Advances in Earthquake Engineering

Volume 1

Series Editors: D.E. Beskos & E. Kausel

The Kobe Earthquake: Geodynamical Aspects

Editor:

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Wessex Institute of Technology, Southampton, UK

Computational Mechanics Publications
Southampton Boston

Series Editors
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Published by

Computational Mechanics Publications
Ashurst Lodge, Ashurst, Southampton, SO40 7AA, UK
Tel: 44(0)1703 293223; Fax: 44(0)1703 292853

For USA, Canada and Mexico

Computational Mechanics Inc
25 Bridge Street, Billerica, MA 01821, USA
Tel: 508 667 5841; Fax: 508 667 7582

British Library Cataloguing-in-Publication Data

A Catalogue record for this book is available
from the British Library

ISBN 1 85312 430 3 Computational Mechanics Publications, Southampton
ISBN 1 56252 345 7 Computational Mechanics Publications, Boston
ISSN 1361 617X Series

Library of Congress Catalog Card Number 95-70470

Printed and bound in Great Britain at Hobbs the Printers Limited, Southampton.

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Chapter 1

The seismotectonic setting of the Kobe area (Japan) - the concomitant geodynamic phenomena of the Hanshin Earthquake (17 January 1995)

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Abstract

The seismotectonic setting of the southern Hyogo prefecture, which was struck by the earthquake of 17 January 1995, is outlined and the characteristics of the seismic sequence are given. Next, certain tectonic features of the reactivated fault zone, which runs through Kobe-Nishinomiya, are presented. The linear distribution of the damage along this fault zone is then shown. Finally, a brief report on the concomitant geodynamic phenomena (landslides and liquefaction) is given, the impact of which was particularly intense.

1 Introduction

The earthquake of 17 January 1995 that took place in the area of Kobe (south-western Japan), also known as the Hanshin or Hyogo-ken Nanbu Earthquake, caused both extensive damage and resulted in numerous victims. According to the official data of 23 February 1995, 5426 people were killed, 26 804 were injured, and more than 300 000 were made homeless. In addition, about 105 000 buildings collapsed or were damaged beyond repair, while a far larger number of buildings suffered minor damage.

The initial estimations showed that the direct cost of the earthquake would amount to 7 trillion ¥, while the long-term impact is expected to be many times more. This is because certain vital components of the financial infrastructure were struck, such as the industrial-commercial port of Kobe, a part of the heavy industry (the area of Hyogo accounts for 17% of the total industrial production of Japan) and the transportation network (highways and trains), which, it has to be noted, is the only terrestrial link between northern and southern Japan. Besides, from the social aspect, the impact on the population was grave, in spite of the fact that the people in Japan are both familiar with and prepared for earthquake emergency cases. This is partly due to the extent of the destruction in an area considered to be of relatively low seismic risk.

In this paper, and after we have given a brief presentation of the seismotectonic setting of the area and the characteristics of the seismic activity of 17 January 1995, we shall describe the strikingly unequal distribution of the damage in the city of Kobe. We shall also present some interesting geodynamic phenomena which radically augmented the extent of the damage and the influence of the earthquake, in general.

2 The geodynamic - seismotectonic setting

The greater area of Kobe, as the Japanese territory is known in its entirety, is characterised by a complex regime of geodynamic evolution and tectonic deformation. This is the direct result of the fact that the Japanese territory is actually where the subduction zones of three tectonic plates exist; that is to say, of the Eurasian plate which overthrusts the Pacific and the Philippine Sea plates. The latter is wedged between the other two, at the area south of Japan and also overthrusts the Eurasian plate (Fig. 1).

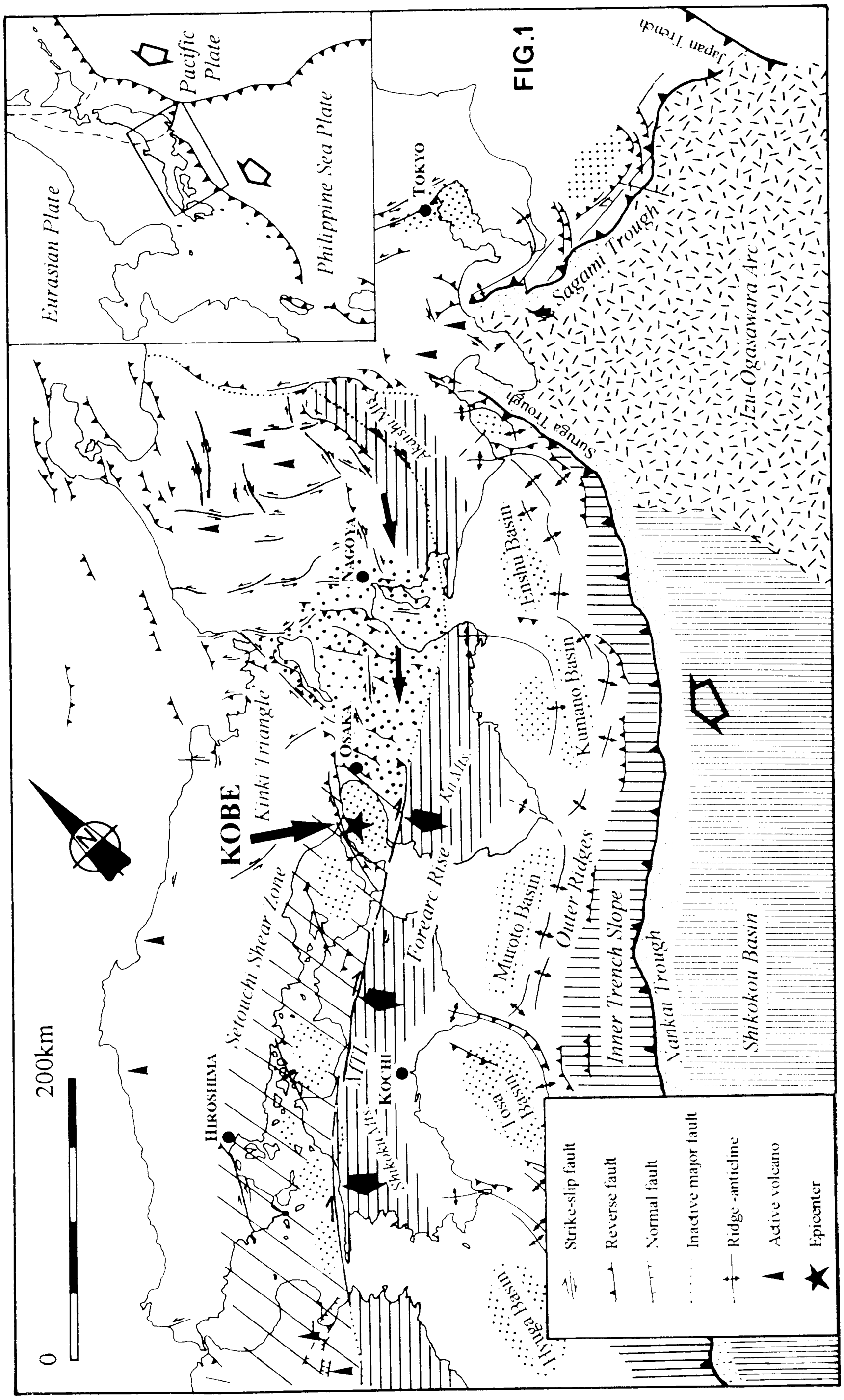
This complex geodynamic setting determines the prevailing geological procedures and structures both on a regional and local level. These are characterised by a general EW compression, giving rise to local transpressional structures (strike-slip structures with a component of shortening across them) (Ishibashi [1]).

The greater area of Kinki i.e. Osaka, Kobe and Kyoto, as well as the offshore regions, together with Awaji Island (Awajishima), is characterised by the presence of such a structure, namely a first-order fault zone (Median Tectonic Line), of pure dextral strike-slip (The Research Group for Active Faults in Japan [2, 3]). This EW trending zone runs south of Awaji Island and the Gulf of Osaka (Fig. 2).

The existence of this fault zone leads to the creation of smaller order tectonic structures present at its northern segment; these structures are arranged in step-like (en échelon) fashion. The dominant trend of these structures is NNE - SSW, bending to NE - SW towards the north. Typical examples of such structures are the tectonic horst of the Rokko Mountains and the graben of the city of Kobe. This picture is, of course, highly simplified, as there is in fact a multitude of alternating horsts and grabens, with relative rotations along their boundaries and complex fault sets.

In particular, the uplifting block of the Rokko Mountains is an autonomous neotectonic unit consisting mainly of geological formations of the pre-Pliocene age. These formations are mainly igneous granites and dykes.

On the other hand, at the subsiding block the outcropping formations are mainly sedimentary rocks, sandstones, clays, marls and volcanic tephra, and various formations of the Miocene - Holocene age (Itahara *et al.*[4], Itahara [5]).


Eurasian Plate
Pacific Plate
Philippine Sea Plate
TOKYO
Japan Trench
Sagami Trough
Izu-Ogasawara Arc
Suruga Trough
Akaishi Mts
NAGOYA
Enshu Basin
Kumano Basin
OSAKA
Kinki Triangle
KOBE
Kii Mts
Forearc Rise
Outer Ridges
Muroto Basin
Inner Trench Slope
Nankai Trough
Shikokou Basin
Setouchi Shear Zone
HIROSHIMA
KOCHI
Shikoku Mts
Tosa Basin
Hyuga Basin
0
200km
Strike-slip fault
Reverse fault
Normal fault
Inactive major fault
Ridge -anticline
Active volcano
Epicenter
FIG.1

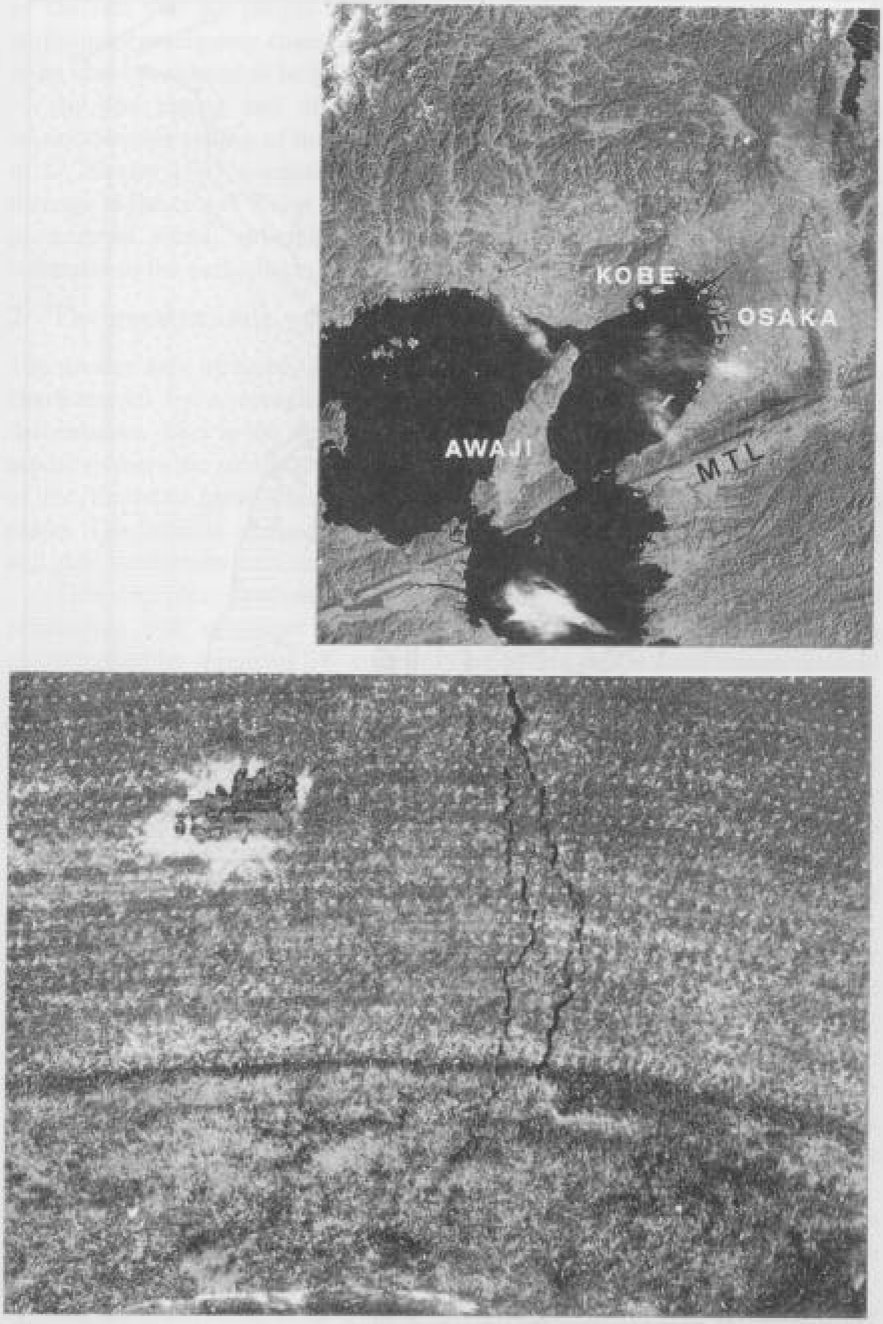


Figure 2: Satellite image of Kinki and adjacent areas including Awaji Island, where the reactivated Nojima Fault lies. (MTL: Median Tectonic Line)

These two tectonic units are divided by complex fault sets, which constitute a NE-SW bearing fault zone. Some segments of this fault zone are visible, towards the flanks of the basin, at the foot of the Rokko Mountains and the outskirts of the urban area, while others are located in the city and are covered either by alluvials or by urban structures. The continuation of some faults, though, is visible either towards the NE, outside the urban region, or to the SW, on Awaji Island.

The faults that compose this large fault zone are active tectonic structures, which did not manifest increased activity, according to the existing seismological data (RCEP-DPRI [6]). On the contrary, the activity at the region located to the northeast of the fault zone had been quite pronounced, as shown by the number of microtremors recorded.

The main shock of 17 January 1995, and the seismic sequence in general, resulted in the reactivating of certain faults comprising the fault zone. The main tremor was due to the fault that crosses the Akashi Straits, the channel between the city of Kobe and Awaji Island. The result was the reactivation of the Nojima Fault, which actually determines the northwestern coast of the island. This fault strikes N40° - N50° E and dips 75° - 80° towards the NE and presents a maximum horizontal (dextral) slip of 1.7 m and a maximum vertical slip of 1.3 m (Figs 3, 4). The survey showed that the fault had been reactivated for a length of approximately 9 km; its continuation in the Akashi Straits, where the waters became brownish, is more than probable. The emergent fault surface cut through Plio-Pleiostocene and alluvial formations and was planar for sections of up to 200 m in length. Locally, it was in a step-like (en échelon) arrangement, a fact that was in accordance with the dextral-slip sense of the seismogenic fault.

3 The Hanshin earthquake

On 17 January 1995 at 05:46 (local time) an earthquake of magnitude M=7.2 occurred. Its epicentre lay offshore Kobe, at the Akashi Straits (34.6° N, 135.0° E). The focal mechanism was of dextral strike-slip, attributed to the general EW compression Japan undergoes nowadays (Ishibashi [1]) (Fig. 3). The seismic fault was estimated to have a length of 40 - 60 km (RCEP-DPRI [6]).

Two foreshocks preceded the main event by approximately 12 hours and they both originated in the same fault zone (Fig. 3). The aftershock sequence included about 6000 events, the largest of which was of magnitude M=4.9 and took place two hours after the main shock. The decrease in time of the aftershocks was normal and fits the Ohmori formula (RCEP-DPRI [6]).

The scientific groups of the nearby universities and institutes reported certain phenomena that could be considered precursory, such as: (i) crust deformations that took place in the vicinity and continued well after the tremor, (ii) abnormal behaviour of animals on Awaji Island, (iii) the above-mentioned foreshocks, (iv) irregular recordings of electromagnetic signals both of high and

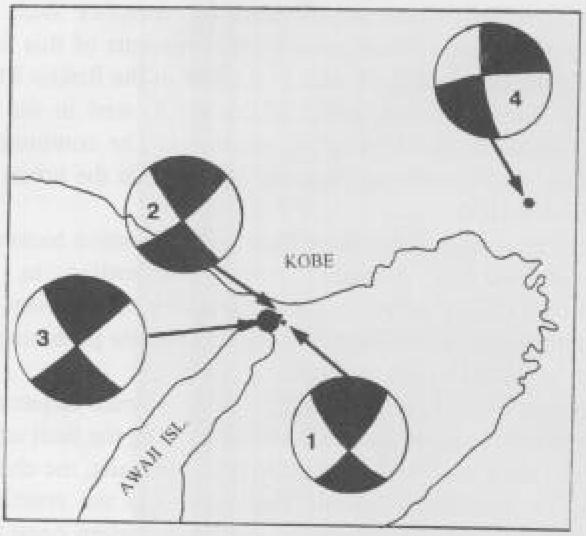


Figure 3: Focal mechanisms (stereographic projection - upper hemisphere) of the foreshocks (1 & 2), the main tremor (3) and the main aftershock (4).

Figure 4: A portion of the surface of the reactivated Nojima Fault showing the relative movement between the fractured blocks.

low frequency, (v) disturbances in the sea water temperature and (vi) disturbance of the physical and chemical properties of subsurface water.

As already mentioned, the earthquake of 17 January 1995 is due to dextral faulting. In fact, the faulting mechanism displays significant strike-slip, which prevails over the vertical component. The focal mechanism solution comes in agreement with the reactivated Nojima Fault on Awaji Island. The latter displayed a maximum horizontal slip of 1.7 m and a vertical slip of 1.3 m; its reverse character, too, is clear. The reactivated portion of the fault is particularly apparent for about 9 km, running parallel to the western coast of the island. However, inside the city of Kobe, and due to intense urbanisation, no indisputable outcrops of an activated fault were observed. Nevertheless, certain cracks, judging from the geometrical and tectonic analysis that was carried out, could be seismic fractures.

The aftershock distribution is impressively linear, trending NE - SW and runs through Awaji Island, the Akashi Straits and the city of Kobe-Nishinomiya. In fact, the spatial distribution of the epicentres determines the trace of the activated fault zone, which, as already mentioned, actually bounds the neotectonic graben of Kobe. Figures 5, 6 and 7 show the distribution, the focal depth and the time-space distribution of the aftershocks and in Fig. 8 the maximum accelerations and velocities recorded during the main shock are given. In this picture, one can also observe the increased values along the seismic fault.

4 The spatial distribution of the damage

The earthquake of 17 January caused extensive damage throughout the city of Kobe-Nishinomiya. In the urban area, there were locations that gave an impression of total devastation.

After the initial recording and mapping of the damage, the first conclusion that can be drawn is the linear distribution of them along a NE-SW trending zone 25 km in length by approximately 1 km in breadth; along this zone the intensities were of grade 7 (the maximum in the Japanese intensity scale) (Figs 9, 10). On the other hand, the recorded intensities outside this narrow zone were significantly lower, with some exceptions of isolated islets of high values, as a result of the manifestation of concomitant geodynamic phenomena (Fig. 11).

The elongated development of the high intensity zone coincides with, and is a result of, the occurrence of a fault, or better, numerous faults that were reactivated. It has to be noted that the epicentre of the main event lay at the continuation of this zone offshore in the Akashi Straits. On top of that, the foci of the aftershocks are inside the zone of maximum intensities and present, as already mentioned, a well-expressed linear distribution. These facts determine the crucial impact of seismic faults on the manifestation of damage.

The case of this earthquake is perhaps the most representative example of such a correlation. Similar ones that can be found for recent earthquakes in the

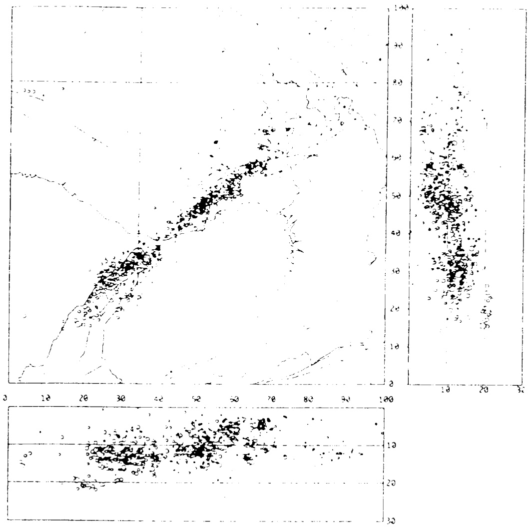


Figure 5: Epicentre distribution of the seismic sequence, with a well-defined linearity that marks the activated fault zone, from RCEP-DPRI[6].

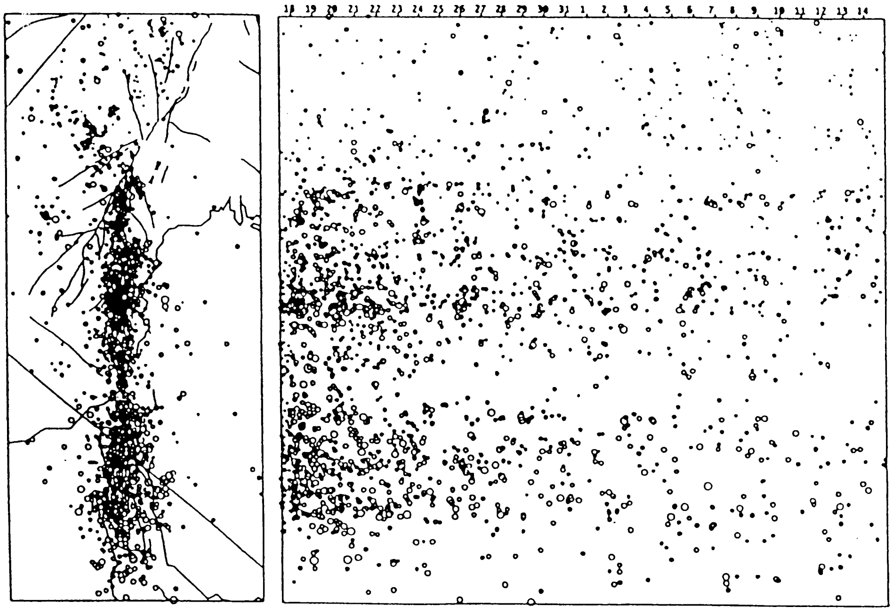


Figure 6: Time-space distribution (17 January - 14 February) of the foci of the seismic sequence, from RCEP-DPRI[6].

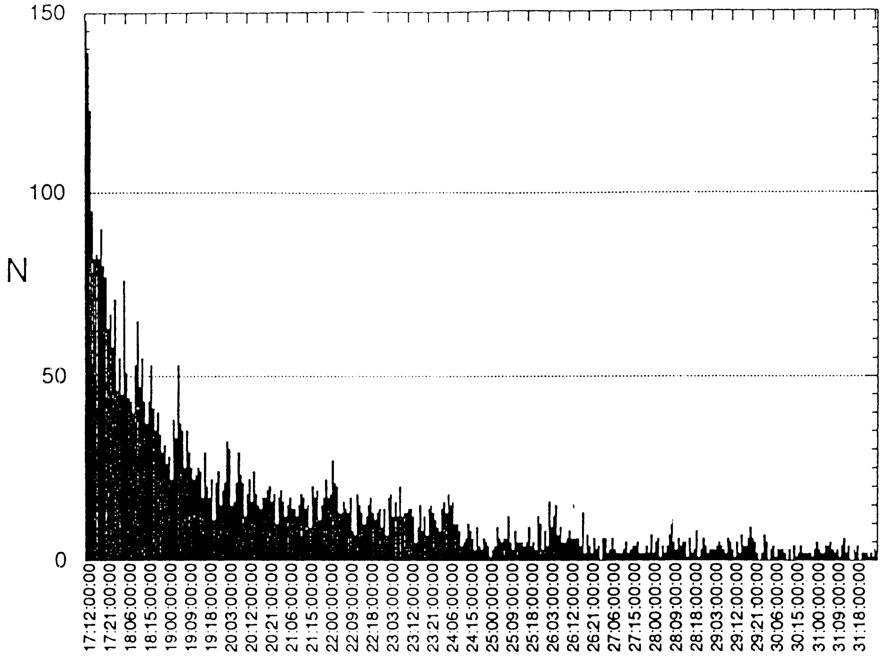


Figure 7: Cumulative number of aftershocks from 17 January to 31 January (Source: RCEP-DPRI[6]).

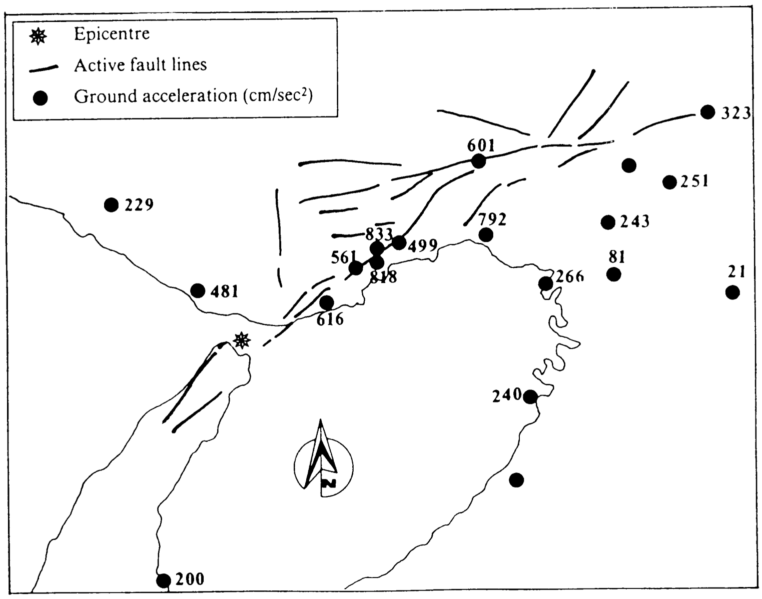


Figure 8: The peak ground accelerations during the main tremor. The values are particularly high along the reactivated fault zone. (Source: RCEP-DPRI[6]).

Figure 9: Distribution of deaths in the urban area of Kobe - Nishinomiya along the activated fault zone.

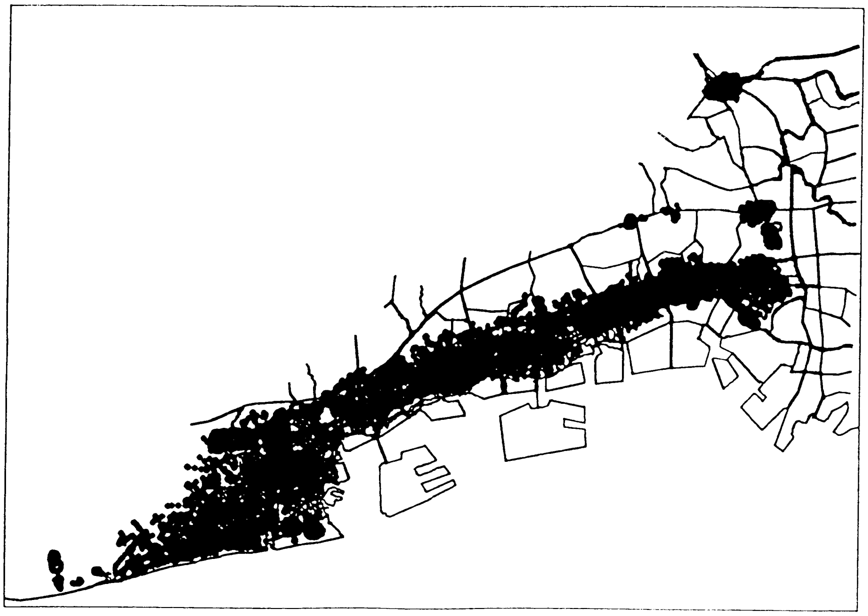


Figure 10: Distribution of collapsed buildings in the urban area of Kobe - Nishinomiya along the activated fault zone.

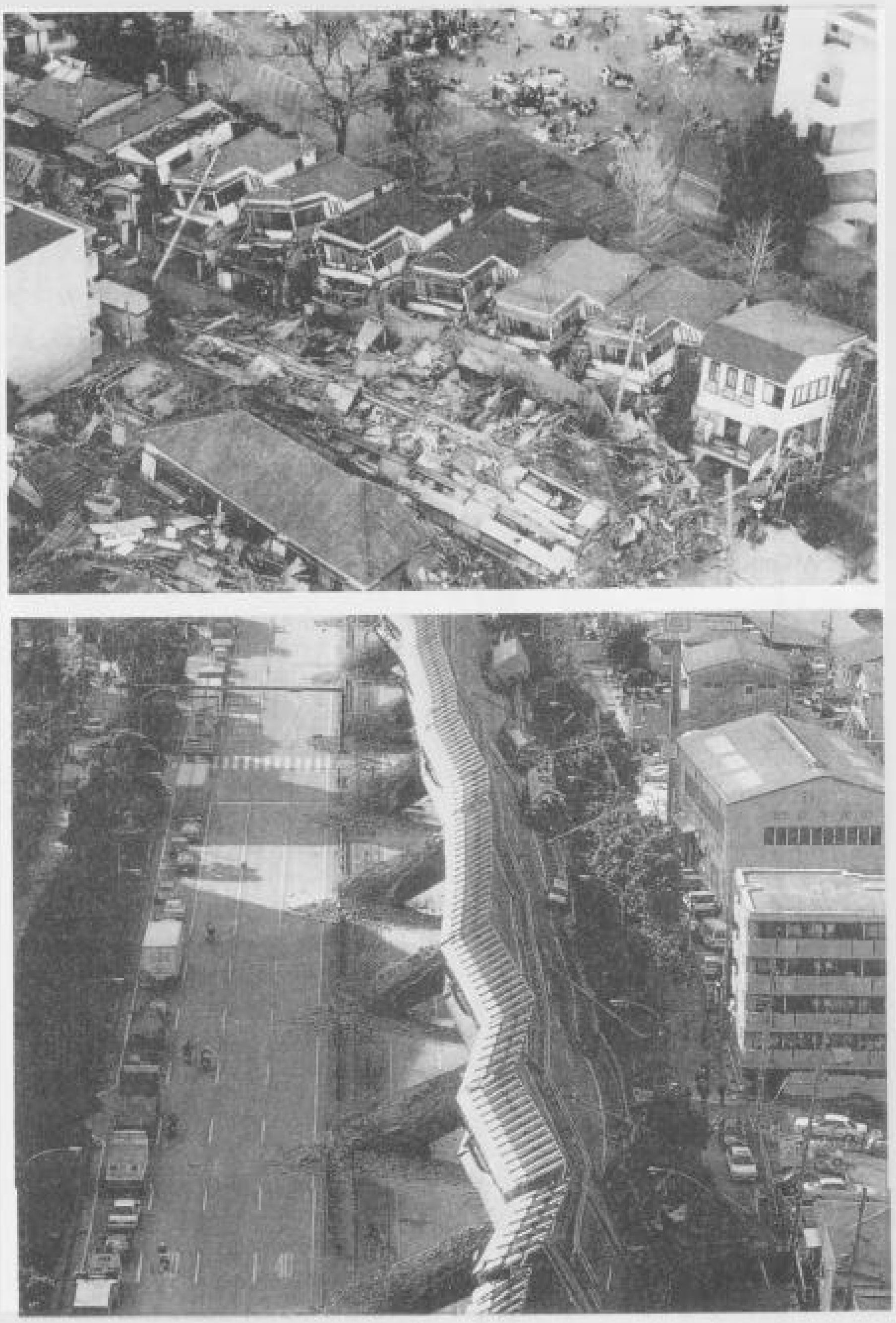


Figure 11: Damage in wooden houses and the highway during the Hanshin Earthquake.

Hellenic territory, the most characteristic being the one in the Pyrgos area (Lekkas[7]).

5 The concomitant geodynamic phenomena

5.1 Landslides

During the Hanshin Earthquake, a considerable number of landslides occurred, both inside and outside the urban area and to the north, where Mount Rokko lies.

On-site investigation and the examination of aerial photos and satellite images showed that the majority of landslides occurred in the vicinity of Mount Rokko, the slopes of which consist mainly of igneous formations. It must be remembered that the mountain is an uplifting horst. The main features of the landslides are as follows:

(i) The dimensions of the landslides were small, not exceeding, in most cases, 10-20 m.

(ii) The dominant trend of the collapsed slopes was NE - SW.

(iii) The slope dips were considerably high, about 60°.

(iv) The landslides were far more numerous than the rockfalls and occurred on the soil cover or on the weathered upper parts of the geological formations.

(v) All landslides occurred at a distance not greater that 4 km from the activated fault zone.

(vi) Many landslides occurred along the traces of the minor faults that constitute the fault zone, or on the slopes of deeply incised currents; this incision is encouraged by the fact that the area is actually an uplifting tectonic block.

(vii) Finally, the landslides that occurred outside the urban area caused minor damage, mainly to the road network and open-air recreational areas.

On the other hand, the landslides that occurred inside the urban area resulted in the loss of human lives, as well as material damage. (Fig. 12) These landslides were bigger in dimension, up to 100 m. This differentiation is attributed, according to the data collected so far, not only to the proximity of the slide locations with the activated fault zone, but also to the extent of human interventions with the natural environment, that is to say buildings, roads and the formation of artificial slopes.

5.2. Soil liquefaction

The main tremor resulted in widespread liquefaction, mainly along the coastal zone. The liquefaction caused extensive damage to buildings - mainly the smaller-scale ones - and roads, while large areas remained unreachable as they had been covered by the emergent liquefied ground material.

The existing geotechnical data and the on-site survey confirmed the fact that the manifested liquefaction took place mainly at the areas of reclaimed land, which are mainly used for harbour extension and, secondarily, housing. Besides, liquefaction occurred in the areas covered by coastal and alluvial

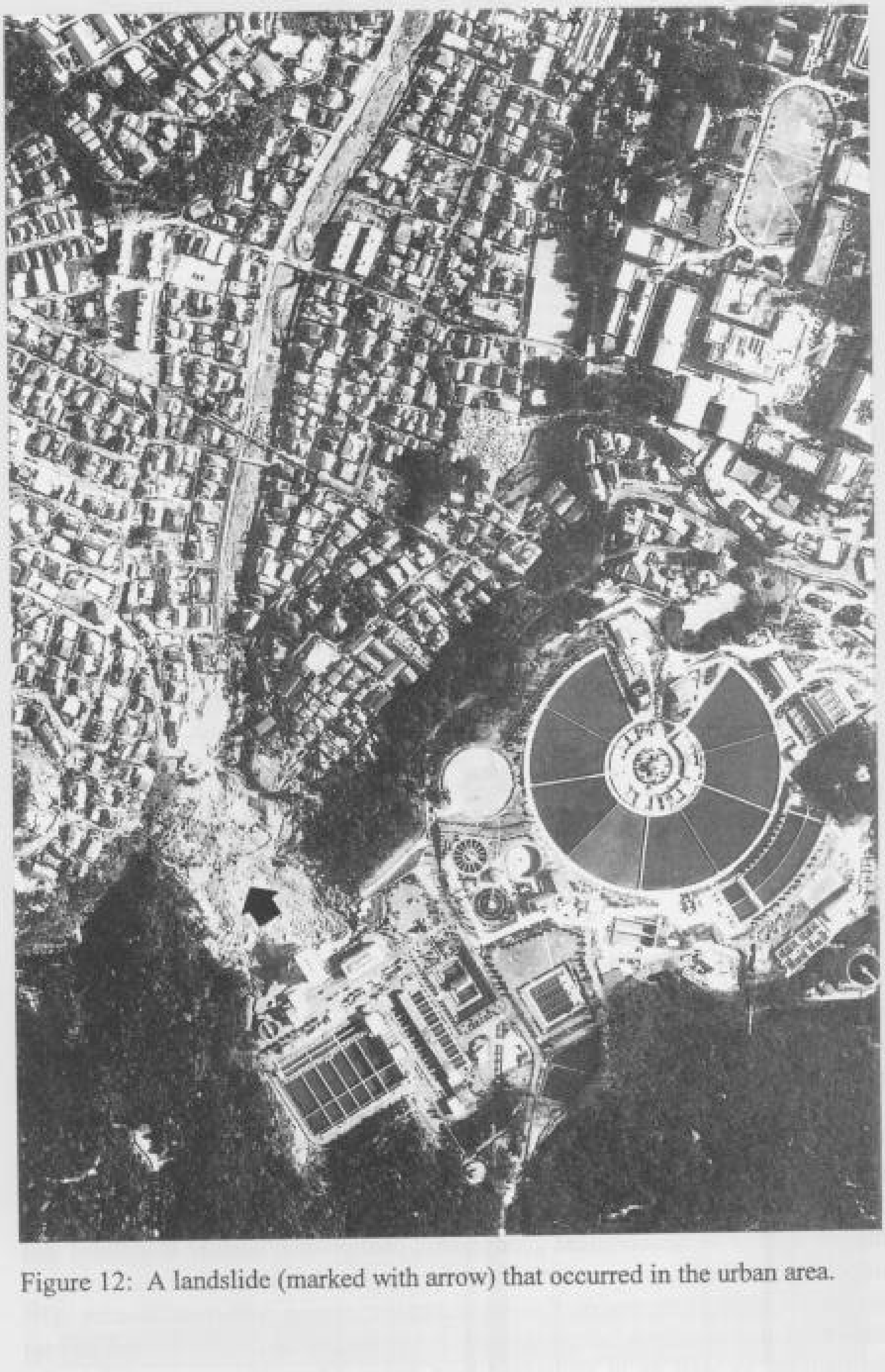


Figure 12: A landslide (marked with arrow) that occurred in the urban area.

formations. In the former case, the tremor caused the liquefied material to emerge on the surface, through discontinuities in the structural units of the constructions founded on the reclaimed land areas. In the latter, the material passed through sets of ground fissures. Finally, there were cases in which the liquefied material did not emerge, but resulted in wave-like deformations of the ground surface.

The evaluation of the data together with our observations shows that the liquefied formations lie at a depth of 5 - 30 m, with few local fluctuations. It is important to note that the liquefied zone lies parallel to the maximum intensity area, which is also linear. However, in other locations, where identical geological and geotechnical conditions were prevalent (mainly towards Osaka Port) no such events took place.

The impact of the liquefaction was particularly grave. The harbour quays and the infrastructure of Kobe Port in general were particularly affected, rendering it useless (Fig. 13). The same was the case for both Rokko Island and Port Island, the reclaimed land islets. Besides, all along the coastal zone, the roads and the surrounding area were affected. However, constructions such as large warehouses, high-rise buildings, liquid-fuel tanks, silos and so forth, remained almost intact due to their foundation in deeper geological formations that were not liquefied during the earthquake.

6 Conclusions

The disastrous earthquake of 17 January 1995 in the area of Kobe (also known as the Hanshin Earthquake) was the result of the intense geodynamic procedures that take place in the Japanese territory. The seismotectonic setting is determined by the geodynamic placement of the Japanese archipelago, in the vicinity of the subduction zones of certain tectonic plates, namely the Eurasian, the Philippine Sea and the Pacific ones. This leads to a general EW compression, with the manifestation of local transpressional structures.

The greater area of Kobe comprises the Rokko Mountain horst and the Kobe graben. The earthquake of 17 January was the result of the reactivation of certain faults that bound these two blocks. The fault movement was primarily strike-slip (dextral), a fact also confirmed by both the surface expression and the focal mechanisms of the earthquakes.

The Hanshin Earthquake resulted in intense damage and numerous deaths. The destruction follows a clear-cut linear (NE-SW) development inside the urban area of Kobe-Nishinomiya.

In addition, serious damage was caused to isolated areas mainly because of the occurrence of concomitant geodynamic phenomena, namely landslides and liquefaction. The former occurred mainly outside the urban area but some of them that took place inside the city complex caused numerous deaths. The liquefaction phenomena occurred along the coastal zone in alluvial and coastal formations, as well as in reclaimed land areas. These phenomena led to the

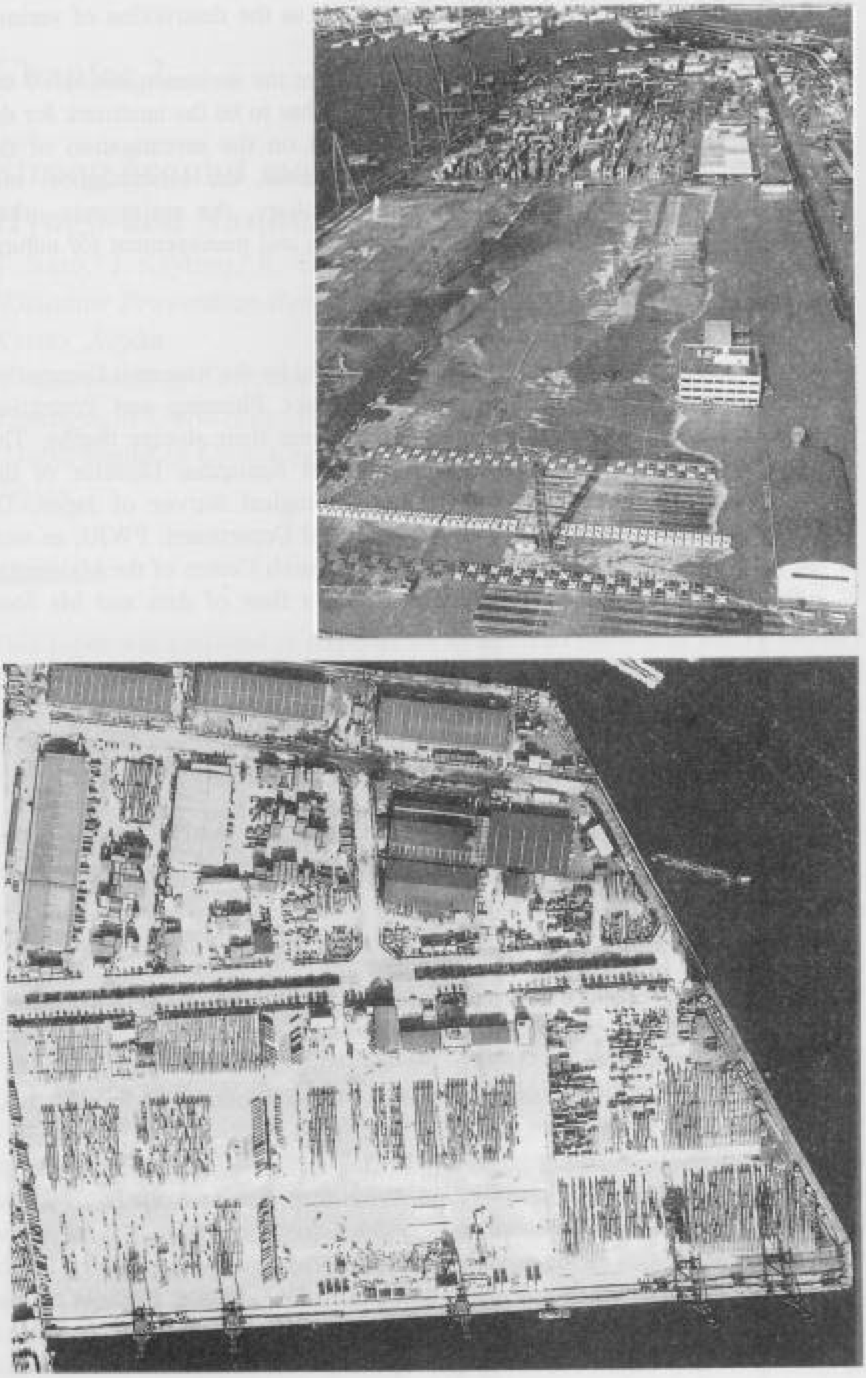


Figure 13: Liquefaction phenomena in reclaimed land areas.

paralysis of the greater part of the port, as well as the destruction of various constructions along the coastal area.

The devastating earthquake of Kobe re-poses the serious question of the antiseismic prevention for large urban centres. It has to be the landmark for the inauguration of new scientific research focused on the investigation of the neotectonic structures that lie in the urban areas, the seismological and geotechnical parameters, the antiseismic technology, the antiseismic urban planning and finally, the operational organisation and management for natural disasters.

Acknowledgements

The investigations carried out in Japan were funded by the Research Committee of the University of Athens and the Earthquake Planning and Protection Organisation, to both of which the authors express their sincere thanks. The authors would also like to thank Dr Yoshihiro Kinugasa, Director of the Seismotectonics Research Division of the Geological Survey of Japan, Dr Yoshiharu Ishikawa, Chief of the Erosion Control Department, PWRI, as well as the colleagues at the Disaster Prevention Research Centre of the University of Kyoto for their assistance and the continuous flow of data and Ms Joan Doran for the review of the manuscript.

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