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Seismic Behavior of Local Soil and Foundations in Bam City During the 2003 Bam Earthquake in Iran

Ikuo Towhata[1)]*, Abbas Ghalandarzadeh[2)], Habib Shahnazari[3)], Masoud Mohajeri[4)] and Ali Shafiee[5)]

[1)] Department of Civil Engineering, University of Tokyo
[2)] Department of Civil Engineering, Tehran University, Tehran, IRAN
[3)] Department of Civil Engineering, Iran University of Science and Technology, Tehran, IRAN
[4)] National Research Institute for Earth Science and Disaster Prevention, Tsukuba
[5)] International Institute of Earthquake Engineering and Seismology, Tehran, IRAN

Abstract

Following the devastating earthquake disaster in Bam city, Iran, a reconnaissance team was sent to the site. The authors participated in its activities with special emphasis on geotechnical issues. A soil investigation in the city revealed that local soils have sufficiently good properties and cannot be the main source of heavy damage to houses. Because bridges and structures other than buildings experienced minor damage during the same earthquake, it seems that the structural weakness of houses made of masonry and adobe is a major problem. A possible mitigating measure may be to use light materials such as ESP, although consideration has to be given to the local climate and the landscape.

Key words: site investigation, sounding, masonry, earthquake

1. Introduction

The City of Bam in south-eastern Iran experienced an earthquake with a magnitude of Mw=6.6 at 5: 26 A.M. local time on 26th December, 2003. Among many research groups of different disciplines that visited the affected area after the quake, the authors carried out their investigation for approximately 1 week from February 24th, 2004. This paper describes the findings of this research visit and discusses the future scope of research.

Figure 1 shows the location of Bam city. Because the city is located far from central Iran, the reconnaissance team arrived in Tehran, flew to Kerman, and then used road transport to travel to Bam. After the investigation in Bam was completed, a brief study was made in Kerman where undamaged traditional buildings could be seen.

2. Ground conditions in Bam city

Photo 1 is an aerial view of Bam city. The north end of the city is bounded by Posht-e-Rud (Posht River), while the eastern side is connected to the Baravat municipality. As the center of the local community, Bam city has a history of over 1,000 (probably 2,000) years.

The city has historic buildings as exemplified by the famous fortress of Arg-e-Bam. The causative fault of the present quake is located between Bam and Baravat and runs in the north-south direction (Photo 1).

In the earliest phase of the present investigation, it was found that damage was substantial in Bam city, where most houses and buildings were destroyed. In contrast, many buildings and houses, although they suffered slight damage, withstood the earthquake in the southern and western parts of the city (Fig. 2). Thus, it was assumed that subsurface soil conditions might have affected the intensity of tremors and consequently damage. This hypothesis seemed to be supported by the existence of the Posht

* e-mail: towhata@geot.t.u-tokyo.ac.jp (3-1, Hongo 7 chome, Bunkyo-ku, Tokyo, 113-8656 Japan)

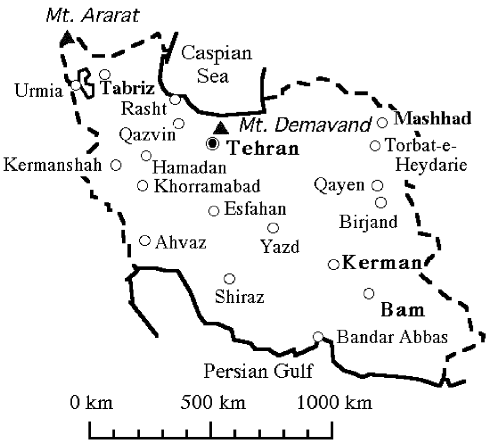

Fig. 1. Location of Bam city.

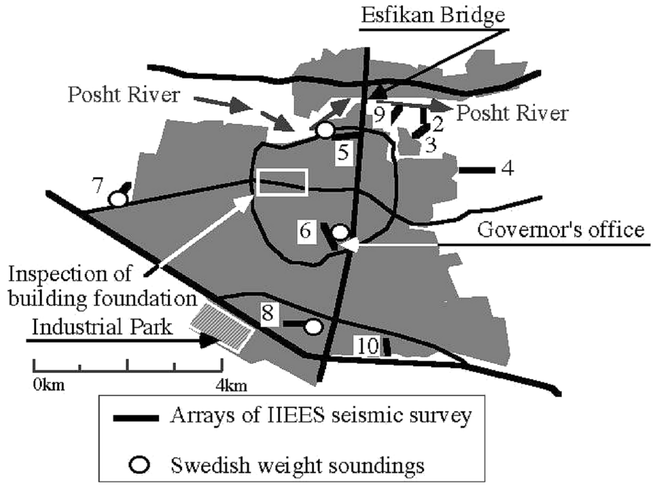

Fig. 3. Locations studied in Bam.

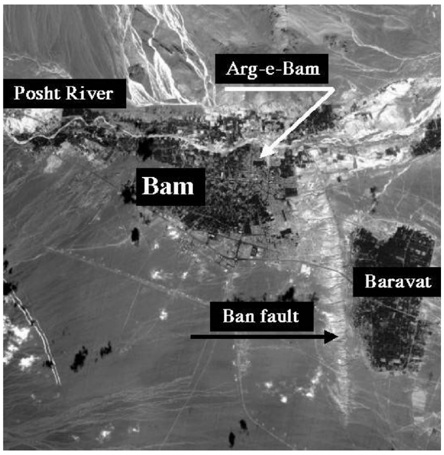

Photo 1. Aerial view of Bam City.

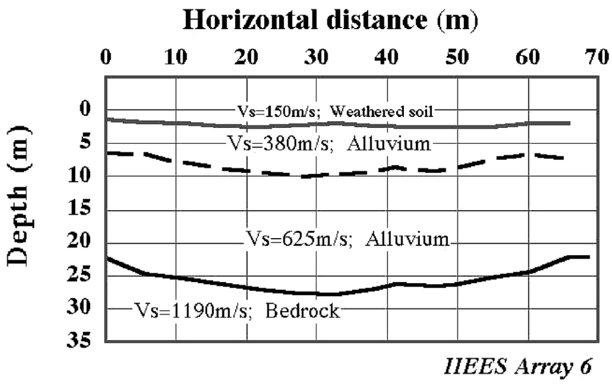

Fig. 4. Example of seismic reflection survey at Array 6 in Bam (study done by IIEES).

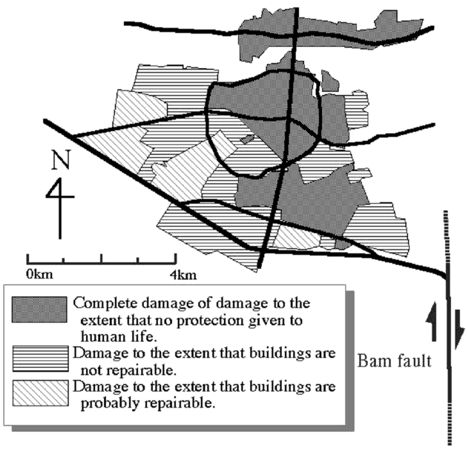

Fig. 2. Variations in damage to houses in different parts of Bam (investigation by Tehran University).

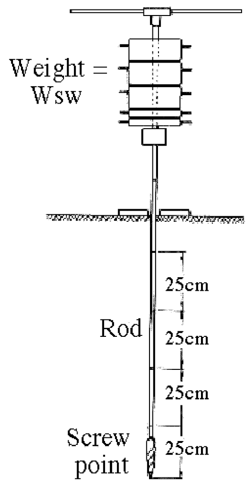

Fig. 5. Swedish weight sounding (Drawn after Japanese Geotechnical Society; http://www.jiban.co.jp/gyoumu/chousa/tyosa02.ht).

River channel deposits near the damaged part of the city. Thus, an investigation of local soil conditions was planned and conducted.

The International Institute of Earthquake Engineering and Seismology (IIEES), which is a Tehran-based research institute and was the counterpart of the present investigation, had carried out seismic reflection surveys in and around Bam city prior to the arrival of the authors. The locations of this survey are indicated in Fig. 3. For this study, geophones were installed at intervals of 4 m, and the soil profile obtained has an accuracy of approximately 2 m in the vertical direction. One of the results of this seismic survey is illustrated in Fig. 4, which indicates that the Bam subsoil consists of a surface soil underlain by alluvium and bedrock. The assessed S wave velocities in this figure show that there is not such a soft soil deposit as may be imagined in coastal alluvial or deltaic deposits.

Although seismic profiling is a useful tool for subsurface exploration, it was felt that its accuracy of 2 m may lead to soft surface soil not being identified. Moreover, seismic profiling is suitable for global exploration of regional geology and may not be able to detect local deposits of soft soils. With these points in mind, the authors conducted a soil investigation that would allow them to study soil conditions in more detail. For a comparison, this investigation was carried out at or near the IIEES seismic arrays (Fig. 3).

The soil investigation method employed is called Swedish Weight Sounding (Fig. 5), by which a screw point is rotated and pushed into the ground. This penetration is helped by a constant surface load of 100 kgf (0.98 KN), which is applied for penetration. During tests, the number of half rotations needed for a 25 cm penetration was counted and multiplied by 4, so the number of half rotations needed for a 1-meter penetration was obtained and designated *Nsw*. Apparently, the higher value of *Nsw* relates to harder soil conditions. Note that the above-mentioned half rotation means a rotation of 180 degrees. Thus, when the equipment is rotated 4 times around the vertical axis, the number of half rotations is 8.

Photo 2 shows Swedish sounding conducted at the site of IIEES array 6. Because rotation is done manually and a weight of *Wsw* is generated by hanging sand bags filled with local soil, this investigation can be carried out at any location without preparing a thrust machine and reaction system. Another advantage of Swedish sounding lies in the empirical formula (Inada, 1960), which converts the measured *Nsw* value to the standard penetration blow counts, *SPT-N* value, which is commonly used in practice. The formula is given as

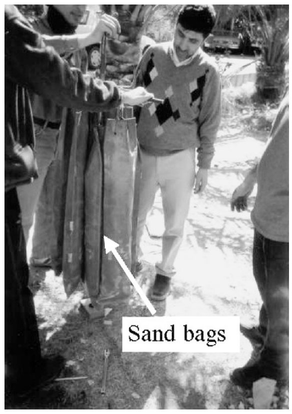

Photo 2. Swedish weight sounding at site of IIEES array 6.

$$(SPT-N) = 0.02 \times Wsw + 0.067 \times Nsw \qquad (1)$$

for sandy ground; *Wsw* in kgf units denotes the weight loaded at the top of the device (Fig. 5) and, in the present study, $Wsw = 100$ kgf was employed for hard soil conditions.

3. Swedish weight sounding at IIEES array 5

The IIEES array 5 is the first of 4 sites where Swedish soundings were conducted. This site is located in the northern part of the city (Fig. 3) and the extent of damage to buildings was significant. It is, however, noteworthy that a few buildings survived the quake without suffering damage among many other damaged neighboring buildings (Photo 3).

Swedish sounding at this site was carried out in the garden of a house which was demolished by the quake. Because the surface soil was compacted, probably when the surface was covered by tiles upon construction, it was not easy for the device to penetrate the uppermost soil. Below this layer, slightly softer soil was briefly encountered, then the soil became hard again, making further penetration impossible.

Figure 6 compares the results of Nsw, the number of half rotations needed for 1-meter penetration, against the average velocity profile obtained by

Photo 3. Damaged and undamaged buildings around the site of IIEES array 5.

Photo 4. Damaged masonry building near site of IIEES array 6.

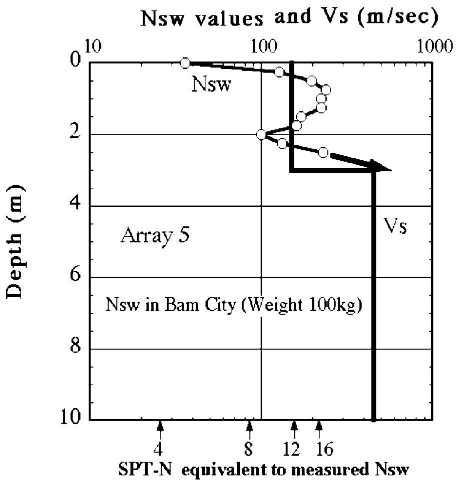

Fig. 6. Comparison of Swedish weight sounding and seismic reflection survey at IIEES array 5.

Photo 5. Undamaged house near the site of array 6.

IIEES. As stated before, Swedish sounding provides detailed soil conditions at a single location, while the seismic profile in contrast provides more global information but less detail on soil conditions. Moreover, the exact surface elevations in these studies are not identical. Despite these issues, there is good consistency between the 2 results; harder soils lie below 3 meters in depth. Note that the soil properties seen in Fig. 6 do not imply soft soil conditions that may cause many seismic problems as often encountered in Japanese alluvial planes.

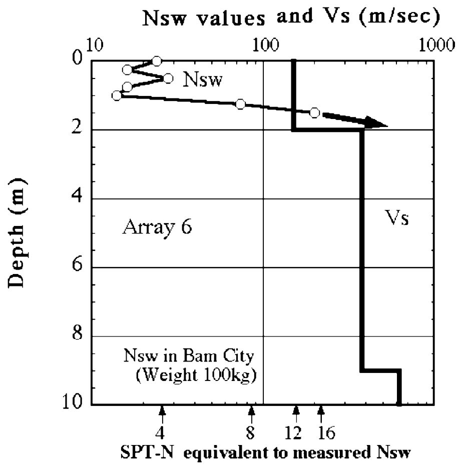

Fig. 7. Comparison of Swedish weight sounding and seismic reflection survey at IIEES array 6.

4. Swedish weight sounding at IIEES array 6

This site is located at the center of the city and many buildings were destroyed by the earthquake (Photo 4). It is again noteworthy that there was 1 house that suffered little damage in this area (Photo 5). Upon visiting this house, its owner said that it had been built by a local contractor who was renown for the good quality of construction. Fig. 7 compares the results of Swedish sounding and IIEES seismic profiling, indicating the overall consistency between them. The top 1 meter shows relatively softer soils, and below this level, the material is significantly hard.

5. Swedish weight sounding at IIEES array 7

The site of array 7 is located in the western part of the city where the extent of damage appears to be less significant (Photo 6) than in the north and central parts of the city, as demonstrated above. Swedish sounding at this site was conducted in a large excavated pit (Photo 7 a), which was approximately 3 meters deep. It was expected that this decision would save time needed to penetrate the top hard soil and more efficiently study subsoil conditions.

An important feature of this site is the gravel deposit observed at the bottom of the pit (Photo 7 b). For this reason the Swedish sounding device could not penetrate deep into the subsoil. Accordingly, the results of Swedish sounding and IIEES seismic profiling are consistent with each other (see Fig. 8), revealing hard soil conditions at this site.

Photo 6. Relatively light damage around site of IIEES array 7.

(a) View of excavation of excavation.

(b) Gravel layer at bottom.

Photo 7. Excavation where Swedish sounding was conducted (array 7 site).

6. Swedish weight sounding at IIEES array 8

This site is located to the south of the city, where urbanization has occurred in more recent times, and the density of buildings is not as high as at the city center. Swedish sounding was carried out at the bottom of a shallow excavation (2.5 meters deep) again to save time (Photo 8). Because the bottom soil was also gravel, penetration of the device was terminated immediately. Fig. 9 compares test results to show clearly that soil conditions are hard here.

7. Summary of Swedish weight sounding

It was concluded from Swedish soundings at 4 sites, as mentioned above, that the subsurface conditions reported by IIEES seismic profiling are consistent with the more detailed sounding test results. Accordingly, the seismic profiling at 9 sites in total in

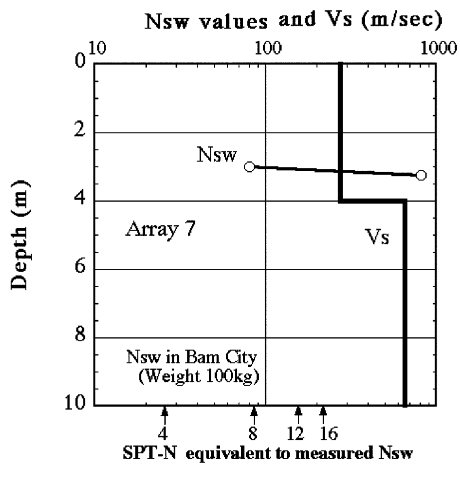

Fig. 8. Comparison of Swedish weight sounding and seismic reflection survey at IIEES array 7.

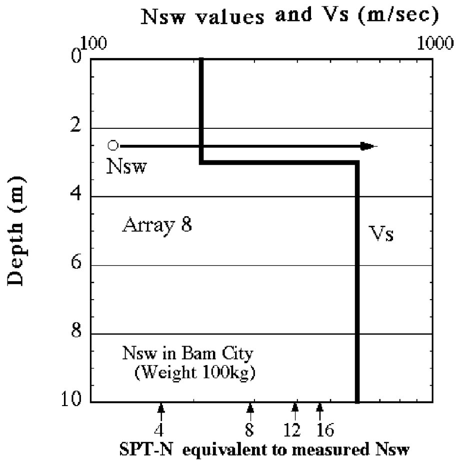

Fig. 9. Comparison of Swedish weight sounding and seismic reflection survey at IIEES array 8.

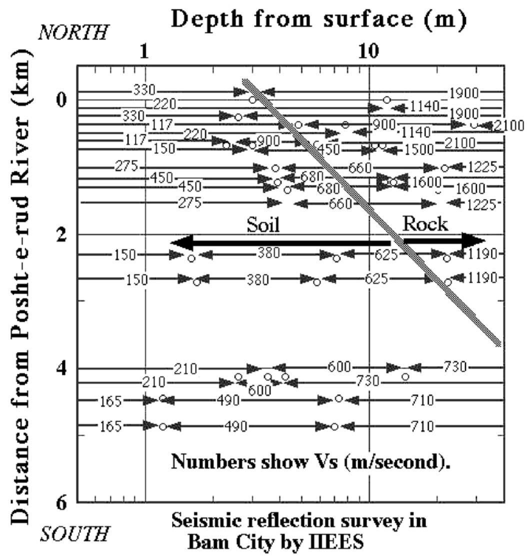

Fig. 10. Assemblage of nine IIEES seismic profiles in Bam city.

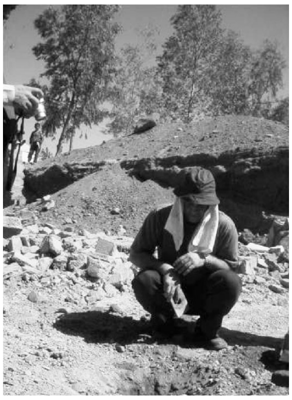

Photo 8. Swedish sounding in excavated pit near IIEES array 8.

the city is judged to be reasonable, and is assembled in a single diagram, Fig. 10. The horizontal axis in this figure designates the depth of strata, while the distance from the north edge of the city is plotted on the vertical axis. From this diagram, the following points can be made.

1) The elevation of the hardest soil or rock becomes deeper in the southern part of the city. In contrast, the hard material occurs at the ground surface in the northern part of the city as is typically exemplified by the hill of Arg-e-Bam (Photo 1). Therefore, the surface geology is inclined slightly towards the south.

2) The angle of base inclination, however, is typically 1%, which is not significant.

3) The S-wave velocity (Vs) a few meters below the surface soil ranges from 220 to 900 m/sec. This depth range was chosen as the typical depth of a building foundation. These Vs values are converted into equivalent SPT blow counts of N using the empirical formula

$$Vs = 80N^{1/3} \quad (\mathrm{m/s}) \tag{2}$$

for sand (Japan Road Association, 2002). Accordingly, the surface cohesionless soil in Bam has SPT-N values of 20 or more, which means hard soil. Therefore, the soil condition in Bam was not the major cause of building damage.

8. Seismic behavior of bridges, tanks, and slope

There are 2 major bridges in the Bam City area. They are the Esfikan and Khaje-Askar Bridges crossing the Posht-e-Rud (Posht River). The Esfikan Bridge is located at the north end of the city (Fig. 3), while the Khaje-Askar Bridge is to the west. Photos 9 and 10 show the appearance of the bridges during the investigation. There is evidently no significant damage to or deformation of these bridges, and road traffic was not suspended. In more detail, Photo 11 shows the situation of the Esfikan Bridge at the top of the pier. Noteworthy is the fact that the lateral displacement is only a few centimeters, and that the function of the bridge was maintained, in spite of the lack of any aseismic measures, during the earthquake. The good performance of the bridges during the quake is in contrast with the complete destruction of houses at the center of the city.

There is an industrial park in the southern suburb of Bam city (Fig. 3). Photo 12 shows the situation at the time the authors visited the site. It was found that the tank and connected pipes received negligible, if any, damage during the earthquake, although it is not certain whether or not this minor distortion of the pipe was caused by the quake. In contrast, the front of the office building was partially destroyed because of its weak masonry structure. Thus, the insufficient seismic resistance of masonry structures compared to other structures was remarkable.

A visit was made to the site of Narmoshir Dam, whose construction was to start 25 km south east of Bam city. Located in a mountainous area, the dam site experienced "strong and long earthquake tremors" according to the chief engineer of dam construction. No seismometer was installed there. The present investigation did not find seismic slope instability in this area, with the exception of a minor rock fall (Photo 13) from the excavation site of the rockfill dam. This situation is again in clear contrast with

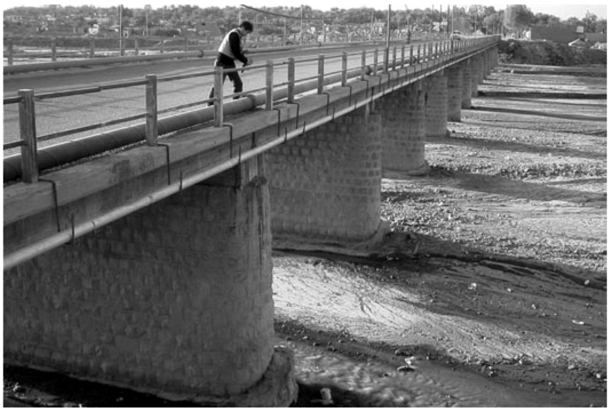

Photo 9. Appearance of Esfikan bridge after the earthquake.

Photo 10. Appearance of Khaje-Askar bridge after the earthquake.

(a) Tank and pipes.

(b) Damaged office building.

Photo 12. Situation of oil refinery plant in south of Bam City.

Photo 11. Minor displacement of Esfikan bridge at the top of pier.

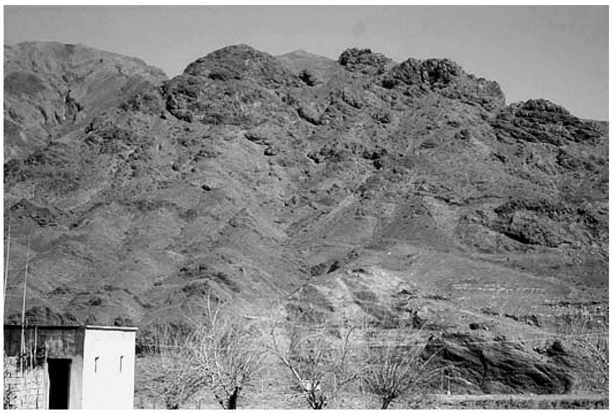

Photo 13. Rock fall near Narmoshir Dam under construction.

the total collapse of masonry houses in Bam city.

9. Damage extent in building foundations

The clear contrast in damage to buildings and bridges led the authors to carry out a more detailed inspection of buildings in the city. Because the mission of the authors was to investigate geotechnical aspects of the damage, special attention was paid to the foundations of damaged and undamaged buildings. This study was conducted in the western part of the city (see Fig. 3), where there were both damaged and undamaged buildings, and differences could be detected easily.

First, the bank building in Photo 14 had no appearance of damage. On the opposite side of the street, there was a building in Photo 15 whose first floor was severely distorted. As has been pointed out, thus, there are buildings in all parts of the city which survived the quake. Conversely, many nearby buildings and houses were severely affected by the same earthquake motion. Because the distance between damaged and undamaged buildings was small, the globally inclined geology in the city (Fig. 10) cannot account for the difference in damage. A more detailed inspection of Photo 15 reveals that the foundation did not deform. This may imply that the foundation and the subsoil had sufficient resistance to the seismically-induced inertia force, while the first floor did not.

Second, Photo 16 shows a completely destroyed adobe house. Adobe is a form of masonry made from local soil, which is mixed with water and sun-baked. Because it is easily available without any special raw material or manufacturing process required, adobe is widely used in Central Asia, which has an arid climate, and in South America. It is important that the base of the wall of this house did not distort, although the upper part totally collapsed. This again suggests that the damage was caused not by weak

Photo 15. Damaged building in front of bank in Photo 13.

Photo 16. Foundation of destroyed adobe house.

Photo 14. Undamaged bank building in western Bam.

Photo 17. Damage of to masonry structure.

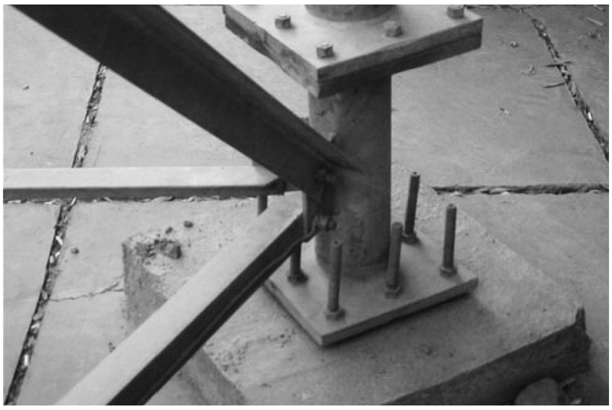

Photo 18. Foundation of communication transmission tower.

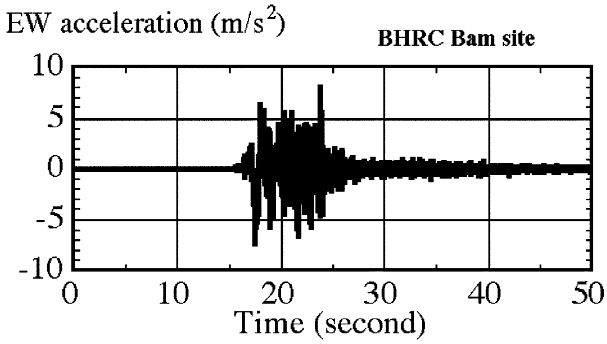

Fig. 11. Acceleration time history in Bam city (recorded by BHRC, Building and Housing Research Center, in Governor's office; see Fig. 3).

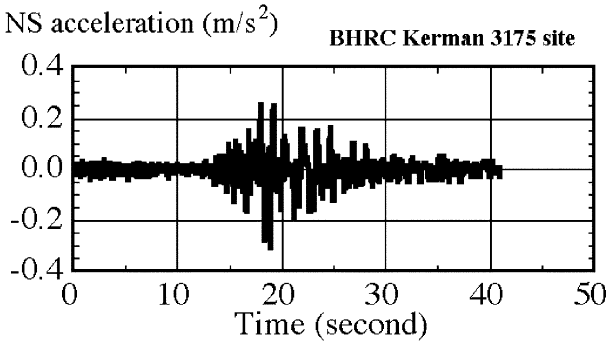

Fig. 12. Acceleration time history in Kerman City (recorded by BHRC).

foundation and soil, but the low strength of the superstructure.

Photo 17 further indicates the form of damage to the masonry structure in which the front wall was lost. It can be seen that the base of the side walls did not deform, showing that the foundation was not responsible for this damage.

Finally, Photo 18 shows the footing of a microwave transmission tower. Apparently, there is no distortion. This is in strong contrast with the substantial damage to masonry houses and buildings in the same part of the city.

10. Remarks on adobe houses

The previous section showed that the extent of damage to buildings and houses in the city was much more significant than that of other engineered structures such as bridges, tower foundations, and even rock slopes. It seems necessary and possible, therefore, to improve the building technology from the present situation to reduce human losses caused by total collapses. To achieve this goal, there are 2 issues to be addressed. The first issue is retrofitting existing buildings in not only Bam, but also in other cities of the region. The second task concerns new buildings which should not collapse under strong tremors.

In response to the first issue of improving existing structures, a visit was made to an adobe house in the nearby city of Kerman (Fig. 1). Kerman was considered to be a good place to do this study, because intact houses without seismic damage could be seen.

Figures 11 and 12 compare the acceleration time histories in Bam and Kerman obtained by BHRC of Iran. Due to the 150 km distance from Bam city, the magnitude of tremors in Kerman was much weaker than in the Bam city. Therefore, most adobe houses in this city received no seismic damage. There was, however, an exceptional case, as shown in Photo 19, in which a wall of an adobe house fell down due to

Photo 19. Exceptional seismic damage to adobe house in Kerman City.

(a) External appearance

(b) Roof covered with mud

Photo 20. Intact adobe house in Kerman City.

Photo 21. EPS temporary house for evacuation in Bam.

the Bam earthquake. This example suggests that some adobe and local masonry houses might have extremely low seismic resistance.

Photo 20 shows an adobe house visited by the authors. Although the surface is covered with beautiful tiles, the internal structure is made of adobe. This visit was intended to examine any possibility of structurally improving the seismic resistance of existing houses. The improvement measure in mind was replacing heavy top roofs with lighter materials. The owner of this house stated during the visit that his family was scared now by earthquakes and slept under a table, which could provide good shelter. He also mentioned that the top roof had new mud added once every 4 years, and its present thickness was about 40 cm.

As shown in Photo 20 (b), the top roof is massive and replacement with a lighter material seemed to be very difficult, if not impossible, for ordinary families. Consequently, it is suggested by the authors that public support should be introduced for retrofitting existing houses, or that furniture that could provide shelter during strong tremors should be made available at reasonable costs.

For new construction, it is definitely a good idea to introduce light materials from an aseismic point of view, because masonry and adobe houses were destroyed by strong inertia force. However, more attention has to be paid to the local climate. People in an arid climate prefer adobe and masonry houses for the following reasons;

- low cost and local availability of materials,
- thermal insulation provided by adobe and masonry under intense sunshine during daytime, and

Photo 22. Other kinds of light temporary houses.

- heat storage in the daytime which warms the inside of the house during the cool night time.

It is, therefore, necessary that a proposed alternative material satisfies these requirements. A promising candidate for a construction material may be EPS (Expanded Polystyrene). This material is very light and has been used as a permanent material beneath road pavements; thus its durability has been verified. Moreover, countries with an oil industry can produce this material at low cost. Thermal insulation is evident. Therefore, EPS appears to be a good construction material for local people who wish to avoid the risk of the total collapse of their houses. Shortcomings may be the inability to provide heat storage and vulnerability to fire.

Photo 21 illustrates a new attempt to use EPS for the above-mentioned purposes. Large EPS plates were reinforced with steel so that their structural integrity could be maintained. Due to its good thermal insulation, this EPS house can provide good shelter for a year or so. Photo 22 shows other kinds of light house made of grasses and PVC. The latter may have problems during the hot daytime.

Another problem associated with EPS houses is their external appearance; see Photo 21. Because the economy of Bam city relies considerably on its historical environment and tourism, the appearance of EPS houses, which might make it difficult for tourists to enjoy the environment, is not welcome. There is a need for decorative EPS blocks to be developed.

The seismic fragility of adobe and masonry houses is a problem not only in Bam and Kerman. There are similar problems in many cities of the region, and historically tens of thousands of people have been killed during each major earthquake. Big cities in Iran are not exceptions, and the tragedy of Bam could be repeated in the near future on a much greater scale.

A recent news announced that a Japanese housing company has started a business of constructing permanent EPS houses. According to the information on WEB (http: //www.dome-house.jp/), this house offers a good living environment and an attractive appearance. The construction period is certainly short. For safety, the material is specially treated to reduce fire problems. By adjusting its design to meet local demands, therefore, it seems possible to sharply reduce the number of victims killed by heavy masonries.

11. Concluding remarks

Seismic damage in Bam city was investigated with emphasis on geotechnical aspects, and the following conclusions were drawn.

1) The subsoil in Bam city is hard and it is not considered to be a soft soil of the type that often triggers seismic problems in other regions of the world.

2) There is a sharp difference in damage between houses/buildings and other engineered structures such as bridges.

3) The seismic resistance of buildings made of masonry and adobes is extremely low.

4) It is very difficult to improve the seismic resistance of existing houses on a private basis. Some public support seems to be necessary.

5) Using any light material for buildings is a promising idea. An EPS permanent house is already available on the market.

6) Damage similar to that in Bam is possible in buildings in other large cities.

Acknowledgement

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2003年バム地震におけるバム市内の地盤と基礎構造の挙動

東畑郁生[1]・Abbas Ghalandarzadeh[2]・Habib Shahnazari[3]・Masoud Mohajeri[4]・Ali Shafiee[5]

[1] 東京大学大学院工学系研究科
[2] テヘラン大学土木工学科
[3] イラン工科大学
[4] 独立行政法人防災科学技術研究所
[5] イラン国際地震工学研究所

要　旨

2003年のイラン・バム地震の後，現地において被害調査を行なった。中心目的は地盤工学的被害であったが，橋梁や鉄塔の基礎および斜面には被害が見られず，大勢の犠牲者を出した家屋の倒壊とは対照的であった。また家屋の基礎の状況を視察したが，特に破壊と呼べるものは無かった。地盤調査によっても現地の地盤は軟弱とは言えず，現地の家屋のありかたに耐震性が欠如していると結論した。将来の安全性向上に向けて，軽量材料による建築と，既存家屋の中にシェルターを設けることを提案したい。ただし現地の風土，観光を中心とする経済を合わせ考えると，解決すべき問題は多い。