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Microtremor Measurements and Building Damage during the Changureh-Avaj, Iran Earthquake of June 2002

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ABSTRACT

A great many buildings were severely damaged or collapsed during the earthquake that struck the northwestern part of Iran on June 22, 2002. We investigated the damage done to buildings and carried out microtremor measurements. Adobe buildings were completely destroyed or suffered heavy damage. Un-reinforced masonry (URM) structures commonly were damaged because of poor construction of their bearing walls. Absence of a lateral resistance system was one cause of failure of semi-steel structures. To examine the ground surface and structural seismic response characteristics in the stricken area, microtremor measurements were conducted on the ground surface in several locations in Abdareh Village, in which almost 100% of the adobe dwellings were completely destroyed, and on an adobe house in Tablashkin Village. A Fourier analysis, based on the H/V spectral ratio, was made to explore the relationship between the strong ground motion of the earthquake and the damage done which may have been affected by local site conditions. Building damage could be explained by the good compatibility between ground microtremor findings and the dynamic characteristics of adobe buildings which collapsed in many places but survived in part of Abdareh.

1. OUTLINE OF THE EARTHQUAKE AND ITS DAMAGE

The Changureh-Avaj earthquake of 22 June, 2002, Mw = 6.3 (07:28 local time, 02:58 GMT) was strongly felt in most parts of northwest Iran. The epicenter, about 250 km west of Tehran, was in a roughly east-west oriented valley just west of Abegarm Village (Fig. 1). The greatest damage occurred in the villages of Abdareh and Changureh. The official report lists 230 fatalities, 1,466 injured, and more than 50,000 people left homeless. The earthquake affected 4 cities and 50 villages (most of which were partially damaged) in four provinces. The macroseismic intensity of VIII+ (EMS-98 scale) was assigned to Abdareh and Changureh in the epicentral area. Based on the length of the surface fissures and estimated focal depth of 7 km, the magnitude Mw = 6.3 was

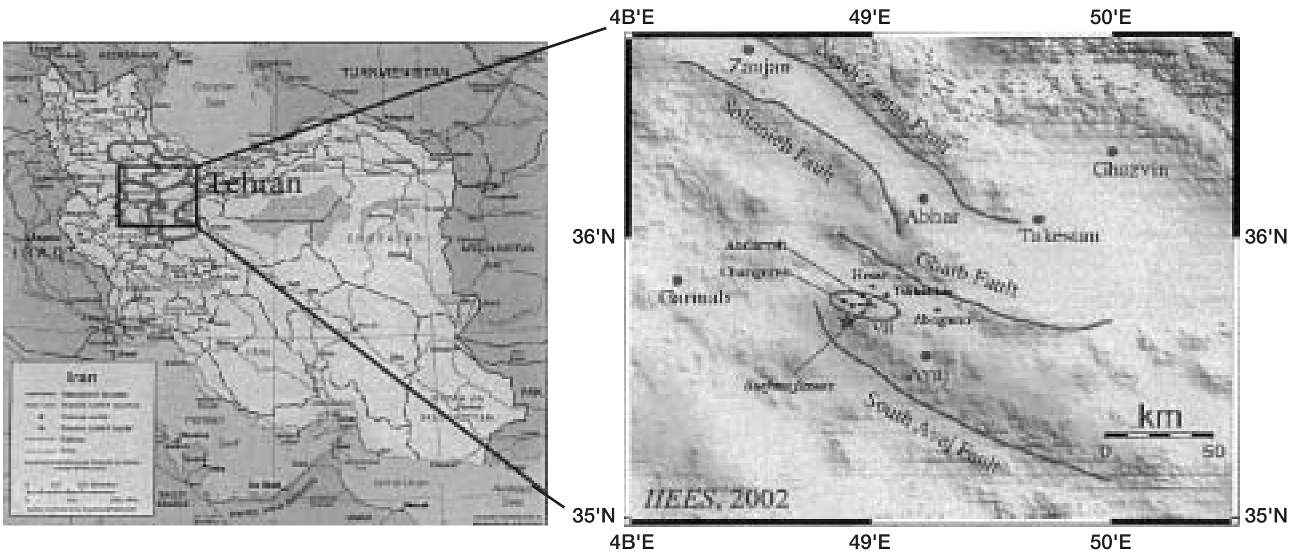


Fig. 1 Site map showing the earthquake affected area (IIEES website)

KEY WORDS: building damage, adobe houses, microtremors, H/V spectral ratio

estimated for this event. Preliminary source parameter estimates indicate a high stress drop and fast ground motion attenuation (Zare, 2002).

2. STRONG GROUND MOTION CHARACTERISTICS

The main shock of the earthquake was recorded by many digital accelerographs (Building and Housing Research Centre, BHRC website; Farzaneghan et al., 2002). A scatter graph of the peak ground acceleration, PGA (average of values in two horizontal directions), of the recorded data versus epicentral distance is shown in Fig. 2. The regression curve for the recorded data was calculated by a general equation for the attenuation relationship;

$$\log A = a - \log R + bR \tag{1}$$

where A is the PGA (cm/s^2), and R the epicentral distance (km). In this case,

$$a = 3.41 \text{ and } b = -0.00047$$

Also shown in Fig. 2 is the attenuation curve proposed by Fukushima et al. (1990). Because of lack of information, the epicentral distance was used instead of the shortest distance between the site and fault rupture. Comparison of the two curves verifies the fast attenuation characteristic of this earthquake.

A peak horizontal acceleration of nearly 0.5g was recorded at the Avaj station about 28 km from the hypocenter. From the digital records at this station (taken from the BHRC website), the acceleration time histories in the longitudinal (L), transverse (T), and vertical (V) directions, as well as their Fourier amplitude spectra and the response spectra for a damping ratio of h = 5% are shown in Fig. 3. Fig. 3-b indicates that the respective predominant frequencies in the L and T directions are 3.2 and 4.2 Hz. According to the azimuth values of 105 and 195, the L and T directions at that station roughly correspond to the EW and NS directions. Moreover, Fig. 3-c shows the maximum response acceleration for a period of about 0.2 s.

3. BUILDING DAMAGE

3.1 Introduction

Many engineered as well as non-engineered structures were severely damaged and collapsed during the earthquake. Un-reinforced masonry (URM) structures commonly were damaged because of poor construction of their bearing walls. The seismic performance of the brick masonry infill in these URM structures was catastrophic. Adobe buildings collapsed or suffered heavy damage, the damage level depending on the distance from the ruptured surface fault.

Most of the destroyed villages were subjected to very intense earthquake motion without attenuation because they were very near the ruptured fault. The site effects amplified the earthquake motion in some areas, causing excessive damage. In general, villages near the epicenter and ruptured fault suffered greater damage.

3.2 Characteristics of the building inventory

Traditionally, single-story adobe buildings have been the type of construction used throughout the region. Adobe structures also were used as warehouses or sheepfolds. The second most widely used type of construction in the villages was masonry structures. Newer construction materials, such as concrete and brick masonry, were found widely throughout the region. The principal structural system used in the villages consisted of un-reinforced brick masonry (URM) bearing walls that supported steel-masonry (Jack-arch) floor slabs or a timber roof. This type of construction, with nearly identical detailing, was seen in most residential units. Although the majority of the buildings were single-story ones, there were some two- and even three-story buildings in relatively large villages.

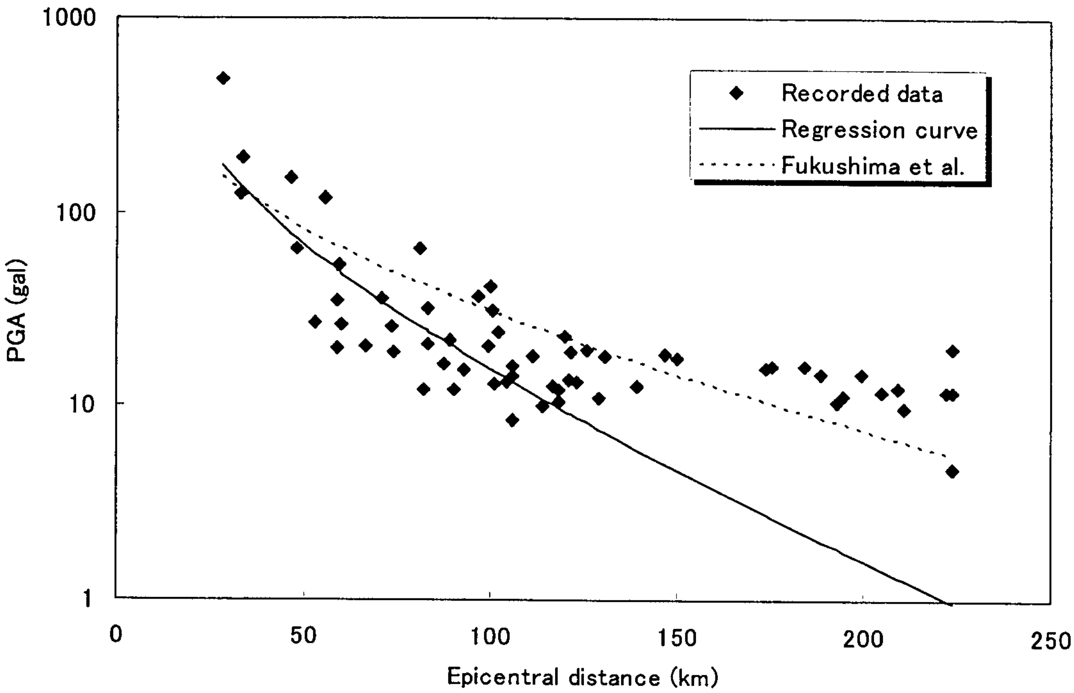


Fig. 2 PGA attenuation curves

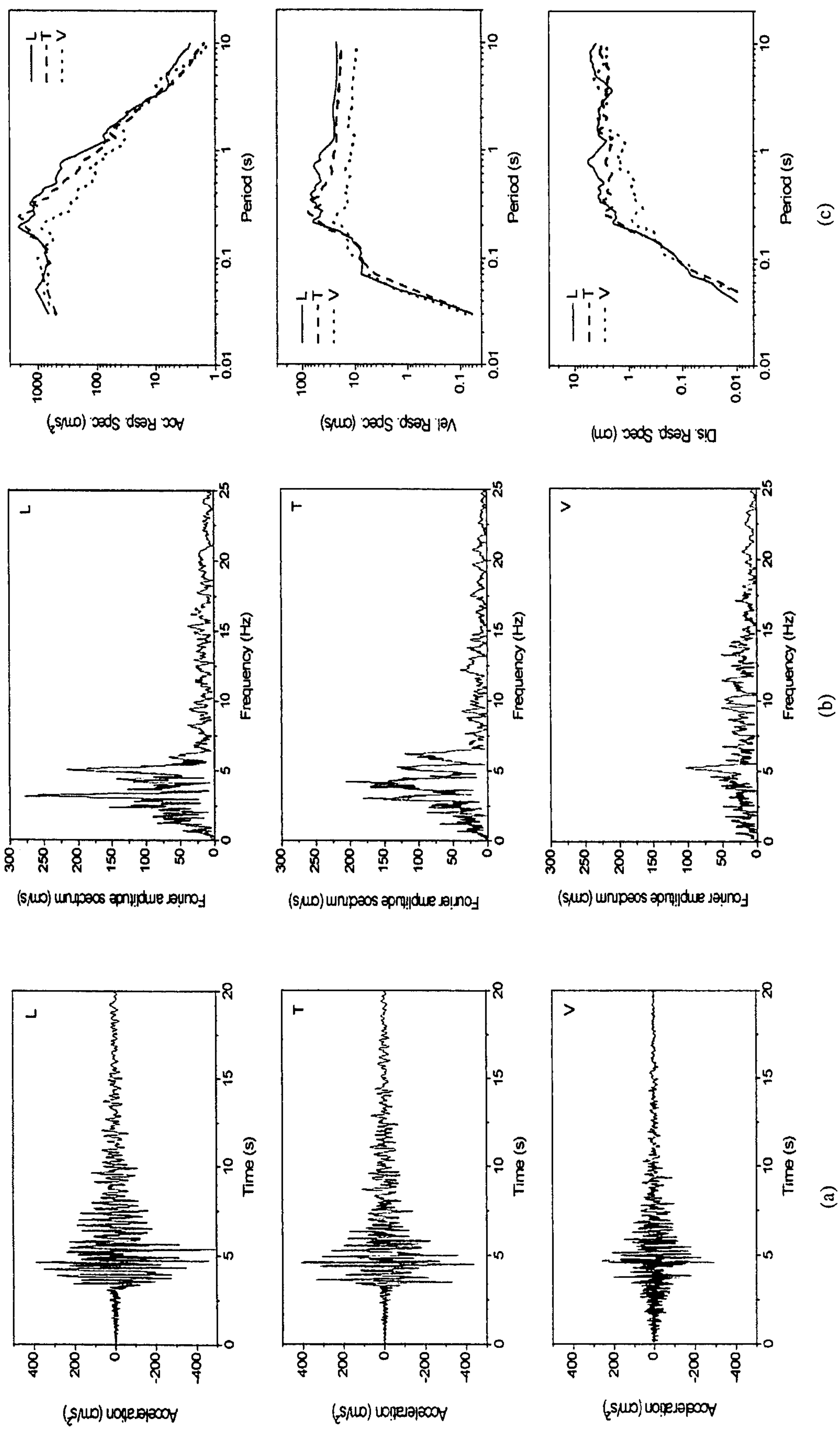


Fig. 3 Strong earthquake motion characteristics at Avaj station: (a) acceleration time histories; (b) Fourier amplitude spectra; (c) acceleration, velocity, and displacement response spectra, h=5%

Photo 1 Collapsed adobe buildings which had arched and /or timber roofs (Abdareh)

Photo 2 A thatched timber roof bonded with asphalt (Tablashkin)

Photo 3 A typical collapsed URM building with a Jack-arch floor slab (Changureh)

Photo 4 Collapse of a URM building with a Jack-arch floor slab (Changureh)

Steel and reinforced concrete frames were rare in this region.

Adobe buildings

Old adobe buildings were used not only as residential units but as warehouses and sheepfolds. The construction of these low quality adobe buildings consisted of mud-brick bearing walls that supported a flat slab or an arch floor slab. Stone was an alternative material used for bearing walls in villages near mountains. Flat slabs were constructed with wooden beams thatched with mud-straw materials, whereas arch slabs built of mud-brick bonded with mud-grout. The seismic performance of such non-engineered dwellings is a function of wall thickness, internal subdivisions, roof mass, nature of the continuity with adjacent dwellings, distance to the fault, and site effects. Photo 1 shows failed adobe buildings with arch floor slabs and/or wooden flat floor slabs.

Un-reinforced masonry structures

Un-reinforced masonry (URM) structures suffered severe damage during the earthquake. Unfortunately, masonry is the most commonly available and economical construction material, and individual owners have used it throughout the region. Photo 2 shows a typical damaged URM building with a timber roof.

URM is commonly used in Iran in combination with steel-masonry (Jack-arch) floors poured on top of the URM bearing-walls. The high in-plane rigidity of the Jack-arch floor system produces good distribution of seismically induced forces on the bearing walls, but reliance on a floor with brittle URM bearing-walls to resist lateral forces ensures that once the strength threshold is exceeded, severe damage and/or dramatic collapse is likely to occur. In-plane, out-of-plane, and combined in-plane and out-of-plane failures occurred, as is normally expected with URM structures. Photos 3 and 4 show collapsed URM structures with steel-masonry Jack-arch slabs.

Brick and mortar quality have a major influence on the in-plane performance of URM structures. The use of solid bricks bonded with mortar in URM bearing walls that have a thickness of 350-mm seems to be sufficient to prevent out-of-plane failure in typical single-story URM structures. Out-of-plane failure of URM bearing-walls was, however, the principal cause of the collapse of URM structures. The use of poor mortar resulted in unstable walls when buildings were subjected to out-of-plane seismic force. Moreover, the absence of any anchorage at roof level between the bearing walls and slabs compounded the problem, causing even greater damage (Photo 4).

The Iranian Seismic Code (BHRC, 1988) has a chapter on URM structures. As the design of newly constructed government buildings, such as schools, conformed to the Iranian Seismic Code for such constructions, although suffering heavy damage, this type of building did not collapse. Unfortunately, it is not mandatory to follow this code in the design and construction of buildings in rural areas. One can erect any type of building as there is no specific code for those areas.

Semi-steel structures

Because of its high cost, structural steel has rarely been used for a lateral resistance system in structures in the region. The use of steel is limited to steel-masonry Jack-arch floors. A few semi-steel structures had steel beams and columns. The exterior enclosures as well as the interior partitions, however, were constructed of non-bearing, un-reinforced brick masonry infill walls. These walls contributed to the lateral stiffness of the buildings during the earthquake and, in many instances, controlled lateral drift and resisted seismic forces elastically. This was true only when the bricks and grout were bonded sufficiently by the use of good construction practices. When the structural response and deformation demands were very high, the masonry walls could not remain elastic. In such buildings, typical diagonal cracks in the exterior as well as the interior brick walls were present. In most cases, out-of-plane failure of the infill walls occurred. Once the brick infill failed, lateral strength and stiffness was provided by the frame alone, which then experienced significant inelastic responses in the critical regions of its members.

Photo 5 shows a two-story, semi-steel structure with steel columns and beams. This building had a relatively light roofing system. Steel beams and columns were used to support the gravity dead load and live load. Obviously there was no lateral resistance system. The presence of reinforcement that tied the infill walls to the columns prevented out-of-plane failure of the infill walls, resulting in a semi-lateral resistance system. This system together with the light roof prevented complete collapse. The building, however, could no longer be occupied, and reconstruction was necessary because of severe deformation of its beam-to- column connections.

Out-of-plane failure of the infill walls was frequent in these types of semi-steel structure systems. Photo 6 shows an example in which the horizontal and vertical steel ties were constructed according to the Iranian Seismic Code. The building itself survived, but failure of the heavy un-reinforced infill walls caused a vast human damage.

4. MICROTREMOR MEASURMENTS

4.1 Introduction

Microtremor measurement is a very useful method for obtaining ground dynamic characteristics, including the predominant period and the site amplification factor (Enomoto et al, 2000). To examine the ground surface and structural seismic response characteristics in the earthquake-stricken area, microtremor measurements were conducted in several locations in Abdareh Village, in which almost 100% of the adobe dwellings were destroyed, as well as on an adobe house in Tablashkin Village. Moreover, a forced vibration test that used human strength was conducted on an adobe house. The dynamic characteristics of the house were determined

Photo 5 A surviving semi-steel structure with a Jack-arch floor slab (Changureh)

Photo 6 Out-of-plane failure of the infill of a semi-steel structure house (Changureh)

Photo 7 Microtremor measurement station sites in Abdareh (Photo: Majid Noorallahpoor, Iran)

Photo 8 Recording ground tremors in Abdareh in front of a public bath (station No. 4)

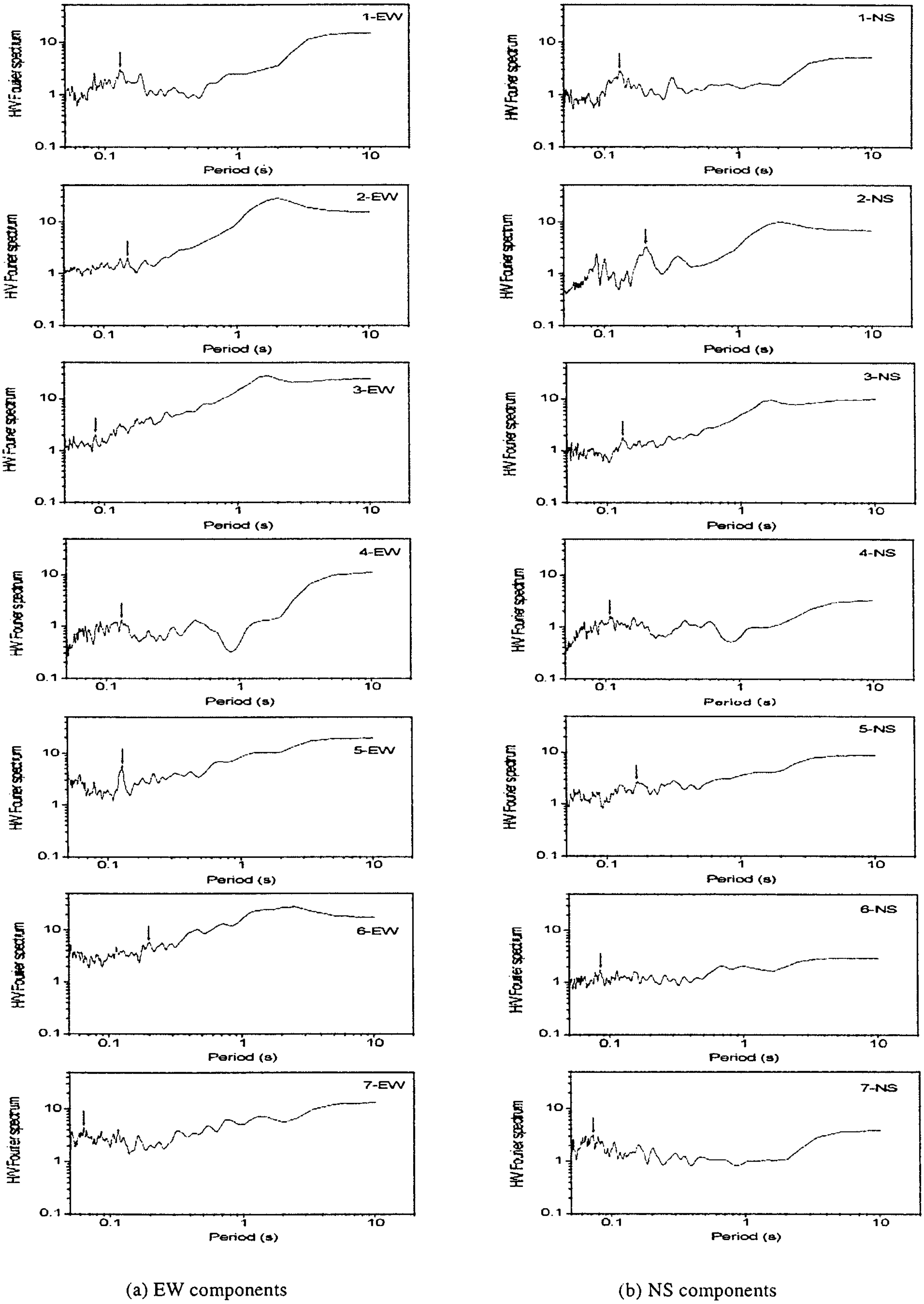
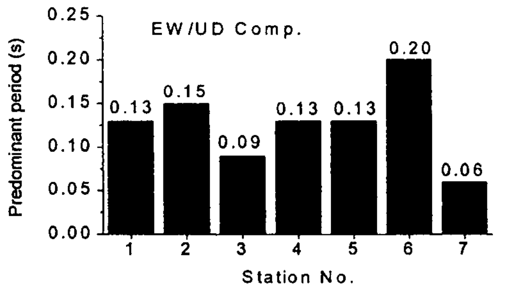


Fig. 4 H/V Fourier spectral ratios of microtremors at stations Nos. 1-7

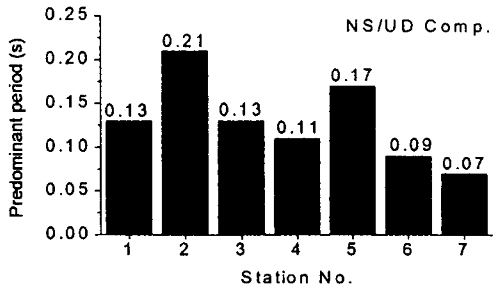
from the free vibration results. To make these measurements, highly sensitive SPC-35N (Tokyo Sokushin) seismometers with three orthogonal components each, two horizontal (H) and one vertical (V), were used. Velocity amplitudes of microtremors at a sampling frequency of 100 Hz with a 0.1 Hz high pass filter were measured. Each record at a point had a time history duration of 300 seconds which, after excising the visible noise, was divided into 5 segments with 1024 data each. A Fourier analysis, based on the H/V spectral ratio (Nakamura, 1989), was made for each segment. The mean spectrum was smoothed by a Parzen window of the 0.4 Hz band. Because of the valley-shape topography of Abdareh, there the Fourier spectra were considered separately for the EW and NS directions and the geometric average of the two directions was calculated to determine the predominant period of the ground surface at each measurement site. Taking into account the natural period of a typical adobe house, the relationship between the strong ground motion of the earthquake and the damage done, which may be affected by local site conditions, is discussed.

4.2 Microtremors in Abdareh

In Abdareh, tremors were measured on the ground surface at 7 stations, whose positions are roughly indicated in Photo 7. Actually, station No. 1 is much further to the left than shown in the Photo, and is behind a large, engineered-built house which suffered slight damage to its masonry walls. No.4 is in front of an undamaged, stiff public bath (Photo 8), No. 7 is nearby some 50%-dam-



(a) EW components



(b) NS components

Fig. 5 Predominant microtremor periods at staions 1-7

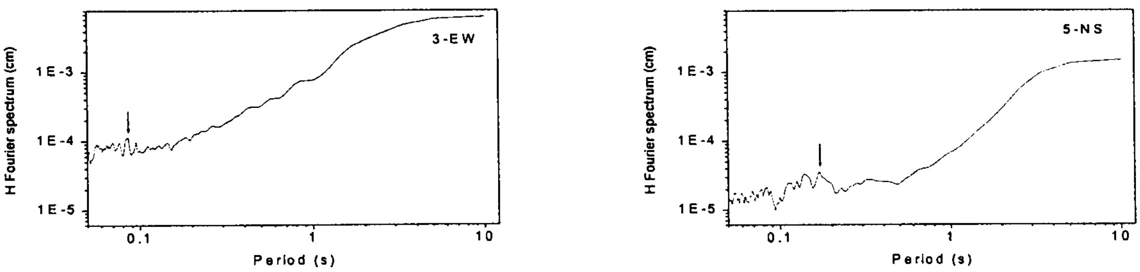


Fig. 6 Horizontal (H) Fourier spectra of the 3-EW and 5-NS components

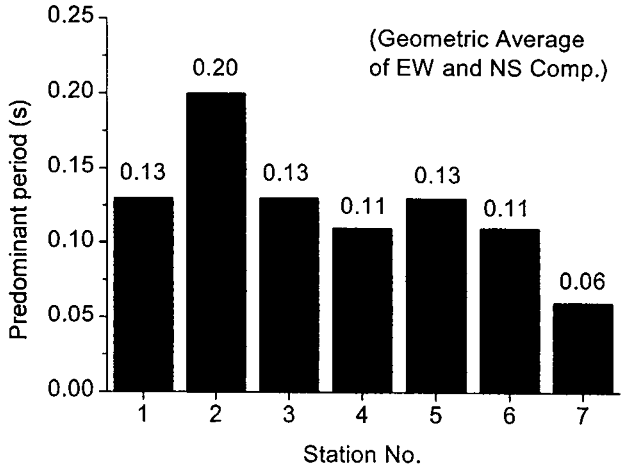


Fig. 7 Predominent period of the ground at the microtremor measurement stations in Abdareh

aged adobe houses. The other stations are in areas of completely destroyed adobe houses. These stations were chosen because they all are located approximately along the fault trace. In each measurement, two horizontal (H: EW and NS) and one vertical (V: UD) components of the tremors were recorded.

The smooth mean H/V Fourier spectral ratios of the noise-free segments of the tremors at stations Nos. 1-7 in the two EW and NS directions are shown in Fig. 4. This figure shows that amplitudes in the EW direction, along the cross section of the valley and roughly along the fault trace, are larger than those in the NS direction. Considering that the predominant period range of ordinary ground is less than 1 s and according to the dynamic characteristics of the sensors, the predominant periods of the ground surface at the measurement sites, the highest peaks on the H/V graphs, were from 0.05 s to about 1 s shown by the arrows in Fig. 4. These periods are collated and shown in Fig. 5. Note that when the peak periods of the H/V spectra are not clear, as in 3-EW and 5-NS, corresponding H spectra, such as those shown in Fig. 6, were used.

The Fourier spectra of the geometric average (square root of the products) of the EW and NS components were used to determine the predominant periods of the ground surface at the measurement sites (Fig. 7). Based on the criteria in Kanai, 1983, the ground conditions were evaluated as Class 2 (medium) at station No. 2, and as Class 1 (good) at the others. As seen, station No. 7 which had the lowest predominant period, 0.06 s, has the hardest ground surface of all the sites, which is in good agreement with the earthquake-induced damage, because in that area of Abdareh alone, some adobe houses survived (Photo 7). Another factor in damage interpretation is the taking into account of the dynamic characteristics of structures. A forced vibration test therefore was conducted on an adobe house in Tablashkin Village.

4.3 Microtremors in Tablashkin

Tablashkin Village is located far from the epicenter unlike the villages of Abdareh and Changureh. Whereas in the latter villages almost all the adobe dwellings were destroyed, Tablashkin Village had a different appearance although there were some collapsed and many damaged dwellings. Due to differences in house plans, it was difficult for the investigation team to identify a typical undamaged adobe house in that village. A slightly damaged adobe house therefore was selected, and both microtremor measurements and a forced vibration test were made to obtain its natural period.

Microtremor and forced vibration tests on an adobe house

The plan and view of the test house respectively are shown in Fig. 8 and Photo 9. The house height is 2.9 m, the lower 0.8 m of which is stone wall and the upper 2.1 m adobe.

The first set of measurements made was for simultaneous microtremors in five channels (Ch.1-5, Fig. 8): three on the ground surface (two horizontal, one vertical), and two horizontal on the

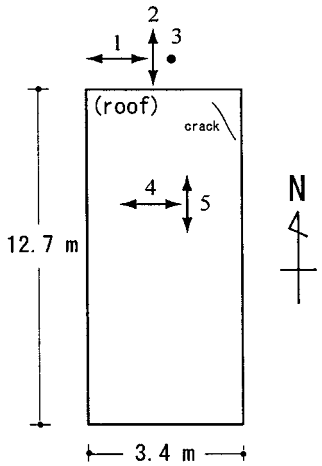
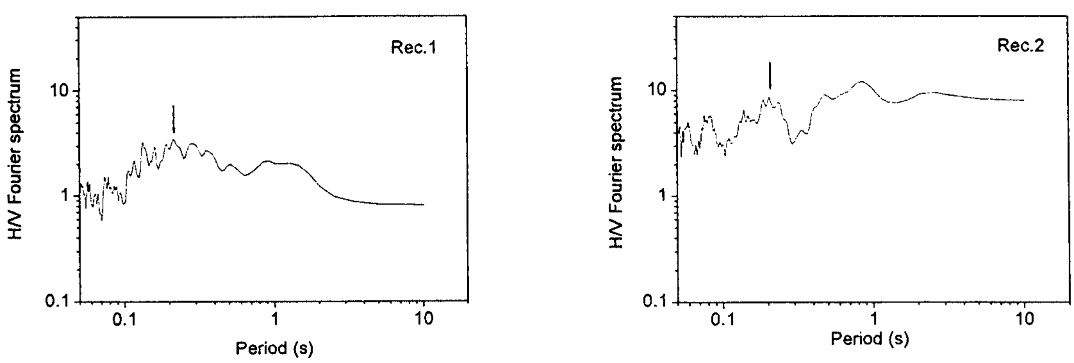


Fig. 8 Plan of the adobe test house

Photo 9 View of the adobe test house



(a) Record 1 (b) Record 2

Fig. 9 H/V Fourier spectral ratios of the ground surface at the adobe test house

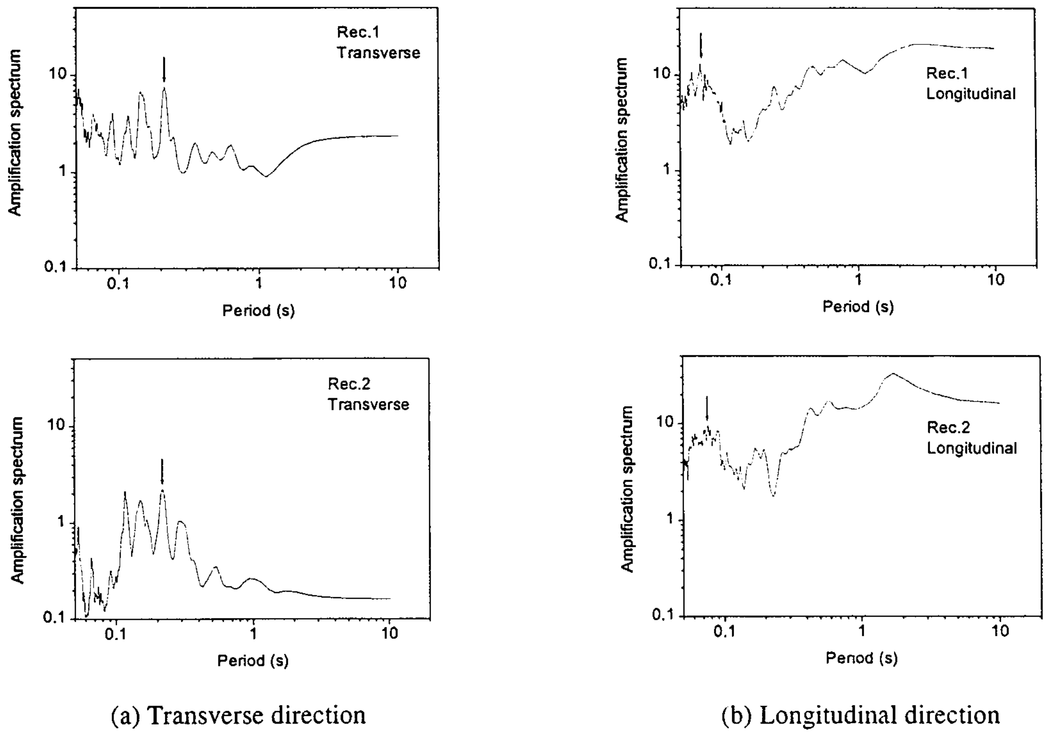


Fig. 10 Amplification spectra of the adobe test house

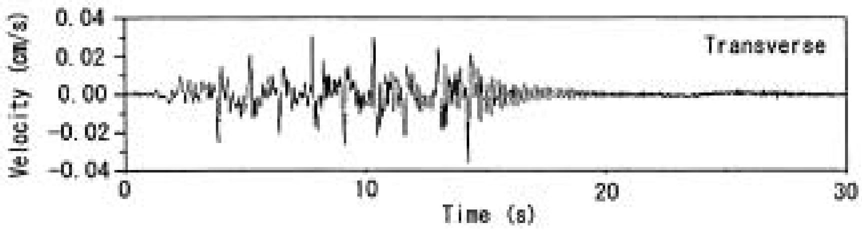


Fig. 11 Transverse recording of shaking by forced vibration on the roof of the adobe test house

Photo 10 Forced vibration test on the adobe house

roof of the house in the transverse and longitudinal directions. The two horizontal channels on the ground (Chs.1 and 2) were set parallel to those on the roof (Chs.4 and 5). In the two 300 s-duration recordings (Recs.1 and 2), an analysis similar to that explained previously was followed. The H/V Fourier spectra for the ground surface were determined (Fig. 9). These findings show the predominant period of the ground to be 0.2 s. The spectral ratios of Ch.4/Ch.1 and Ch.5/Ch.2 respectively give the amplification spectra in the transverse and longitudinal directions (Fig. 10), in which the respective natural periods of the house in the transverse and longitudinal directions are 0.2 s and about 0.08 s. The relatively large difference, 2.5-fold, between these two periods may be due to the large length-over-width ratio of the house; more than 3.7.

A forced vibration test was performed on the adobe house for tremors generated by human swaying on the roof in the transverse direction (Photo 10) to distinguish the natural period and damping ratio of the house in that direction from the ensuing free vibration. After some trials the swaying period was adjusted to the natural period of the house in order to record relatively large amplitudes. Only two channels on the roof were recorded. The transverse direction dealt with in Fig. 11, shows the recorded time history, in which about the last 15 s is that of free vibration. The Fourier spectrum of this part gives the natural period of the house as 0.2 s, which is the same as the results of the microtremor experiment (Fig. 10-a). Furthermore, using that part, the damping ratio of the house was calculated to be about 3%.

5. CONCLUSIONS

The erection of non-ductile structural systems such as adobe and un-reinforced masonry (URM) structures resulted in catastrophic earthquake damage. URM structures which conformed to the Iranian Seismic Code suffered heavy damage but survived collapse. Other URM structures readily collapsed due to out-of-plane failure of their infill walls. The absence of anchorage, as well as the use of poor mortar, was the cause of the out-of-plane failure of the infill. Beyond the elastic limit, seismic survival of a building depended heavily on the ductility of its structural components. The use of slender columns and the absence of a lateral resistance system in semi-steel structures was another primary cause of structural failure.

Microtremor measurements were made on the ground surface in Abdareh Village and on an adobe house in Tablashkin Village. The measured microtremors in Abdareh were in good agreement with the damage done by the earthquake. The focus there was on adobe houses, because, although adobe houses are very vulnerable even to mild earthquakes, the remarkable difference in ground conditions in one area of the village was the main reason for relatively less damage being done to adobe houses there.

In rural areas, adobe houses are very similar in size, usage, and method of construction, and therefore in their dynamic characteristics. Because no undamaged adobe house survived in Abdareh, microtremor and forced vibration tests were carried out on a typical adobe house in Tablashkin. From the findings for that house, its natural period was 0.2 s and the damping ratio about 3%. Because the predominant period of ground during an earthquake is larger than during microtremors owing to the nonlinear effect, most of the predominant periods of the ground surface at the measurement stations in Abdareh (Fig. 7) are concluded to have shifted to 0.2 s or more, and therefore amplification led to widespread severe damage.

ACKNOWLEDGMENTS

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