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# PILE FOUNDATIONS SUBJECTED TO LARGE GROUND DEFORMATIONS: LESSONS FROM KOBE AND RESEARCH NEEDS

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## ABSTRACT

While most of the research on the dynamic response of piles has in the last 20 years focused on the interaction between piles and soil, triggered either by the inertial forces of the structure or from the passage of seismic waves through the soil, the 1995 Kobe earthquake revealed in a most dramatic way that damage to piles can be caused by large ground displacements. On the other hand, pile foundations in many cases survived liquefaction-induced deformations of significant magnitude. The paper discusses the research needs in this field, in view of the lessons from Kobe.

## KEYWORDS

Pile Foundation; Earthquake Engineering; Seismic Damage; the 1995 Kobe earthquake; Ground Deformation; Liquefaction.

## INTRODUCTION

The Hyogo-ken Nanbu earthquake, simply known as the Kobe earthquake (Japan Society of Civil Engineers, 1995), a direct-below-land type earthquake occurred on 17th January, 1995. It measured a magnitude of 7.2, caused about 6300 deaths and unprecedented human suffering. With the progress of damage investigation and the restoration activities, the research and development needed to mitigate similar damage are gradually being clarified. In general, much time and expense are required to discover the damage to piles, because piles are in-ground structures. While damage to building and highway bridge pile foundations from the Kobe earthquake has been reported (Shamoto, *et al.*, 1995, 1996, Mizuno, *et al.*, 1995, Nagai, 1995, Oh-oka, *et al.*, 1996, Tokimatsu, *et al.*, 1996), these reports are just beginning to be filed, and it will take time to elucidate the extent of damage to pile foundations.

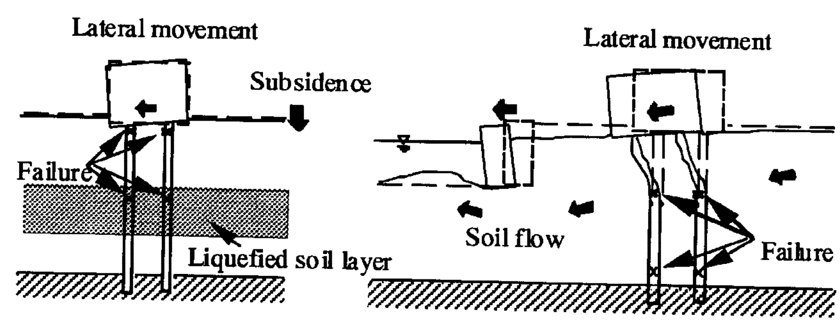
During the Kobe earthquake, extensive ground liquefaction and liquefaction-induced ground movement took place in uncompacted reclaimed lands along much of the shoreline on the north side of Osaka Bay. A salient characteristic of pile damage due to ground liquefaction and liquefaction-induced ground movement is that the damage may occur not only at the pileheads but also in the middle portions and at the pile-tips. In the cases where damage occurred in the middle portions and at the pile-tips, identification and retrofitting become impractical and expensive, when compared to damage at the pileheads.

What should we do in order to mitigate such damage? What were the predominant external causes? How can we find out which parts of the in-ground piles were damaged? How should the damaged piles in the ground be repaired? These are simple and important questions in view of the damage in the Kobe earthquake. This paper states various thoughts on pile foundation earthquake engineering research and development subjects which demand close investigations as indicated by the damages caused by the Kobe earthquake.

## SEISMIC DAMAGE

Although seismic damage to pile foundations has been an area of great interest in past large earthquakes, little is known about damage to pile foundations compared to that to superstructures, due to survey limitations of in-ground structures. Mizuno (1987) surveyed 28 cases of seismic damage to pile foundations. This was caused by seven large earthquakes which occurred in Japan during a sixty-year period from the 1923 Great Kanto earthquake to the 1983 Nihonkai-Chubu earthquake. They are classified into five categories based on predominant external causes of damage, as follows: (1) Lateral displacement of cohesive and/or organic soil, (2) Failure and movement of embankment or earth fill, (3) Ground liquefaction and liquefaction-induced ground movement of sandy soil, (4) Vibration effects of the soft soil deposit, (5) Vibration effects of the superstructure and resulting inertial forces. The pile damage patterns were classified into four types as follows: (a) Shear and compressive failure of pileheads involving subsidence, (b) Ring-type cracks due to bending moment (no subsidence), (c) Separation of pile and pile cap, (d) Pile welding joint buckling failure. Mizuno drew the following conclusions: compared to steel piles, the damage to precast concrete piles, especially AC piles (precast centrifugally compacted autoclaved prestressed concrete pile; pre-tension prestressing) and PC piles (precast centrifugally compacted prestressed concrete pile; pre-tension prestressing), is significant. AC and PC pile damage patterns exhibit not only ring-type cracking due to bending moment with no subsidence, but also failure with subsidence. From retrofit and underpinning cost viewpoints, pile failure with subsidence should be prevented. The effects of ground shaking on piles during earthquakes should be included in seismic design.

Shamoto *et al.* (1995, 1996) surveyed the seismic damage to pile foundations in 14 cases caused by the 1995 Kobe earthquake. The surveyed buildings were constructed on artificial fill deposits or near waterfronts with evidence of ground liquefaction. Damage was governed by ground liquefaction or liquefaction-induced ground movement. They found that the damage is mainly of two types: ground liquefaction and liquefaction-induced ground movement as shown in Figure 1. Figure 1 (a) shows the damage pattern caused by ground liquefaction. Lateral soil resistance to the piles was diminished due to liquefaction; consequently, the piles suffered cracking or crushing not only at the pileheads but also at the boundaries between liquefied and unliquefied soil layers. Figure 1 (b) illustrates the damage pattern caused by liquefaction-induced lateral ground movement. Piles of structures located near the waterfront suffered damage by liquefaction-induced ground movement of the sandy soil filled to the back and the base of the quaywall or revetment. Failure occurred in the middle portions of piles and/or at the pile-tips.




(a) Damage pattern by ground liquefaction

(b) Damage pattern by liquefaction -induced ground movement

Fig. 1. Damage patterns caused by ground liquefaction and liquefaction -induced ground movement (Shamoto, *et al.*, 1995)

Another example of pile deformation is shown in Figure 2, in terms of pile deformation angle. The superstructure is a girder-type road bridge, length = 50 m across a river. The abutments of the two sides of the bridge are supported by 45 piles each. The diameter and length of the piles are 0.50 m and 34 m, respectively. The piles consist of three parts: the upper part is an eight meter long composite pile of steel pipe and concrete, and the middle and lower parts are thirteen meter long PC sections. Lateral movement of the ground surface induced by liquefaction was about 1 m. It can be seen from Figure 2 that between 5 m - 12 m from the pilehead sever damage may have occurred, because the change in the deformation angle becomes significant at that point. An interior inspection, carried out with a fiberscope, revealed many cracks on the concrete between 9 m to 18 m from the pilehead.

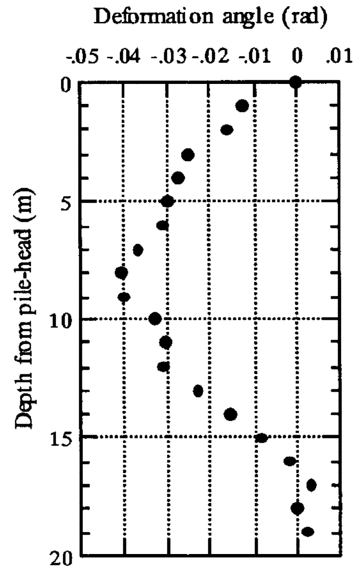


Fig. 2. Measured deformation angle of pile damaged by liquefaction-induced ground movement during the 1995 earthquake (Shamoto, *et al.*, 1996)

In order to develop a clear understanding of the mechanics of such failures several tools are available and must be utilized to their fullest extent: shaking table tests at 1-g, centrifuge model tests, and numerical analyses. Comparison of the results of such tests with carefully-conducted field measurements will help in providing answers to some of the questions posed in the introduction. Furthermore, developments in counter-measures to mitigate damage to piles, in nondestructive testing methods to investigate damage and severity of that damage to parts along piles, and in strengthening damaged pile foundations are also crucial.

## SHAKING TABLE TEST AND SEISMIC OBSERVATION

Sato *et al.* (1996) carried out shaking table tests of pile foundation structure systems utilizing centrifuge modeling to clarify the dynamic behavior of piles caused by liquefaction-induced ground movement. Figure 3 shows the testing model which was conducted on a 1/30 scale. The structure which is supported by six piles was constructed on sandy soil behind a caisson-type quaywall. The model was constructed in order to simulate the actual behavior of a particular building damaged in the Kobe earthquake. A laminar shear box was used in the tests. The maximum bending moments along the piles were obtained as shown in Figure 4. From this figure, it can be evaluated that damage may occur at the middle part four meters downward from the pilehead of pile A and at the pilehead in pile B, which were located near to and far from the quay, respectively. This damage pattern is similar to that of the three-story RC building investigated by Oh-oka *et al.* (1996) which is examined later.

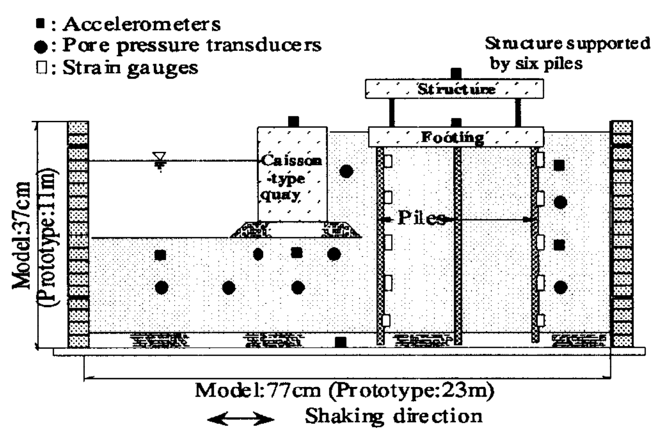


Fig. 3. Centrifuge testing model of a pile-foundation-structure system in a laminar shear container (Sato, *et al.*, 1996)

In recent years, the use of centrifuge modeling has become increasingly accepted as an appropriate technique for geotechnical problems. Centrifuge modeling, as well as the 1-g modeling (Kagawa *et al.*, 1995), is very important when investigating the causes of actual damage due to ground liquefaction.

Tazoh *et al.* (1987) and Shimizu *et al.* (1992) carried out seismic observations on a road bridge and a 12-story building, respectively, constructed on soft soil deposit. These observations were made with accelerometers, strain meters, and pore water pressure meters on the superstructure, its foundation piles, and the ground. The observations aimed at investigating the actual response of piles and the predominant factors causing stresses and deformations in piles. As a result of the observations, the following conclusions were drawn. The axial strains on the piles decrease with the depth of the piles, but the bending strains are large not only at the pileheads, but also at the boundaries of soil layers where the stiffness varies significantly. The bending strains of the pileheads are primarily affected by superstructure inertia, while those at the pile-tips are significantly affected by ground shaking (Gazetas *et al.*, 1993).

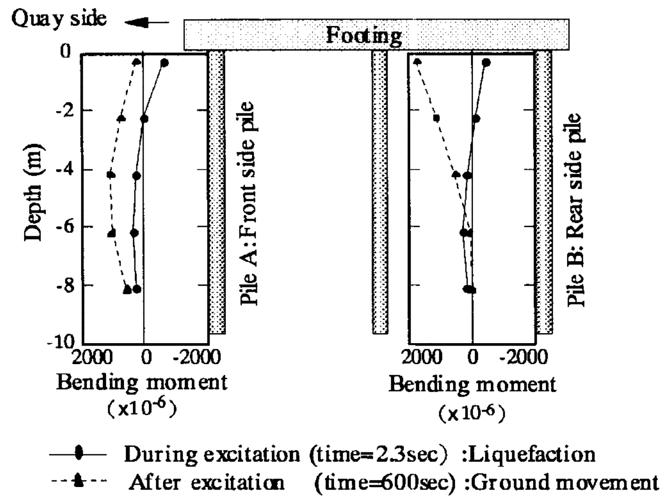



Fig. 4. Maximum bending moment along piles (Sato, *et al.,* 1996)

## EARTHQUAKE RESPONSE ANALYSIS TAKING INTO ACCOUNT GROUND LIQUEFACTION AND LIQUEFACTION-INDUCED GROUND MOVEMENT

It is obvious from the damage patterns during the Kobe earthquake that analytical studies on the earthquake response analysis of pile foundation structure systems which take into account ground liquefaction and liquefaction-induced ground movement are quite important.

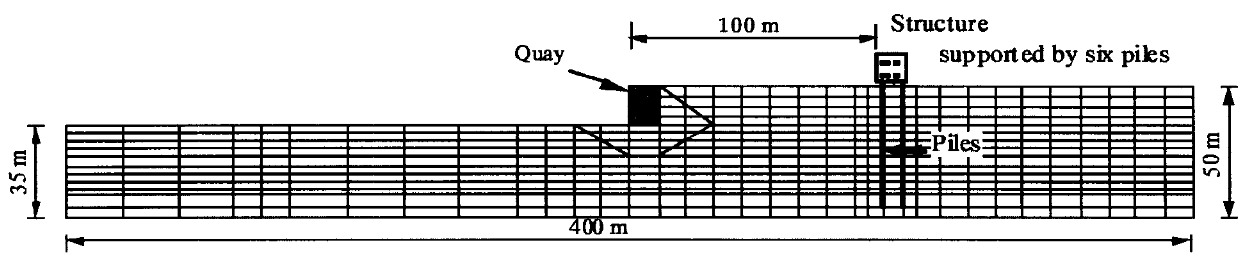



Fig. 5. FEM model for ground liquefaction and liquefaction-induced ground movement (Fuchimoto, *et al.*, 1996)

Fuchimoto *et al.* (1996) studied the earthquake response analysis of a building which was damaged in the Kobe earthquake. Taking into account ground liquefaction, the study validates the theory, and investigates the predominant cause of the damage to the pile foundation. The damaged building is a two-story office building supported by six PHC piles (PHC pile; pretensioned spun high strength concrete pile; d = 400 mm from pilehead to 30 m below, and d = 300 mm from 30 m below to pile-tip, l = 42 m).

Two-dimensional effective-stress analysis was implemented to examine the dynamic behavior of the piles during ground liquefaction. Figure 5 shows the analytical model. Modified Ramberg-Osgood model and the Bowl dilatancy model were used for the stress-strain and stress-dilatancy relationships, respectively. The analysis for the liquefaction-induced ground movement was conducted pseudo-statically, accounting for soil degradation due to development of pore water pressures; the latter were obtained from effective stress analysis. A static analysis is justified since liquefaction-induced ground movements often occur after the shaking has stopped.

Figure 6 plots the computed horizontal deformations versus depth. It can be seen that failure may occur at the pilehead, the middle part of the pile, and the pile-tip. The failures are apparently caused by large ground deformation due to liquefaction. The pile failure modes obtained from the analysis are compatible with those based on the damage investigation by Shamoto *et al.* (1995).

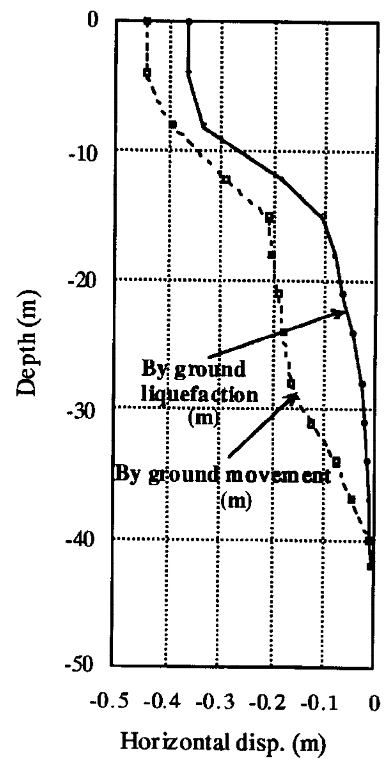



Fig. 6. Maximum horizontal displacement of pile (Fuchimoto, *et al.*, 1996)

## NONDESTRUCTIVE TEST FOR IDENTIFYING PILE DAMAGE

In cases where subsidence and/or tilting occurs to buildings supported on piles, it should be presumed that there are some problems with the piles. For investigation of such damage, direct visual inspection by excavation around the pilehead is usually adopted. However, in most cases excavation can not be possibly carried out. Moreover, damage by liquefaction may occur not only at the pileheads, but also in the middle parts and tips. It is quite difficult, except in some special cases, to excavate along the entire length of the piles. For the reconstruction of damaged buildings, it is then necessary to have sufficiently accurate knowledge of how serious the damage to piles is and where it occurred. It is also important to have detailed knowledge of the damage in order to examine countermeasures for retro-fitting and strengthening. Consequently, the development of reliable inspection methods, especially nondestructive methods, is necessary.

Oh-oka *et al.* (1996) conducted televiewer observation and integrity sonic tests on piles (PC pile; d = 400 mm, l = 20 m) of a three-story RC building damaged by liquefaction-induced ground movement during the Kobe earthquake. As a result of the investigation, the damage shown in Figure 7 was observed. The televiewer

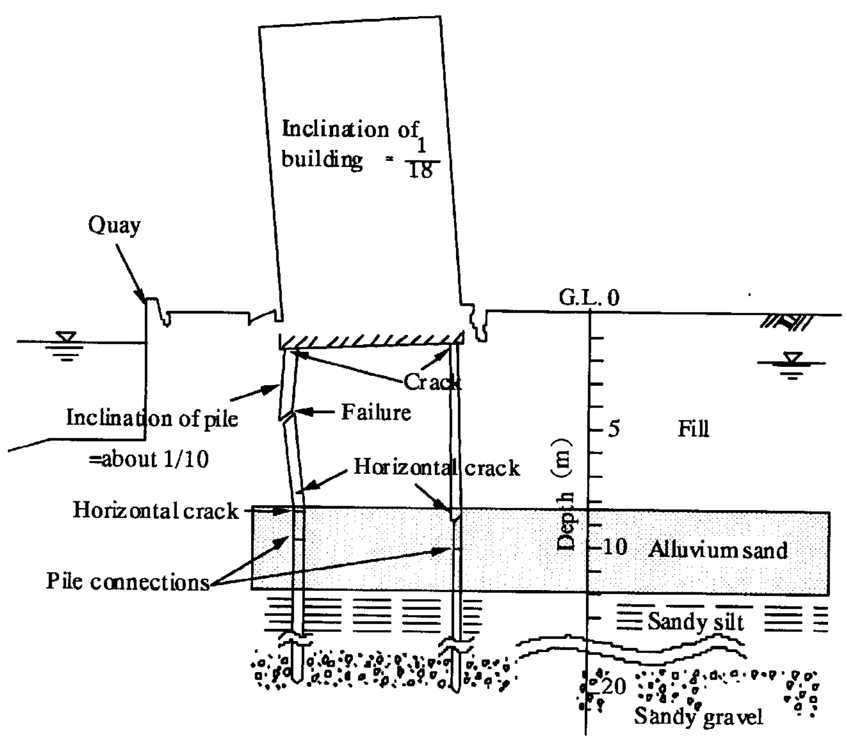



Fig. 7. Seismic damage to pile foundation of a three-story building by liquefaction-induced ground movement during the 1995 Hyogo-ken Nanbu earthquake (Oh-oka, *et al.*, 1996)

observation detected both diagonal cracks at a depth of 4.5 m and horizontal cracks at a depth of 9 m. On the other hand, the pile integrity tests identified only the cracks nearest to the pileheads. In both cases, the depths of the detected cracks corresponded approximately to the boundaries between soil layers where stiffness varies significantly.

Mori *et al.* (1995) proposed a new nondestructive testing method for detecting concrete pile damages utilizing acoustic emission effect. These authors noticed that an acoustic emission is discharged from damaged parts of the concrete pile to which the body force of the superstructure is applied. An outline of this method is sketched in Figure 8. Acoustic emission sensors are installed into boreholes near the piles to detect the acoustic emission discharged from the damaged parts of the pile. This new method has great merits in that there is no need to expose the pilehead as in integrity sonic tests.

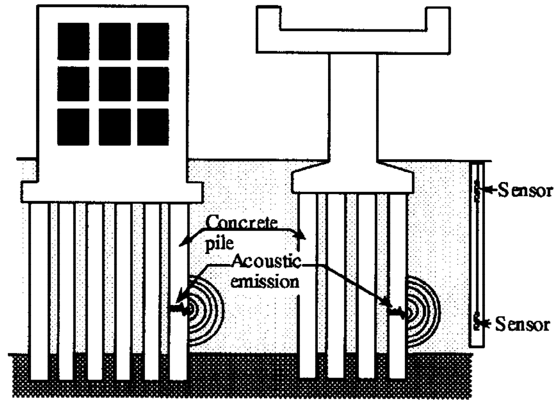


Fig. 8. New nondestructive testing method for detecting concrete pile damage utilizing acoustic emission effect (Mori, *et al.*, 1995)

## RETROFIT OF DAMAGED PILE

A great amount of damage occurred to cast-in-place concrete piles of highway bridge piers during the Kobe earthquake. Especially severe was the damage to the piles of the bridges of the Harbor Highway. These bridges link the artificial islands with the coast of Kobe, and were therefore founded through soils that experienced large flow-type deformations. Since the girders and piers of the bridges suffered only slight damage, it was decided that only the pile foundations should be strengthened in the restoration of the bridges. To be precise, 151 piers of a total 225 bridge piers were judged to be in need of repair and/or strengthening. In regard to restoration methods, 75 piers will be strengthened by increasing the number of piles and 76 piers will be strengthened through soil improvements (Nikkei Construction, 1995).

There are many technical aspects to strengthening damaged piles. For example, if the piles are to be strengthened by increasing their number, how should the existing damaged piles be evaluated? In the case that additional piles are constructed near existing piles, there may be no remarkable efficiency because of pile group effect. How can we evaluate the effect of soil improvement on the future seismic performance of the piles? It is clearly important and urgent for seismic restoration that considerable progress be made in research and development on design and construction techniques for strengthening of damaged piles.

## COUNTERMEASURES TO EXISTING STRUCTURE AGAINST LIQUEFACTION MOVEMENTS

Many structures suffered from ground liquefaction and liquefaction-induced ground movement during the Kobe earthquake as mentioned above. Existing structures in other seismic areas have a possibility of being damaged in ways similar to those experienced in the Kobe earthquake. Therefore, countermeasures must be taken with existing structures against liquefaction. To this end, it is necessary to consider a number of different factors as they were made clear from the results of the earthquake.

Figure 9 shows examples of countermeasures to existing above-ground oil tanks (Suzuki *et al.*, 1995, Sakemi *et al.,* 1995). Sheet piles are constructed in ground, surrounding the tank to restrain the shear deformation of the ground under the tank in order to mitigate against ground liquefaction. The effectiveness of the proposed countermeasures has been clarified through seismic observation, finite element analysis, and vibration tests using centrifuge modeling. It is necessary that countermeasures to existing structures should be both effective and inexpensive.

Many quays and revetments were moved laterally a few meters toward the sea or river by liquefaction-induced ground movement during the Kobe earthquake. Economical countermeasures against such damage should also be developed. Figure 10 represents a new low-cost countermeasure applicable to quays and revetments proposed by Yamada *et al.* (1996) in which braced soil-cement mixing-walls is coupled with vertical ones. The effectiveness of this countermeasure has been studied both numerically and in the centrifuge.

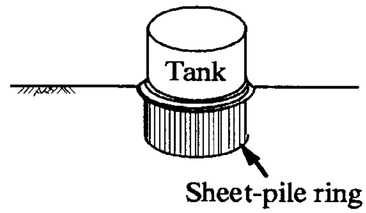



Fig. 9. Countermeasure for existing oil tank using sheet-pile ring (Suzuki, *et al.*, 1995)

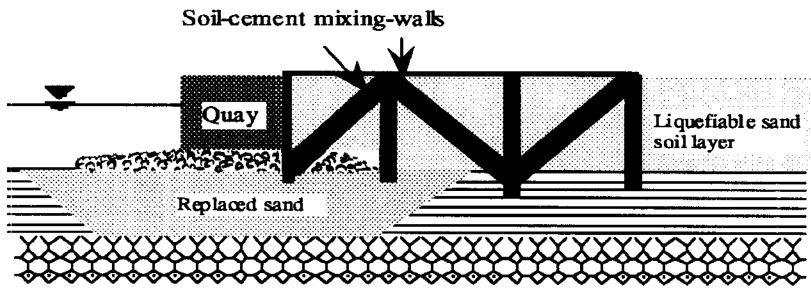



Fig. 10. Countermeasure against liquefaction using inclined and vertical soil-cement "walls" (Yamada, *et al.*, 1996)

## CONCLUSION

It is hoped that the lessons learned from the 1995 Kobe earthquake will help in developing strategies to minimize the extent of damage in future strong earthquakes.

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