Characteristics of the 2007 Kameyama Earthquake with some emphases on unusually high strong ground motions and the collapse of Kameyama Castle wall

Ömer AYDAN*,1, Naohiko TOKASHIKI*2 and Kenrou SUGIURA*3

Abstract

The Kameyama earthquake with a moment magnitude of 5.0 occurred at 12:19 on JST on April 15, 2007. The earthquake took place on a previously known active fault segment. The strong ground motions were quite high in the epicentral area with high frequency components although its moment magnitude was only 5.0. The northern masonry wall of Kameyama Castle, built in 1590, collapsed. This article first covers both scientific and engineering aspects of the earthquake. Some emphases were given to the unusually high strong ground motions and the collapse of the Kameyama Castle wall and its back analysis.

1. INTRODUCTION

The Kameyama earthquake occurred at 12:19 on JST on April 15, 2007 and it had a magnitude (Mj) of 5.3 on the magnitude scale of Japan Meteorological Agency. The earthquake injured 12 people and caused some structural damage.

The strong ground motions were quite high in the epicentral area with high frequency components although its moment magnitude was only 5.0. The earthquake fault was associated with Mukumoto sub-segment of the northern segment of Nunobiki-sanchi-toen fault zone. This fault dips beneath Suzuki Mountain range. Since the earthquake was small and hypocenter was 16km deep, no surface ruptures were observed in Geino town, which is the closest settlement to the earthquake epicenter.

The earthquake caused some damage to some old wooden houses with heavy roofs. The ceiling panels of a drive-in building were fallen and injured the customers. The northern masonry wall of Kameyama Castle, built in 1590, collapsed. The embankments of rivers and some bridges of roadways were damaged. The earthquake induced some small-scale slope failures in the vicinity of the mountainous terrain.

The region also has some abandoned lignite mines and underground quarries for abrasion sand (migaki suna), which were exploited using room and pillar mining method. The authors investigated the earthquake-affected area and covered many parts of the area of concern (Figure 1). This paper covers both scientific and engineering aspects of the earthquake. Some emphases were given to the unusually high strong ground motions and the investigation results of the Kameyama Castle wall collapse.

2. GEOLOGY AND TECTONICS

The geology of the earthquake epicenter area is shown in Figure 2. The geology broadly consists of Pre-Miocene formations, Miocene formations, Pliocene Tokai Group, terrace deposits and alluvium (i.e. Yoshikawa and Yoshida, 1989). Pre-Miocene formations constitute the basement rock of the region and they are either metamorphic rocks and dioritic granite or granite. Miocene rocks are soft sedimentary rocks of mudstone, sandstone, siltstone and conglomerate and it also contains lignite seams. Tokai group generally consists lacustrine and fluvial deposits composed of gravel, sand
and mud with volcanic ash layers and it includes turbiditic lignite seams. The group is about 1200m thick and it is divided into the Saigydani, Kusuhara, Kameyama and Sakuramura Formations in ascending order. Tokai Group is widely distributed in the Kameyama area.

The tectonics of the region is well studied and many active faults are identified through paleo-seismological trenches (Mie Prefecture, 2007). The active faults are named as Yoro fault, Kuwana fault, Yokkaichi fault, Suzuki-toen fault, Nunobiki-sanchi-toen fault, Ise Bay faults (Figure 3). Median Tectonic Line (MTL), which is a dextral thrust tectonic structure, runs almost in E-W direction in the south of the epicentral area. The fault activated during the earthquake is associated with Nunobiki-sanchi-toen fault (Mie Active Fault Studies Committee, 1999). This fault is divided into northern segment (L = 27km) and southern segment (19km). The northern segment is also divided into three sub-segments. The epicentral estimations and post-seismicity implies that the Mukumoto sub-segment is activated during this earthquake (Figure 4). Although the seismic reflection studies imply that the fault dips to the west with an inclination ranging between 45-50°, some of trenches yielded also east-dipping ruptures. These structures are probably due to the decollement of the fault front near ground surface.
Characteristics of the 2007 Kameyama Earthquake with some emphases on unusually high strong ground motions and the collapse of Kameyama Castle wall.

Figure 2 Geology of the earthquake area (from Yoshikawa and Yoshida, 1989)
Figure 3  Faults of Mie prefecture and its close vicinity (modified from Mie Prefecture)
3. SEISMICITY AND CHARACTERISTICS OF THE EARTHQUAKE

3.1 Past Seismicity

The past seismological records indicate that the region experiences some large events from time to time. Most of the events are either inter-plate or intra-plate type. Figure 5 shows epicenters of seismic events \((M > 3)\) for the last 30 years while Figure 6 shows the same data together with damaging earthquakes \((M > 6)\) in the last 150 years. The seismicity shown in Figures 5 and 6 is aligned in certain directions, which generally correspond to known tectonic structures. The bottom part of Figure 5 shows projections of the hypocenter of earthquakes on an E-W cross-section. It is seems that the subducting Pacific plate may extend beneath Ise Bay and the subduction front of the Pacific plate may be inferred from Figures 5 and 6. Another important feature is that the hypocenters at the western side of Kii Peninsula are aligned along a plane dipping eastward. No large seismic activity in the region is noted in the last 30 years.

3.2 Characteristics of the Earthquake

The seismic parameters of the earthquake and its focal plane solutions estimated by different seismological institutes in Japan and worldwide are listed in Table 1 and illustrated in Figure 7. If the west-dipping fault is chosen as the causative fault, the fundamental mode of faulting was thrust-type with a slight sinistral or dextral component depending upon the institute. The focal plane solutions were provided by JMA and Hi-Net and F-Net systems of NIED. These institutes estimated that the fault dipping SW would be the causative fault from the computed mechanisms and the dip of the causative fault should be ranging between 42–45°.

3.3 Fore–Post Seismicity and Shock Distributions

Following the earlier reports of the main shock, it was found that there was a foreshock with a magnitude of
Figure 5  Seismicity of the region between 1973–2007 bounded by latitudes N34–38 and longitudes E134–143 (data from USGS–NEIC)
Figure 6  Past seismicity together with epicenters of damaging earthquakes (M>6) in the last 150 years.

Table 1  Parameters of the earthquake estimated by different institutes

<table>
<thead>
<tr>
<th>Institute</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth (km)</th>
<th>Magnitude</th>
<th>Strike</th>
<th>Dip</th>
<th>Rake Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>JMA</td>
<td>37.79</td>
<td>136.407</td>
<td>16</td>
<td>Mj=5.3</td>
<td>NP1 145°</td>
<td>43°</td>
<td>90°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NP2 325</td>
<td></td>
<td></td>
</tr>
<tr>
<td>USGS</td>
<td>37.537</td>
<td>136.438</td>
<td>16</td>
<td>Mw=5.0</td>
<td>NP1</td>
<td>47°</td>
<td>90°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NP2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hi-NET</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(NIED)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F-NET</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(NIED)</td>
<td>11</td>
<td></td>
<td></td>
<td>Mw=5.0</td>
<td>NP1 148°</td>
<td>45°</td>
<td>77°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NP2 347°</td>
<td>46°</td>
<td>103°</td>
</tr>
</tbody>
</table>
3.2 about 2 minutes before the main shock. The mechanisms of this foreshock obtained by JMA and Hi-NET were almost the same as those for the main-shock.

Since the epicenter data of aftershocks determined by Japan Meteorological Agency (JMA) are only available on INTERNET, the data released by the JMA is used to infer the possible dimensions of the activated fault plane. Figure 8 shows the epicenter distributions together with cross-sectional and longitudinal distributions of aftershocks in selected directions. The distribution of aftershocks on April 15 indicates that the main fault should be about 4-5km long and 5-6km wide as seen in Figure 8. In addition, it is expected that it would not cause any surface rupture, as the rupture area is relatively deep. Furthermore, the after-shock activity implies that the inclination of the fault would be quite similar to that estimated from focal plane solutions (Figure 8). Nevertheless, the same aftershock activity implies that earthquake also activated a conjugate fault zone to the main fault.
4. STRONG GROUND MOTIONS

The strong motion networks of Japan Meteorological Agency and K-NET and KIK-NET of NIED recorded very high ground accelerations in the epicentral area although the moment magnitude (Mw) of this earthquake was only 5.0. The maximum ground acceleration was observed at Geino strong ground motion station of KIK-NET, which was 3 km away from epicenter, and it was about 850 gal at ground surface while the maximum acceleration was 338 gal at base (rock), implying an amplification factor of 2.3–2.5, which is close to the theoretical expected value. Figure 9 shows the acceleration records at several locations around the epicenter. As noted from the acceleration records, they are strikingly different from each other. These records clearly indicate that there is a strong directivity effect associated with rupturing process as noted from Figure 9. The contours of maximum ground acceleration are plotted in Figure 10. The observed results indicate that the amplification of accelerations on soft ground may be several times that on the hard ground. The damage observed in the epicentral area clearly confirm this conclusion. Figure 11 are comparisons of attenuation of maximum ground acceleration and velocity with empirical relations proposed by Aydan (2007). In-spite of the small magnitude of this earthquake, the maximum ground acceleration and velocity exceed those estimated from empirical equations. This topic probably deserves further studies.

Figure 12 shows the ground response spectra for Kameyama station of K-NET and Geino station of KIK-NET. The response spectra for Kameyama station implies that the ground above the basement rock has a natural period of 0.122 seconds while it has dominant peaks at 0.27s and 0.72s for Geino station. Figure 13 show the normalized acceleration response spectra for Geino strong motion station (base and ground surface) and Kameyama records with a damping ratio of 5%. Basicaly the response spectra of all stations are similar while their absolute values are different. The peak acceleration spectra values imply that the structures having small natural periods might be affected by this
Figure 9  Acceleration records in the vicinity of the earthquake epicenter
Figure 10  Contours of maximum ground acceleration (Amax)

Figure 11  Attenuation of maximum ground acceleration (Amax) and velocity (Vmax)
Figure 12  Ground response spectra for Kameyama and Geino strong motion stations
Figure 13 Normalized acceleration response spectra for EW, NS and UD components of acceleration records at Geino and Kameyama strong motion stations.
earthquake. Nevertheless, the acceleration response spectra exceeds the design levels even though the earthquake has a small magnitude. Furthermore, the normalized response spectra for the base and surface records of Geino station for all components are shown. Although the acceleration response of the ground surface is generally affected by the existing of soft layers above the basement rock, its effect is not so pronounced for this earthquake. The reason may be the close proximity of the earthquake fault and the overall response depends upon the rupture process rather the characteristics of the ground above the basement rock.

5. STRUCTURAL AND GEOTECHNICAL DAMAGE

5.1 Structural Damage

Mainly old wooden houses were damaged. The mode of damage was quite similar to those observed in previous earthquakes. The damage mechanism fundamentally involved hinging of wooden columns at the base and also at the connections between 1st floor and 2nd floor as a result of large horizontal earthquake forces. Many wooden houses suffered from cracking in the walls. The number of damages was highest in Kameyama city (109 households) while it was only 1 household in Geino town, which is the nearest settlement to the epicenter. 7 households were suffered some damage in Suzuka City, which is situated over relatively soft ground.

RC buildings in the epicentral region are few and they are used as schools, public offices and a few as residential buildings. The number of stories is mostly 3 to 5. Furthermore, the infill walls of the RC buildings are reinforced concrete shear-walls. Some of public reinforced concrete buildings were retrofitted with steel frame bracing. Almost all RC buildings performed well during the earthquake. However, Mie prefecture reported some
light damage in the form of cracking in walls or floors. While there were 5 incidents of light damage to Public RC buildings Kameyama City, it was 7 incidents in the case of public RC buildings in Suzuka City. This may be due to poor ground conditions.

Large halls for various social events at hotels, conference centers, indoor sport centers and restaurants generally have suspended ceiling panels. The fall of ceiling panels injured two people at the second floor of a drive-in restaurant nearby Seki I.C. The similar incidents also occurred in indoor sports halls and swimming pools in Suzuka City. Since the earthquake occurred on Sunday and the schools were closed, there was luckily no incident resulting in injury (Aydan et al. 2007).

There was no damage to temples and their shrines (torii) made of granitic columns and beams in this earthquake. However, the masonry lantern monuments were dilapidated at their base or dislocated (Figure 14).

![Dislocated and rotated cemetery stones](image1)

**Figure 15** Dislocated and rotated cemetery stones

<table>
<thead>
<tr>
<th>Stone Number</th>
<th>Height (mm)</th>
<th>Width (mm)</th>
<th>Breadth (mm)</th>
<th>Rotation Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>400</td>
<td>200</td>
<td>130</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>1600</td>
<td>340</td>
<td>340</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>640</td>
<td>200</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2** Dimensions and rotation angle of cemetery stones

![Damaged embankment along Suzuka River in Kameyama City](image2)

**Figure 16** Damaged embankment along Suzuka River in Kameyama City
The height of these lanterns was 210cm with a square base with a side length of 85cm. For example, the main compound of Kameyama Temple was intact although slight traces of dislocations were observed. The temple is about 18km away from the hypocenter.

Cemetery stones with good geometric shapes are commonly used in Japan. These well-shaped stones were used to infer the ground motions caused by the earthquakes in the past and they are still utilized to infer the ground motions where strong motion instrumentation is scarce or non-existent. Figure 15 shows some pictures of cemetery stone dislocated and rotated in Kameyama City. The distance from the hypocenter to this cemetery in the picture was about 19km. The dimensions of the stones are given in Table 2. All stones were rotated in a clock-wise sense. The rotation angle ranges between 20 and 25°. Most of stones were made of diorite or granite and a few of them were made of tuff. Furthermore, their base is saw-cut without any polishing.

Land transportation in Mie Prefecture is done through state and prefectural roadways, Meihan National Highway and Ise-wan Expressway (Figure 1). Meihan National Highway and Ise-wan Expressway run next to the epicenter area. The visual inspection of the expressway and viaducts indicated there was no damage to the expressway and viaducts inspite of high ground accelerations.

The earthquake induced some geotechnical damage such as embankment failures and surficial slope failures. The embankment damage was observed along Suzuka River at 10 locations (Figure 16). The damaged embankments were generally more than 4m. The embankment inclination is generally 45°. When one side of the embankment is non-stepped while the other side

![Diagram of Kameyama Castle](image)

**Figure 17** Plan and cross sectional view of Kameyama Castle (not to scale)
Characteristics of the 2007 Kameyama Earthquake with some emphases on unusually high strong ground motions and the collapse of Kameyama Castle wall.

(a) View of Castle from south

(b) SW corner

(c) Collapsed NE Corner

(d) Eastward view of NE corner

(e) Southward view of NE corner

Figure 18 Views of intact and collapsed section of Kameyama Castle
is stepped, the cracking and settlement occurred on the non-stepped side. There was also some cracking of pavements on embankments with a relatively small height due to full saturation conditions next to rice paddies. No liquefaction incident induced by this earthquake was observed or reported.

5.2 Kameyama Castle Wall Collapse

Kameyama castle was built in 1590 on a 10m high hill. The inclination of south, east and west walls is about 50° while the inclination of north wall is much steeper and it is about 70–75°. The earthquake caused the collapse of NW corner of the 5m high northern wall, where a masonry stone stair is located. The collapsed section was 2m wide and this section was actually damaged by a typhoon in 1972 and it was repaired (Aydân et al. 2007). The stones used at NW corner were typically 30 cm wide, 30cm high and 55cm long and rock itself is either andesite or diorite. Figure 17 shows plan and cross-section illustrations of the castle while Figure 18 shows some views of the intact and collapsed sections of the castle.

6. THE STABILITY ANALYSES OF MASONRY WALLS

6.1 Mechanical Models for Stability Analyses

The authors has been investigating the stability of masonry walls under both static and dynamic conditions in relation to the stability of masonry structures in Ryukyu Islands using experimental, analytical and numerical techniques (Aydân et al. 2001, 2002; Tokashiki et al. 2006). Several mechanical models developed during this collaborative study and they are validated through shaking table experiments on masonry walls with back-filling. There are four different modes for walls, namely, 1) Stable; 2) Sliding; 3) Toppling; 4) Toppling and sliding. If the seismic coefficient method is employed, the initiation of sliding failure can be obtained in the following forms (Figure 19):

a) Transition from stable to sliding mode

\[ q_s = \frac{a}{g} = \frac{(\sin \theta + \cos \theta \tan \phi) - k}{\frac{h}{\tan \phi} + \frac{h}{\tan \phi} - \frac{1}{2} \left( \cos \theta - \sin \theta \tan \phi \right)} \]  

b) Transition from stable to toppling mode

\[ q_t = \frac{a}{g} = \frac{(h \sin \theta + t \cos \theta) - k}{\frac{h}{\tan \phi} + \frac{h}{\tan \phi} - \frac{1}{2} \left( \cos \theta - t \sin \theta \right)} \]

Where:

- \( a \): maximum horizontal acceleration
- \( g \): gravitational acceleration
- \( \theta \): wall inclination & base inclination
- \( \phi_{w} \): friction angle between wall and backfill soil
- \( \gamma_{c} \): unit weight of backfill soil
- \( \gamma_{w} \): unit weight of wall
- \( h \): length (height) of wall
- \( t \): width of wall
- \( K \): lateral force coefficient resulting from backfill

c) Transition from stable to combined sliding and toppling failure mode requires that both equations (1) and (2) must be satisfied.

It is also possible to model the rigid body translation and rotation of walls with the consideration of inertia term. In this type formulation the earthquake force assumed to be proportional to the mass of retaining masonry wall.

6.2 Back Analyses and Discussions

The collapsed north wall of the castle is about 5m high with an inclination of about 70° and block sizes range between 50–60cm. The block size of older parts of the castle walls is more than 100cm and their inclination is about 50°. Furthermore, the other walls of the castle are more than 10m high. The friction angle of backfill soil and friction between the wall and backfill soil are not measured. Nevertheless, they would be greater than 30° in view of past experiences. Figures 20 and 21 show the effects of base angle of the wall and thickness/height ratio on the limiting acceleration to induce either sliding or toppling mode of failure of walls. As understood from both figures, the instability of the wall can be induced under very low seismic intensities for north wall of the castle. Assuming higher values will increase the limits of ground acceleration for sliding and toppling modes. However, these simple analyses are sufficient to explain why the northern wall of the castle collapsed.

In the next two computations, the NS component of the acceleration records taken at Kameyama strong motion station of K-NET was used and the responses of the castle wall during shaking for sliding and toppling failure modes were computed. The computed displacement responses shown in Figure 22 correspond to those of the wall mass center. The sliding mode indicates that the wall would be displaced about 160cm while the toppling mode implies rotation of about 10° (45/250). These results imply that the earthquake shaking was sufficient to induce both sliding and toppling modes of failure. Nevertheless, the effect of sliding mode is more
Characteristics of the 2007 Kameyama Earthquake with some emphases on unusually high strong ground motions and the collapse of Kameyama Castle wall

(a) Toppling mode

(b) Sliding mode

(c) Mechanical model

*Figure 19* Failure modes and a mechanical model for masonry wall under ground shaking
Figure 20  The effect of basal inclination on the limiting seismic coefficient to induce the instability of the wall

Figure 21  The effect of lateral force coefficient on the limiting seismic coefficient to induce the instability of the wall
Figure 22  Computed displacement and velocity responses of mass center for sliding and toppling modes of failure
dominant. Since the displacement exceeds the wall width, it may be inferred that the failure of the castle wall was a natural consequence of earthquake shaking.

7. CONCLUSIONS

2007 Mie-ken Kameyama earthquake caused limited damage in the epicentral area in spite of high ground motions induced by this relatively small magnitude earthquake. The main characteristics of this earthquake can be summarized as follows:

1) The faulting was of thrust type and it was an intra-plate earthquake. The earthquake was associated with Mukumoto sub-segment of Nunobiki-san-chi-toen fault zone. Since the hypocenter depth was 16 km and the size of rupture area was small, no surface ground ruptures were observed. Since un-ruptured parts still remain, it has a high potential for future earthquakes in this region.

2) High ground accelerations with pronounced directivity effects did occur although the magnitude of earthquake was relatively small. Due to close proximity of the epicenter, the shaking effects become more pronounced. Available attenuation relations could not estimate the attenuation of ground motions such as maximum ground acceleration and maximum ground velocity in the very close proximity of the earthquake faults.

3) Ground liquefaction was not observed in the epicentral region.

4) Some embankment failures took place along Suzuka River and its branches.

5) Building damage was generally limited to roof tiles and some cracking in the walls and floors. The fall of suspended roof ceiling panels in large halls indicated the potential danger to the safety of occupants, which may be a great problem in future large earthquakes.

6) High ground shaking induced by this earthquake did not cause any structural damage to RC buildings, bridges, roads, highways, railways and expressways.

7) A part of dry masonry walls of Kameyama Castle collapsed. This collapsed castle wall was studied to clarify the causes of the collapse of masonry castle walls, which may be useful for the stability assessment of similar structures in Japan and world-wide during earthquakes.

8) The simple limiting equilibrium analyses of the masonry wall for sliding and toppling modes of failure with the consideration of seismic coefficient concept implied that the instability of the wall could be induced under very low seismic intensities for north wall of the castle. However, assuming higher values will increase the limits of ground acceleration for sliding and toppling modes.

9) The dynamic computations based on the rigid body translation or rotation of the wall models with the use of the NS component of the acceleration records taken at Kameyama strong motion station of K-NET yielded that the earthquake shaking was sufficient to induce both sliding and toppling modes of failure. Nevertheless, the effect of sliding mode should be more dominant than the toppling mode. Since the displacement exceeded the wall width, it was inferred that the failure of the castle wall was a natural consequence of earthquake shaking.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. Y. Suzumura of Tobishima Corporation (Nagoya Branch) for joining the authors during the damage investigation of 2007 Mie-ken Kameyama Earthquake on the behalf of Earthquake Disaster Investigation Committee of JSCE and Prof. Dr. M. Hamada of JSCE President and Prof. Dr. K. Kawashima, Chairman of Earthquake Engineering Committee of JSCE for encouragements to investigate this earthquake despite the magnitude was relatively small in Japan.

REFERENCES


(in Japanese)

要 旨
2007年三重県亀山地震の特徴
と
その地震動の特性および亀山城の城壁崩壊について

アイダ・オメル
東海大学海洋学部海洋建設工学科
渡嘉敷 直彦
琉球大学工学部環境建設工学科
杉浦 乾郎
飛島建設株式会社 名古屋支店

亀山地震は日本時間で2007年4月15日（平成19年4月15日）12時19分に発生し、気象庁によるそのマグニチュードは5.3であった。地震は既存に知られている断層にそって発生し、震源地塊には高い周波数特性を有し、強い地震動が観測された。固有周期が短い家屋などへの影響が大きかったが、大半の土木構造物・建築物に被害は発生しなかった。盛土の崩壊や沈下などが鈴鹿川にそって起きた。また、レストランやスイミングプールの天井部分が落下し、それらの耐震性に問題があることが明らかになった。1590年に建てられた亀山城の石積石壁が崩壊した。本論文では2007年亀山地震の特性を説明し、その強震記録についての分析および解析結果について述べている。また、K-NETの亀山観測点で計測された強震記録を用いて、亀山城の北壁の崩壊要因とその移動量を解析的に求めることができた。