Dynamic response of ancient masonry structure due to seismic loads

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Abstract

This research aimed to evaluate the dynamic response of a masonry structure, the Chediluang (Pagoda), located in Chiangmai province in the northern part of Thailand. The analyzed pagoda was partly destroyed by the past earthquake. Dynamic response of the structure was computed using the finite element method (FEM). The input parameters such as Poisson's ratio, compressive and tensile strength, shear modulus and shear wave velocity are selected from the report and in-situ testing. Strong ground motions of magnitude of 4, 6 and 7) were generated from two most nearby active faults. Analytical results revealed that some parts of the structure might subject to tensile stress greater than the allowable values, when ground motion from earthquakes of magnitude 6 were used as the input motion.

1. Introduction

Earthquake has been recognized as one of the most damaging natural hazards. Earthquakes typically strike without warning and after few seconds leave damage in their strikes. Many old masonry structures belong to cultural heritage. Chediluang (1411 A.D.) is located in Chiangmai province, Thailand. This is one of the most important structures in Chiangmai since the past. The main structure systems consist mostly of brick and stone masonry. Its square base is 60x60 meters and initial height being believed to be about 70 meters before it was partly destroyed by an earthquake in 1545 A.D. The present structure is approximately 40 meters in height as shown in Figure 1.

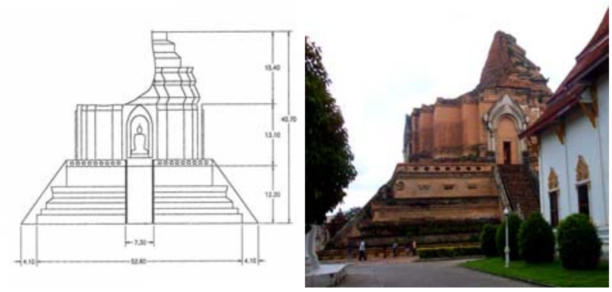

Figure 1 The present Chediluang structure is approximately 40 meters height.

The dynamic behavior of ancient structures is too complicated to be interpreted by simple model. Furthermore it is very difficult to conduct any reliable quantitative strength test. In addition, deterioration of structural resistance with time is another hindrance in study of such ancient structure. The most appropriate method to investigate seismic effects on ancient structure would be the measurement of real structure response during earthquake or simulating seismic excitation. According to many reasons as mentioned above, therefore, the seismic analysis was carried out using the FEM program in order to provide a board view of past history and guidelines for future restoration.

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2. Literature Review

The seismic response of the structure is often studied by two-dimensional plane strain finite element model. There are numerous studies concerning the behavior of masonry structure under seismic load. Mawinthorn [1] investigated the behavior of a masonry structure during earthquakes by using commercial FEM program. The basic assumption was that the structure is a thin shell structure which varying depth from base to top of the structure. He found that under a medium earthquake, the structure was not able to resist the seismic loads. Juhasova [2] analyzed the seismic response of the masonry structure and described experiences with modeling of boundary conditions during the test of large heavy model on shaking table. The main purpose of the research was how to increase dynamic resistance capacity of old masonry buildings under the medium and strong seismic effects. Jaishi [3] investigated the dynamic properties of multi-tiered temples by using finite element method. Those temples are test by ambient vibration methods under wind-induced excitation to obtain real dynamic properties. Seismic capacity evaluation was performed using seismic coefficient method. The results show that the failure modes of masonry temple are associated with tensile and compressive stresses. A simplified procedure for assessing seismic capacity of masonry arches was proposed by De Luca [4].

Although abundant literature related to the seismic response of old masonry structures can be found, the results have never been applied or calibrated to the actual seismically failed structures. The remains of the Chediluang (Figure 1), which was destroyed by an earthquake event in the past, is therefore a very important case to calibrate the applicability of the current state of seismic analysis.

3. Fault investigation

The largest known historical earthquake in Thailand record within at least 1300 A.D. has probably not exceeded Richter magnitude 6.5 [5]. According to recent studies, there are two active faults; Maerim and Maetha faults, located closest to Chiangmai city (Figure 2). Maerim fault, located 23 km. away from the city, is lying northwest to southeast striking. Maetha fault, located 38 km from Chiangmai city, is one of very long faults observed in Thailand.

Figure 2 Location of Chediluang and historical earthquake epicenters generated by Maerim and Maetha faults (USGS).

4. Modeling assumption and material properties

The materials adopted in the analysis are assumed to be homogeneous and linear elastic. It should be noted that the geometrical non-linearity was considered. The properties of the bricks are taken from previous work by Mawinthorn [1]. The compressive strength of masonry was derived base on ASTM C67. The tensile strength of masonry was conducted based on ASTM C1006-84. Their test results are summarized in Table 1.

Failure mode	Ultimate strength (MPa)
Compressive	2.71
Tensile	0.15

Table 1 Ultimate stresses on masonry.

Sub soils are stratified in layers of different thickness resting on rock with decreasing damping with depth. It is assumed that the rigid bedrock is available at a depth of 17.83 m. The shear wave velocity of the subsoil was measured using the down hole seismic test as summarized in Table 2 and Figure 3.

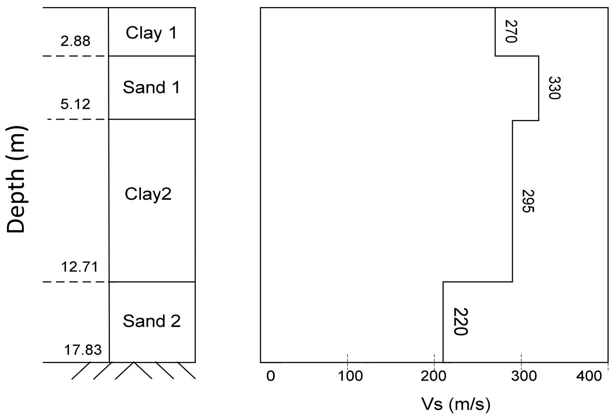

Figure 3 Shear wave velocities from down-hole seismic test at site

Layer	Thickness (m)	Unit weight (kg/m^3)	Poisson's ratio	Max shear Modulus (MPa)	Shear modulus (MPa)	Damping ratio	V_s (m/s)	V_p (m/s)
1	2.88	2200	0.45	160	80	0.04	270	890
2	2.24	2100	0.40	229	153	0.07	330	820
3	7.59	2000	0.35	174	87	0.04	295	610
4	5.12	1900	0.30	91	46	0.07	220	410

Table 2 Properties of soil type condition

5. Determination of ground motion

Waveform of strong ground motion is one of the most important parameters for conducting dynamic analysis. The method for simulating ground motion is to combine parametric or functional descriptions of the ground motion's amplitude spectrum with a random phase spectrum modified such that the motion is distributed over a duration related to the earthquake magnitude and to the distance from the source. It is widely used to predict ground motions for the regions of the world in which recording of motion from potentially damaging earthquakes are not available. One of the essential characteristics of the method is that it distills what is known about various factors affecting ground motion (source, path and site) into simple function forms Boore [7]. The parameters for generating small ground motion are based on current knowledge from the studies of various geologists [8]. Finally, those parameters are summarized in Table 3.

The synthetic waveforms of Maerim fault M6 and M7 at bed rock of the structure are shown in Figure 4 and Figure 5, whereas the synthetic waveforms of Maetha fault M6 and M7 on Richter scale are shown in Figure 6 and Figure 7.

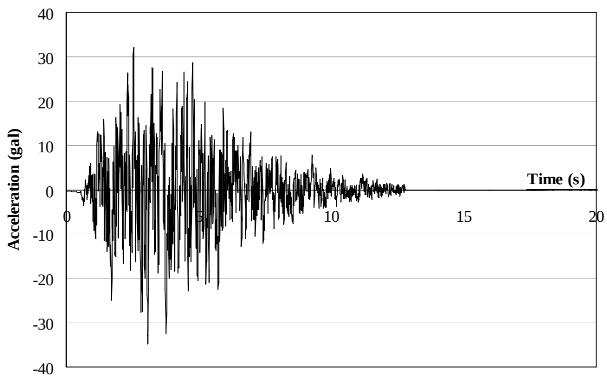

Figure 4 Maerim, M6, synthetic wave form generated by stochastic method.

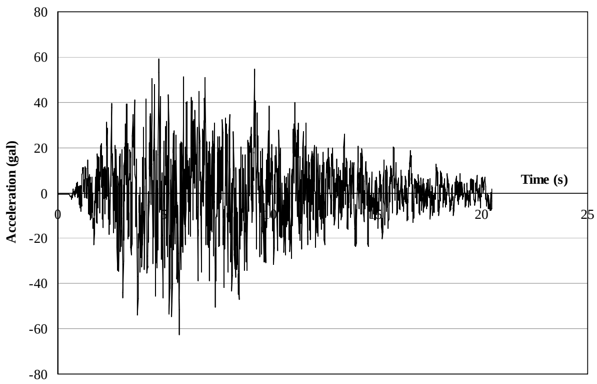

Figure 5 Maerim, M7, synthetic wave form generated by stochastic method.

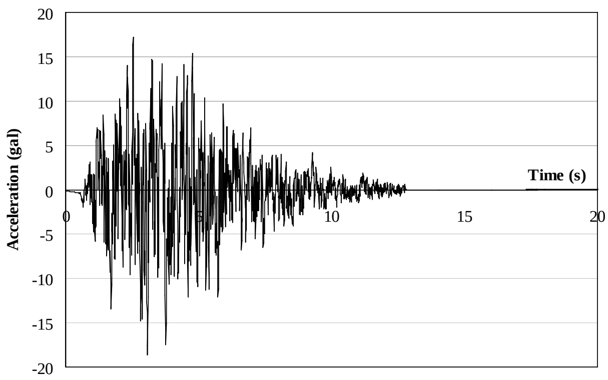

Figure 6 Maetha, M6, synthetic wave form generated by stochastic method.

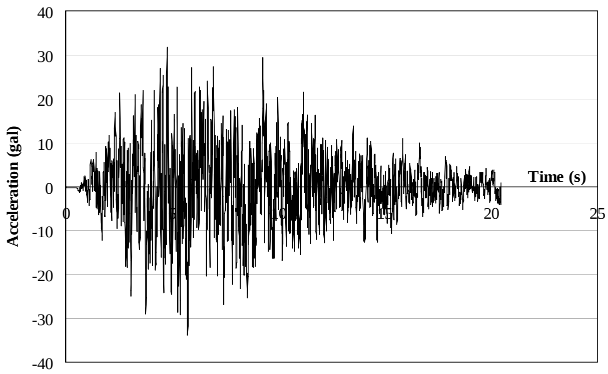

Figure 7 Maetha, M7, synthetic wave form generated by stochastic method.

Data	Maerim M6	Maerim M7	Maetha M6	Maetha M7
Time step (sec)	0.01	0.01	0.01	0.01
Radiation coefficient	0.63	0.63	0.63	0.63
Influence of ground surface	2.0	2.0	2.0	2.0
Cut off frequency in high frequency region (Hz)	10.5	10.5	10.5	10.5
Rock density (g/cm^3)	2.7	2.7	2.7	2.7
Shear wave velocity (m/s)	3500	3500	3500	3500
Stress drop (bar)	50	50	50	50
Focal distance (km)	23	23	38	38
Seismic moment of small earthquake, M_o (dyne-cm)	$7.21\text{x}10^{24}$	$1.05\text{x}10^{26}$	$7.21\text{x}10^{24}$	$1.05\text{x}10^{26}$
Moment Magnitude of small earthquake, M_w	6.0	7.0	6.0	7.0

Table 3 Summary of parameters used for ground motion generation

6. Result and Discussion

Examples of the computed acceleration time history under the action of various assumed ground motions from base, mid-height and top of pagoda are shown in Figure 8-10. It can be clearly seen that acceleration has been largely amplified (compared to the equivalent input ground motion shown in Figure 7). The relevant peak acceleration from these three points along the height of the pagoda is summarized in Table 4.

From the distribution of compressive stresses in the pagoda body, there is no part of the structure that compressive stress being larger than the allowable compression of the brick. Nevertheless, the tensile stress distribution provides a different view. Figure 11 (a) and (c) shows locations where the tensile stresses are greater than the allowable tension of the brick. The ground motion from Maerim may be able to cause more severe damages to the pagoda than the earthquake from Maetha fault. The potentially location where tensile stress exceeding its allowable values can be fairly well mapped to the present geometry of the pagoda (Figure 1)

The normalized peak acceleration at any pagoda level (against the base peak acceleration) is shown in Figure 12 and Figure 13, for earthquakes from Maerim and Maetha faults, respectively. The acceleration increases rapidly when its height exceeding one-third of the overall height of the structure approximately 4 – 5 times.

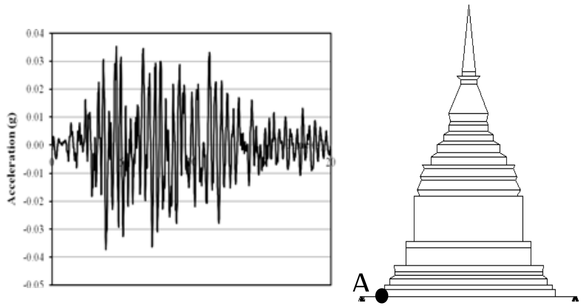

Figure 8 Maetha, M7, Acceleration-Time history at base of the structure at point A.

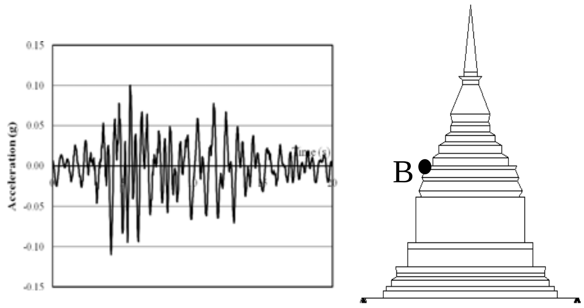

Figure 9 Maetha, M7, Acceleration-Time history at mid-height of the structure at point B.

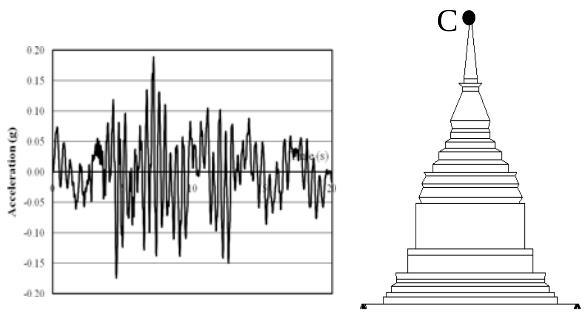

Figure 10 Maetha, M7, Acceleration-Time history at top of the structure at point C.

Maximum Acceleration (g)	Maerim M6	Maerim M7	Maetha M6	Maetha M7
Acceleration (g), point A At time (s)	0.044 3.85	0.066 4.60	0.027 3.85	0.037 3.85
Acceleration (g), Point B At time (s)	0.119 4.17	0.185 4.17	0.073 5.53	0.109 4.17
Acceleration (g), Point C At time (s)	0.209 4.54	0.345 7.21	0.122 5.54	0.189 7.21

Table 4 Peak accelerations from time history analyses under earthquake ground motions along longitudinal direction of Maerim and Maetha faults.

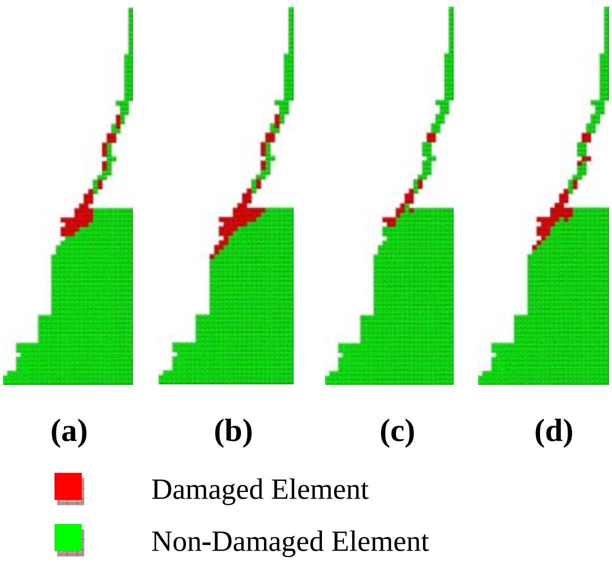

Figure 11 Damage comparison (a) Maerim M6 (b) Maerim M7 (c) Maetha M6 (d) Maetha M7

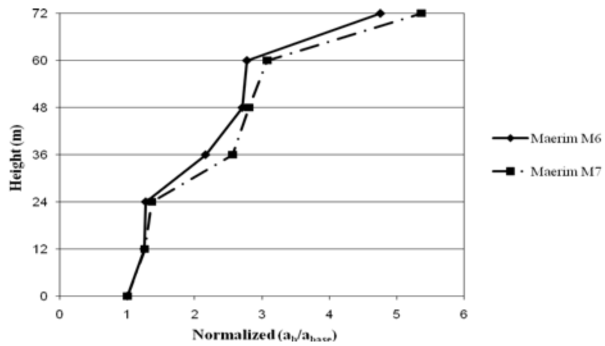

Figure 12 Normalize peak acceleration (a_h/a_{base}) of Maerim fault for M6.0 and M7.0.

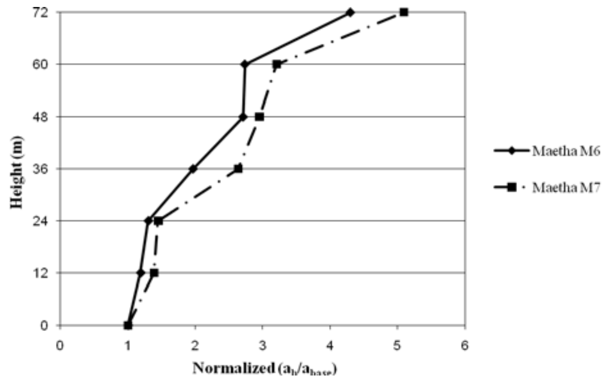

Figure13 Normalize peak acceleration (a_h/a_{base}) of Maetha fault for M6.0 and M7.0.

7. Conclusion

In this paper, the dynamic response of an ancient masonry structure in Chiangmai was studied. A simplified procedure using finite element method is adopted. It aim was to provide a history view of possible damages of the structure by past earthquakes from nearby known active faults. It was found that at some specific location of the pagoda, the tensile stress induced by the generated earthquakes may exceed its allowable value. Location where allowable tension being exceeded was fairly well correlated to the present geometry of the pagoda.

Acknowledgement

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