强度较大时,文物仍能保持稳定振动状态。(2)不同点:地震波强度较小时,陈列柜固定条件下,文物滑移响应没有陈列柜滑移条件下明显。地震波强度较大时,底部固定的陈列柜产生摇晃,造成上部文物滑移量明显增大;而陈列柜浮放条件下,陈列柜自身产生滑移,该运动可产生减震效果,使得文物滑移量减小。

2.1 陈列柜基频

通过对陈列柜分别施加 $PGA=0.07\text{ g}$ 、 0.14 g 、 0.28 g 、 0.56 g 及 0.7 g 的白噪声,获得两种形式陈列柜的基频范围在 $f=23.7\sim 34.6\text{ Hz}$ 之间,且基频随着输入地震波强度增大而降低。此外,由于该频段与 3 种地震波的基频 ($f=1.27\sim 2.27\text{ Hz}$) 相差甚远,因此输入地震波不会引起陈列柜的强烈振动^[14]。

2.2 位移响应

基于试验结果,获得不同工况条件下节点 3(即文物上部)的位移响应状况。限于篇幅,仅绘出 Taft 波作用下节点的位移响应曲线,见图 2 所示。其中 C1 表示陈列柜固定工况,即工况 1; C2 表示陈列柜浮放工况,即工况 2。

(1) $PGA=0.1\text{ g}$ 时,地震波强度较小,文物的滑移响应不明显。此时浮放陈列柜底部与振动台面之间的摩擦作用不明显。陈列柜滑移条件下文物的位移响应峰值要大于陈列柜底部固定条件。

(2) $PGA \geq 0.2\text{ g}$ 时,随着输入地震波强度的增加,文物滑移响应增强,且陈列柜浮放条件下文物的滑移响应峰值小于陈列柜固定条件。这主要因为地震波强度较大时,陈列柜底部固定时,陈列柜产生晃动;而陈列柜底部浮放时,陈列柜与振动台面产生相对滑移,这种滑移可产生摩擦减震作用,因而减小了文物的滑移响应。

(3) 无论上述输入地震波的强度如何,文物均

保持稳定的滑移运动状态,其响应曲线表现为以平衡位置为中心的稳定振动。

由上述分析可知,对于以滑移震害为主的文物而言,为减小其滑移量,陈列柜底部宜浮放为主。

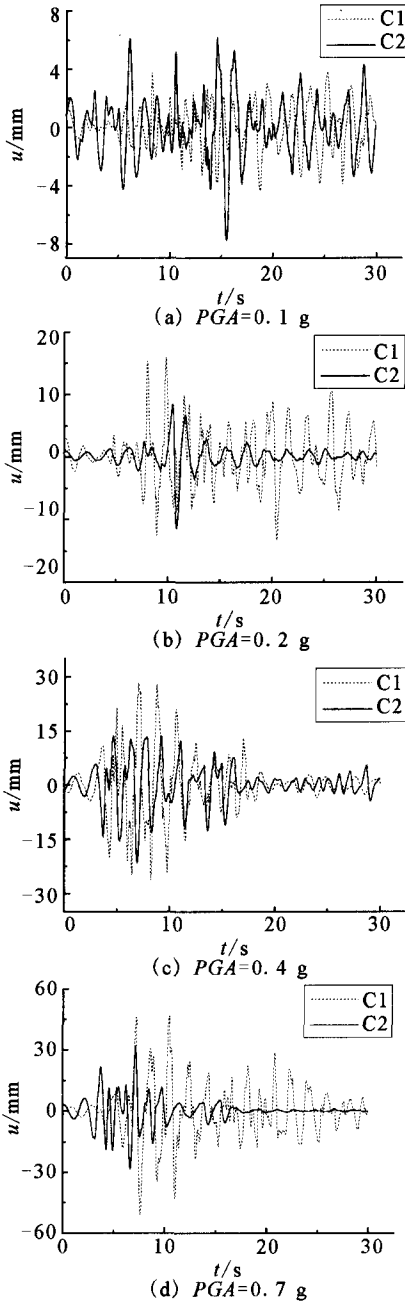


图 2 文物位移响应曲线(Taft 波)

Fig. 2 Displacement response curves of relic (Taft wave).

2.3 加速度响应

试验还获得不同工况条件下节点 1~3 的加速度响应状况。限于篇幅,仅绘出 Taft 波作用下节点 3(即文物上部)的加速度响应曲线,见图 3 所示。易知文物的加速度响应曲线表现的特点与位移响应曲线类似,即在地震波强度较小时,陈列柜浮放条件

下文物的加速度响应要比陈列柜固定条件明显;而随着地震波强度增加,其加速度响应特征相反。另一方面,文物加速度响应曲线也可反映出其稳定振动状态。

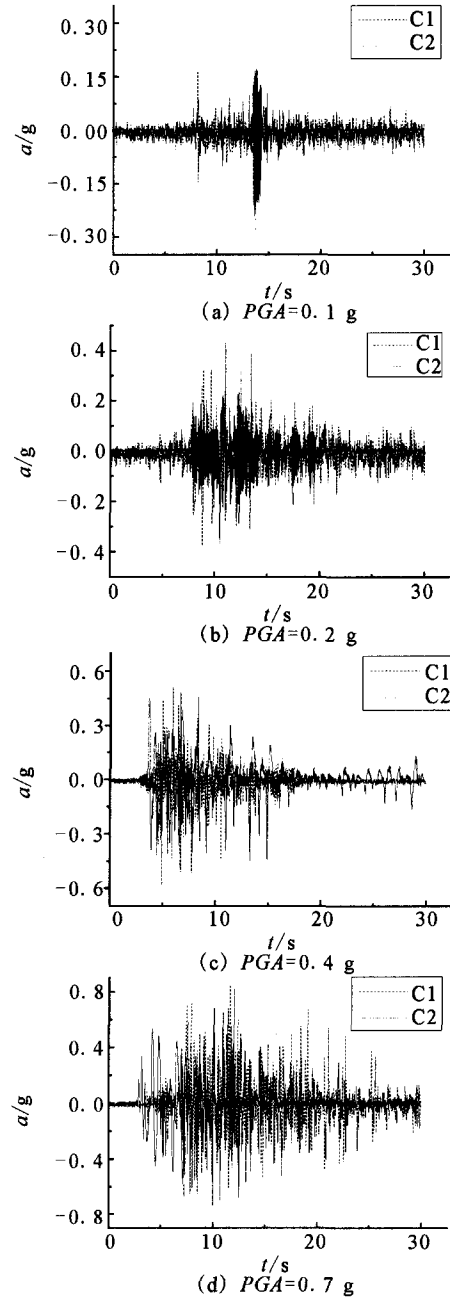


图 3 文物加速度响应曲线(Taft 波)

Fig. 3 Acceleration response curves of relic (Taft wave).

表 1~2 为文物在不同条件下的加速度峰值。易知对于 3 种输入地震波,文物的加速度响应峰值均表现为类似的规律,即 $PGA=0.1\text{ g}$ 时,陈列柜固定条件下文物的加速度峰值小于陈列柜浮放条件; $PGA\geq 0.2\text{ g}$ 时,陈列柜固定条件下文物的加速度响应峰值大于陈列柜浮放条件,且地震波强度越大

时表现越明显。由此可知,浮放文物产生滑移震害时,为减小其加速度响应,陈列柜宜以浮放为主。实际工程中,为保证陈列柜在强震作用下的滑移距离,还应保证陈列柜之间有适当间距。

表1 文物加速度响应峰值(工况1)

Table1 The response peaks of cultural relics acceleration (operating condition 1)

输入波	输入强度(PGA)			
	0.1 g	0.2 g	0.4 g	0.7 g
EL-centro	0.26	0.50	0.65	0.89
Taft	0.17	0.44	0.61	0.85
人工	0.25	0.52	0.69	0.93

表2 文物加速度响应峰值(工况2)

Table2 The response peaks of cultural relics acceleration (operating condition 2)

输入波	输入强度(PGA)			
	0.1 g	0.2 g	0.4 g	0.7 g
EL-centro	0.23	0.39	0.48	0.52
Taft	0.29	0.37	0.45	0.58
人工	0.32	0.44	0.50	0.57

2.4 动力放大系数

定义陈列柜动力放大系数 $\beta_1 = a_2/a_1$, 文物动力放大系数 $\beta_2 = a_3/a_1$ 。其中 a_1 为振动台面加速度峰值, a_2 为陈列柜顶部加速度峰值, a_3 为文物加速度峰值。基于试验相关数据, 绘制不同情况下 β_1 、 β_2 曲线见图4、5所示, 其中E代表EL-centro波, T代表taft波, A代表人工波。

易知, 在3种不同类型地震波作用下, β_1 、 β_2 值表现为基本相同的规律, 即: (1) 对于两种不同边界条件的陈列柜而言, 随着地震波强度增加, 陈列柜及文物的动力放大系数有减小的趋势, 反映了地震作用下它们的动力响应不很明显。(2) $PGA = 0.1 g$ 时, 陈列柜浮放边界条件下的 β_1 、 β_2 值略大于陈列柜固定条件; $PGA \geq 0.2 g$ 时则相反。这是因为地震波强度较小时, 浮放陈列柜底部与振动台面存在静摩擦力, 摩擦减震作用未能发挥; 而地震波强度增强时, 浮放陈列柜与振动台面之间产生摩擦滑移, 可产生减震效果, 减小陈列柜及其上文物的滑移响应, 且在地震波强度增强时表现明显 ($PGA = 0.7 g$ 条件下, β_1 、 $\beta_2 < 1$); 而底部固定陈列柜则在地震作用下产生摇晃, 文物及柜顶加速度响应始终大于振动台面 (β_1 、 $\beta_2 > 1$)。

3 结论

(1) 对陈列柜而言, 无论底部固定还是浮放, 地震作用下产生的动力响应不明显, 这与陈列柜的基

频远大于地震波的卓越频率密切相关。

(2) 对浮放文物而言, 地震波强度较小时, 不同条件下文物的滑移响应为: 陈列柜浮放 > 陈列柜固定条件; 地震波强度较大时, 文物的滑移响应为: 陈列柜浮放 < 陈列柜固定条件。

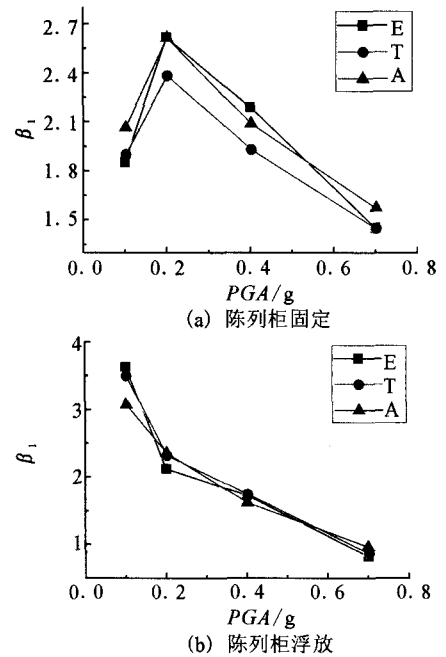


图4 陈列柜动力放大系数(β_1)曲线
Fig.4 The dynamic magnification coefficient curves(β_1) of showcase.

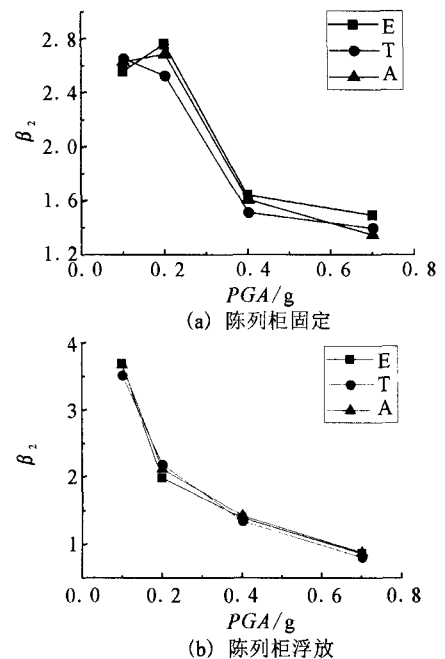


图5 文物动力放大系数(β_2)曲线
Fig.5 The dynamic magnification coefficient curves(β_2) of relic.

(3) 在实际工程中,为减小浮放文物滑移震害,高宽比较小的陈列柜底部宜浮放,且陈列柜之间宜设置适当间距,以保证地震作用下陈列柜的滑移距离。

[参考文献]

- [1] Anne C, Debra F L, Mairead F. Sample Preparation and Testing Methods for the Evaluation of Microcrystalline Waxes for the Seismic Protection of Art Objects[J]. Journal of Testing and Evaluation, 2008, 36(1): 24-33.
- [2] Mustafa E, Eser D, Nevra E, et al. Earthquake risk mitigation in Istanbul museums[J]. Nat Hazards, 2010, 53:97-108.
- [3] 周乾,闫维明.汶川地震可移动文物震害研究[J].文物保护与考古科学,2010,22(3):36-43.
ZHOU Qian, YAN Wei-ming. Analysis of Damage to Free-standing Cultural Relics Caused by the Wenchuan Earthquake[J]. Sciences of Conservation and Archaeology, 2010, 22(3): 36-43.
- [4] 韦荃,陈显丹.5·12汶川大地震对四川可移动文物的损坏与启示[J].四川文物,2008,(4):10-13.
WEI Quan, CHEN Xian-dan. Experiences from Damages of Movable Cultural Relics by Wenchuan Earthquake on May 12th, 2008[J]. Sichuan Cultural Relics, 2008, (4):10-13.
- [5] 黄永林,杨伟林,章熙海.地震作用下浮放物体的运动研究[J].地震学刊,1994,(3):1-5.
HUANG Yong-lin, YANG Wei-lin, ZHANG Xi-hai. Study on Motion of Free-standing Body Excited by Earthquake[J]. Journal of Seismology, 1994, (3):1-5.
- [6] 王云剑,陈汝斌.浮放设备抗震技术标准[A]//王亚勇,李爱群.现代地震工程进展[G].南京:东南大学出版社,2002:932-936.
WANG Yun-jian, CHEN Ru-bin. Aseismic Technology Standard for Free-standing Equipments[A] // WANG Ya-yong, LI Ai-qun: Development of Modern Seismic Engineering [G]. Nanjing: Southeast University Press, 2002:932-936.
- [7] 郭恩栋,吴伟,胡煜文,等.浮放设备地震滑移反应数值模拟研究[J].地震工程与工程振动,2007,27(6):124-129.
GUO En-dong, WU Wei, HU Yu-wen, et al. Numerical Study on Seismic Response of Free-standing Equipment. Journal of Earthquake Engineering and Engineering Vibration[J]. 2007, 27(6):124-129.
- [8] Harry W S, Nicholas P J. Base Excitation of Rigid Bodies. I: Formulation[J]. Journal of Engineering Mechanics, 1991, 117(10):2286-2306.
- [9] Harry W S, Nicholas P J. Base Excitation of Rigid Bodies. II: Periodic Slide-rock Response[J]. Journal of Engineering Mechanics, 1991, 117(10):2307-2328.
- [10] Harry W S. Criteria for Initiation of Slide, Rock, and Slide-rock Rigid Body Modes[J]. Journal of Engineering Mechanics, 1996, 122(7):690-693.
- [11] 施卫星,刘凯雁,王立志.网架减震球型钢支座减震性能振动台试验研究[J].西北地震学报,2009,31(4):344-348.
SHI Wei-xing, LIU Kai-yan, WANG Li-zhi. Shaking Table Test Study on Damping Performance of Steel Ball-bearing for Grid Structure [J]. Northwestern Seismological Journal, 2009, 31(4): 344-348.
- [12] 石玉成,李舒,刘琨.地震作用下骆驼城土遗址的安全性评价[J].西北地震学报,2011,33(3):255-260.
SHI Yu-cheng, LI Shu, LIU Kun. Safety Evaluation of the Camel Town Soil Relics under Earthquake Action[J]. Northwestern Seismological Journal, 2011, 33(3):255-260.
- [13] 吴小峰,孙启国,狄杰建,等.抗震分析反应谱法和时程分析法数值仿真比较[J].西北地震学报,2011,33(3):275-278.
WU Xiao-feng, SUN Qi-guo, DI Jie-jian, et al. A Numerical Simulation Comparison between Response Spectrum Analysis and Time History Analysis[J]. Northwestern Seismological Journal, 2011, 33(3):275-278.
- [14] 周乾,闫维明,纪金豹.基于陈列柜边界条件的馆藏文物摇晃响应试验[J].土木工程与管理学报,2011,28(3):401-406.
ZHOU Qian, YAN Wei-ming, JI Jin-bao. Experiments on Oscillation Response of Museum Cultural Relics under Earthquakes Considering Different Showcase Boundary Conditions [J]. Journal of Civil Engineering and Management, 2011, 28(3): 401-406.
- [15] Zhou Q, Yan W M. Sliding Response of Free-standing Cultural Relics under Earthquakes by Simulation[J]. Advanced Materials Research, 2011, 163-167:2142-2146.
- [16] Zhou Q, Yan W M. Simulation of Oscillation Response of Free-standing Object under Earthquakes[J]. Applied Mechanics and Materials, 2012, 105-107:417-422.