SEISMIC VULNERABILITY OF HISTORICAL BRICK MASONRY TOWERS

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ABSTRACT :

Response of historical masonry towers to earthquake loading is somewhat different to that of other old buildings, mainly due to their material properties and unique geometry. In this paper, first the effects of these parameters on the dynamic properties of brick towers are explored. The influence of underlying soil on the dynamic response of the towers is also investigated. Then, considering two further variables, including earthquake magnitude and distance of the tower from the epicenter, the seismic vulnerability of historical masonry towers is evaluated with respect to the five aforementioned variables. It is concluded that the effects of underlying soil on the degree of vulnerability of the tower is profound. It is also shown that the distance of the tower from the epicenter and the geometric aspect ratio of the tower are also important parameters when evaluating the vulnerability of such structures to earthquake loading.

KEYWORDS: Masonry, towers, historical, seismic vulnerability, attenuation

1. INTRODUCTION

During earthquakes, the response of masonry towers to ground shaking appears to be somewhat different to other surrounding structures. This stems from their different dynamic properties caused primarily by their unique geometry. The response of these structures depends not only on the intensity of ground shaking but, to a larger extent, also on the frequency content of the earthquake wave and the type of underlying soil. Observations made in a number of earthquakes point to a different response for tall masonry towers compared to other structures. In one earthquake, it is noted that most masonry buildings have been destroyed or damaged in the earthquake, whereas tall towers have survived and in other cases, the opposite is observed. Attenuation of ground shaking, both in terms of ground acceleration and the dominant ground frequency occurs away from the epicenter. The acceleration attenuation invariably reduces the vulnerability of buildings to damage, whereas frequency attenuation may cause higher damage away from the epicenter due to dynamic magnification. On the other hand, the slenderness of these towers has made them flexible structures with low natural frequencies, usually outside the band of strong frequencies of near earthquakes, increasing the chances of their survival. Therefore, it is important that the dynamic properties of the tower and the frequency content of ground shaking should be considered together when evaluating the vulnerability of such buildings to earthquakes.

In a review of historical sources, Maheri (2004) investigated around one hundred major earthquakes occurring during the last millennia in Iran for which some accounts of damage to masonry towers were available. The earthquakes range in magnitude from 5.3 to 7.8 on the Richter scale, producing estimated building location intensities from VIII to X^+ on the MM scale. A comprehensive account of the relevant historical sources is given by Ambraseys and Melville (1982) and others (Maheri 1990, Razani and Lee 1973, Nouri 1996). He categorised the masonry towers into two groups of squat and slender. The earthquake performance of the squat towers was found to have been exceptionally good. A large number of these buildings have survived centuries of earthquake destruction with virtually no or very little damage. They have most of the main criteria for an earthquake-resistant building including: complete symmetry and simplicity of plan, very small openings enabling shear wall resistance in all directions and the use of good quality brick or stone and mortar for construction. In all the historic sources reviewed, there was no direct reference to any towers of this type being destroyed by an earthquake. There were, however, many references to the contrary. The 55m tall, 10th century, Gunbad-i Kavus monument (Fig. 1) has survived a number of destructive earthquakes. Two of these events were; the earthquake of 1436 AD with an estimated magnitude M = 5.3 and earthquake of 1470 with a magnitude M = 6.5. In Mazandaran province, a number of similar, but smaller, burial chambers of the early Seljuq period have survived repeated major shocks in their vicinity, the last shock being the Kusut earthquake of 1935 (M = 6.3). The Lajin tomb tower built around 1022 AD is situated only 10 km from the epicentre of this earthquake. It survived the shock with absolutely no damage. The famous *red dome* in Maragheh, is another structure of this type, which has been subjected to numerous earthquakes without sustaining any damage.

The second group of towers investigated by Maheri (2004), comprises tall, slender brick masonry towers used mainly as watch towers or guide posts and tall chimneys of old brick kilns. Similar to minarets, the earthquake response of these structures depends on the frequency content of the travelling earthquake waves. Their slenderness renders them flexible structures with low natural frequencies, usually outside the strong frequency range of most earthquakes. Therefore, their chances of surviving an earthquake are high. Many examples of their sole survival in major earthquakes exist today. The tower of Jam, built between 1163-1203 AD, the leaning tower of Kirat, built in the late 11th century and the 30m high tower of Khusrowgird, dated to the early 12th century are but three examples.

Using the historical evidence, Maheri (2004) determined 'collapse' and 'survival' intensity regions for the squat and slender towers as shown in Fig. 2 and Fig. 3, respectively. In these figures, the black circles signify damage and hollow circles signify the survival of the towers in their respective earthquake intensity. He then developed a specific intensity scale for masonry towers.

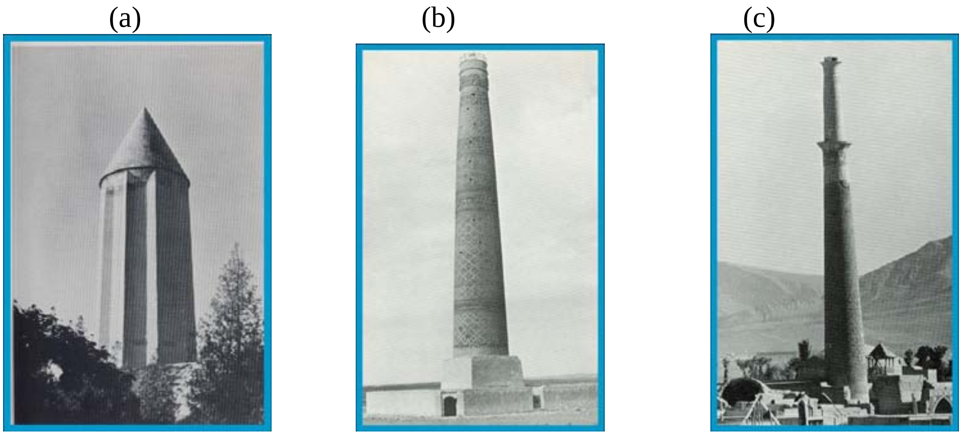

Fig. 1. Typical Iranian historic towers (a) Gunbad-i Kavus, (b) Khosrowgerd tower and (c) Monar-Ali tower

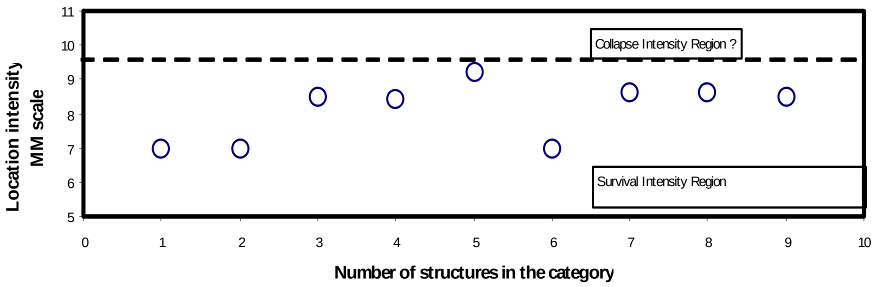

Fig. 2. Damage and survival intensity zones for squat towers (Maheri 2004)

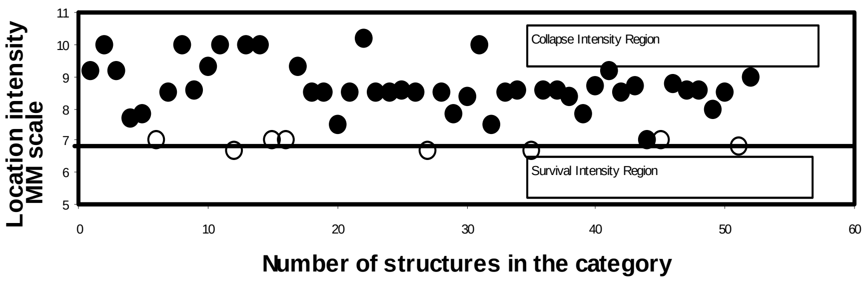

Fig. 3. Damage and survival intensity zones for slender towers (Maheri 2004)

2. THE EFFECTS OF GEOMETRY, MATERIAL PROPERTIES AND SOIL CONDITION

Considering that the vulnerability of towers to distant earthquakes depends on the dynamic properties, particularly the fundamental frequency of the tower, here the parameters affecting this property is investigated. Of the parameters influencing the fundamental frequency, the geometry of the tower in the form of height/diameter ratio and diameter/thickness ratio can be named. These ratios affect the stiffness and mass of a tower, hence its natural frequency. Material properties of the tower including the density and elastic modulus also affect the fundamental frequency, though to a lesser extent than the geometry of the tower. Another important parameter in this regard, is the properties of the underlying soil. In a series of parametric analyses the influence of the above four parameters on the dynamic response of masonry towers is investigated. For determining the dynamic properties of the towers, ANSYS computer program was used. The tower's body was modelled using shell elements and the underlying soil was modelled using equivalent spring elements.

To verify the accuracy of the FE models, an initial analysis was carried out on St. Bernardino tower. This tower was previously analysed by Niaw and Chopra (1973) and Maheri et-al (1986). The result for the fundamental frequency of this tower carried out here was identical to that obtained by Niwa and Chopra (1973). For higher frequencies the results were also very close.

To investigate the effects of geometry on the frequencies of the towers, three different geometries were considered; The 25m high Khorramabad brick tower having an average outer diameter, D = 5.60m and a thickness of t = 0.7m and two other towers being 10.0m and 35.0m high , both being 5.0m in outer diameter and 1.0m thick. For material properties, the brickwork density was assumed to have four different values of 1500, 1700, 1900 and 2100 kg/cm^2 and four different values of 1.0E9, 2.0E9, 4.0E9 and 5.0E9 kg/cm^2 were considered for elastic modulus of brickwork. The underlying soil was also assumed to be type III according to the Iranian seismic code (Standard 2800).

The dynamic analyses of the three towers with the specified variable parameter were carried out and the main natural frequencies and their associated mode shapes were determined. The first three modes of vibration of the shorter (squat) tower and the taller (slender) tower are shown in figures 4 and 5, respectively. The periods of vibration of the first two modes of vibration (T1 and T2) of the squat and slender towers having different variable parameters are presented in Table 1. These results are also plotted in Figs. 6 to 8. In figure 6, the influence of density of brickwork on fundamental period of the towers can be seen. The variation in the period with respect to density is linear. It is also noted that the variation of density has little influence on the period of vibration of the squat tower, but as the tower becomes more slender, the influence of E on the period increases. The reason for this lies with the fact that the squat towers have high stiffness and the period is dominated by stiffness of the system rather than the mass. By increasing height of the tower and the consequent reduction in its stiffness, the mass of the system dominates the value of its fundamental period.

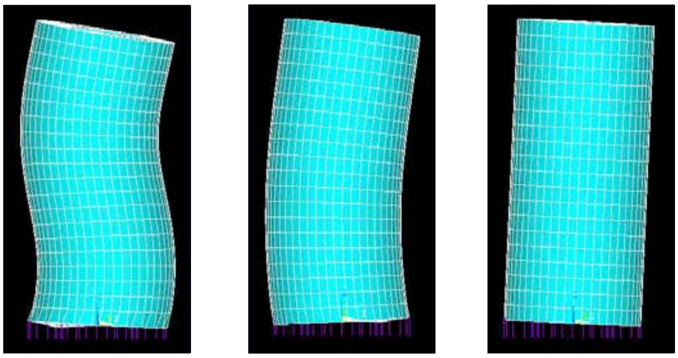

Fig. 4. The main modes of vibration of squat tower

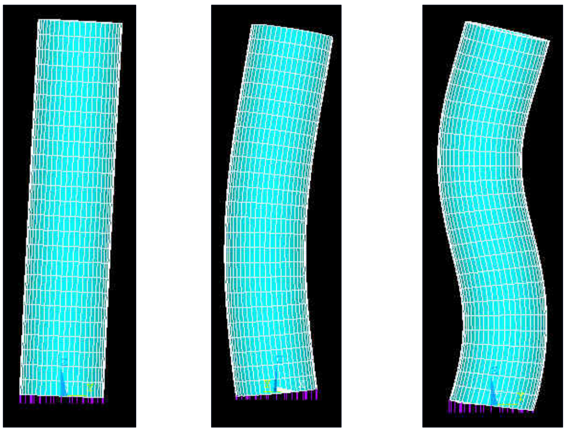

Fig. 5. The main modes of vibration of slender tower

Figure 7 shows the variation of the fundamental period with respect to elastic modulus of brickwork, E. As expected, in squat towers, the elastic modulus has little effect on the period as the geometry dominates its stiffness. However, by increasing the height of tower, the effect of geometry on the period is reduced, and consequently the effects of E is somewhat increased.

The effects of underlying soil on the period of vibration are shown in Fig. 8. In comparison to the other variables, the effects of soil type on the fundamental period are very high. This variation is somewhat less for stiffer soils and more profound for the more flexible towers.

Table 1. The periods of vibration of the towers (sec.)

Density (kg/m^3)	E (N/m^2)	Soil Type	Squat Tower		Slender Tower	
			T1	T2	T1	T2
1500	2.0E9	III	0.35	0.035	1. 26	0.128
1700	2.0E9	III	0.38	0.040	1.35	0.137
1900	2.0E9	III	0.40	0.040	1.42	0.144
2100	2.0E9	III	0.42	0.040	1.50	0.152
1700	1.0E9	III	0.47	0.070	1.55	0.210
1700	4.0E9	III	0.40	0.030	1.29	0.109
1700	5.0E9	III	0.39	0.020	1.27	0.098
1700	2.0E9	I	0.15	0.029	0.69	0.124
1700	2.0E9	II	0.20	0.029	0.81	0/129
1700	2.0E9	IV	1.35	0.030	4.35	0.140

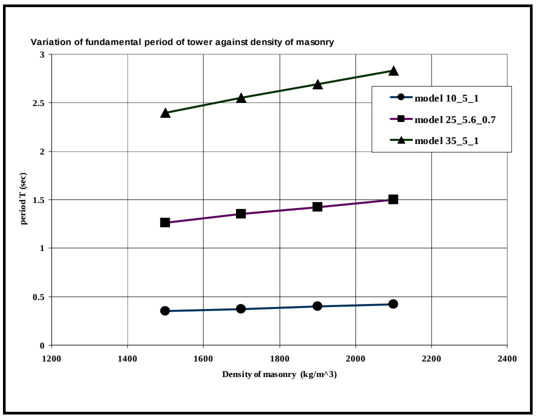

Fig. 6. The effects of brickwork density on the period of vibration of towers

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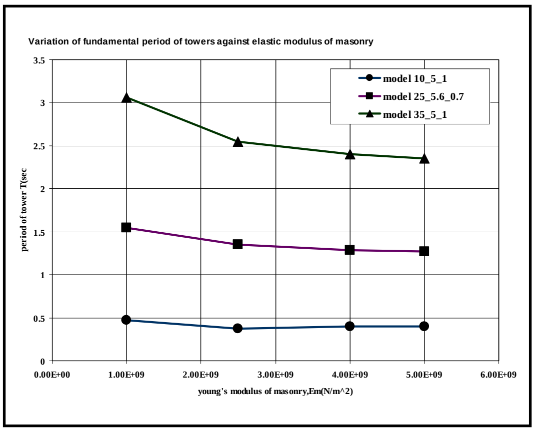

Fig. 7. The effects of elastic modulus of brickwork on the period of vibration of towers

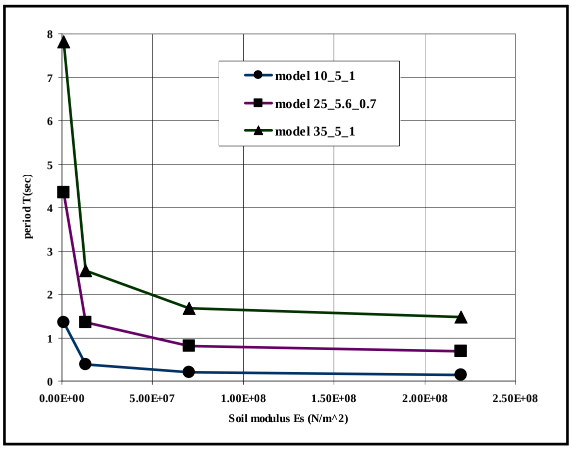

Fig. 8. The effects of underlying soil on the period of vibration of towers

3. VULNERABILITY ACCORDING TO MAGNITUDE AND DISTANCE FROM EPICENTER

The main ground motion parameters affecting the seismic response of a structure include; the ground acceleration and frequency content of the motion. The influence of the first parameter stems from the nature of the earthquake loading which is basically an inertia load, dependent on the acceleration. The second parameter affects the seismic response when the fundamental frequency of the tower falls within the main frequency range of the earthquake and dynamic magnification occurs. The level of ground acceleration depends primarily on the magnitude and focal depth. A number of investigators have developed empirical relations between the maximum ground acceleration and the earthquake magnitude. Of these, the relation presented by Ambraseys (1982) is more appropriate for the location under study. On the other hand, as the earthquake waves move away from the epicentre, attenuation, both in ground acceleration and frequency of the waves occur, Of these two, frequency attenuation can have a significant effect on the seismic response of the towers with lower natural frequencies situated at further distances from the epicentre. Therefore, both the magnitude of the earthquake and the distance of the tower from the epicentre are important parameters when studying the seismic vulnerability of these structures. To determine the dominant period of ground vibration at different distances away from a particular earthquake many different attenuation relations exist. Here, the attenuation relation presented by Zare (1994) for central Iranian plateau is considered.

To evaluate the degree of vulnerability of the masonry towers according to their distance from the epicentre and for earthquakes having different magnitudes, the fundamental period of vibration of the tower was used in the attenuation formulae to calculate the critical distance from the earthquake. In this way the distance at which the highest dynamic magnification occurs for the tower was assumed to correspond to the distance at which that tower is the most vulnerable to ground shaking. The results thus obtained for the squat tower having reference properties and resting on four different soil type presented in the Iranian seismic code (2005) are presented in Table 2. The results given in this Table indicate some interesting points. It can be noted that when such a tower is situated on soft soil, its vulnerability to stronger earthquakes is less than that of medium size earthquakes. This can be explained when we consider that the period of ground vibration on such a soil is much more than the fundamental period of vibration of the tower. This tower is therefore most vulnerable on soft soil and when it is between 50km to 60km away from the epicentre of a medium size earthquake of magnitude between M=5.5 and M=6.0. On the other hand, if the tower is situated on harder soil (types II and III), its most vulnerable location during strong earthquakes is nearer to the epicentre (less than 70km) and during a medium size earthquakes is further away (over 100km away from the epicentre). However, if the tower is located on weak soil (type IV), it would only be vulnerable to strong earthquakes at long distances away from the epicentre.

The vulnerability of the slender towers according to their distance away from the epicentre is somewhat different to that of the squat towers. Table 3 shows the vulnerability level of this tower when situated on different soils and at different distances away from the epicentre. For this tower the maximum vulnerability is when situated on harder soils (types I, II and III) and at long distances away from the epicentre (Over 200km).

Table 2. The most vulnerable distance of squat tower from the epicentre (km)

Soil Type	Period of Tower	Magnitude (M)						
		8.0	7.5	7.0	6.5	6.0	5.5	<5.5
I	0.15	-	-	-	-	50	60	-
II	0.20	-	<40	55	70	100	130	-
III	0.38	60	70	90	125	200	300	-
IV	1.35	200	230	-	-	-	-	-

Table 3. The most vulnerable distance of slender tower from the epicentre (km)

Soil Type	Period of Tower	Magnitude (M)						
		8.0	7.5	7.0	6.5	6.0	5.5	**<5.5**
I	0.15	265	-	-	-	-	-	-
II	0.20	310	-	-	-	-	-	-
III	0.38	205	235	-	-	-	-	-
IV	1.35	-	-	-	-	-	-	-

4. CONCLUSIONS

The results of the dynamic and vulnerability studies of the historic masonry towers lead us to draw the following conclusions.

1. The effect of material density on the fundamental period of vibration is linear. This effect for squat towers is limited but for more slender towers can be considerable.

2. The effect of elastic modulus of masonry on the period of vibration of the tower is limited.

3. The effects of properties of the underlying soil on the period of vibration of the towers are considerable. This effect for harder soils is comparatively less.

4. Squat towers when situated on medium soils of types II and III are highly vulnerable to high magnitude earthquakes at short distances away from the epicentre. These towers when situated on soft soils (type IV), have limited vulnerability to distant strong earthquakes. They also are less vulnerable to medium-size earthquakes at close distances to epicentre, when situated on hard soil (Type I).

5. Slender towers are generally less vulnerable to high magnitude distant earthquakes when situated on soil types II, III and IV. These towers, when located on hard soil (type I) can withstand high magnitude earthquakes.

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