The Doppler-Fiseau effect on the damage distribution during the Kobe earthquake (Japan)

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Abstract

The earthquake in Kobe (M=7.2 R) killed more than 5,400 people and caused huge material damage. The recording of the damage showed that it was linearly distributed, along a NE-SW axis, both on Awaji island and in Kobe town. This layout coincides with the trace of the reactivated fault zone, that gave both the main shock and the ensuing seismic sequence. The elaboration of the damage data with the use of the E.M.S.-1992 showed that in Kobe the maximum intensity reached grade XI, while on Awaji the maximum intensity was VIII. The analysis of the seismic fracturing showed that the main shock can be broken down to three partial ruptures, along a 13-km long rupture plane. The total rupture time was 11 sec and the rupture propagated to the NE. The north-eastward propagation of the rupture is held responsible for the increased observed ground accelerations along the fault trace in Kobe, as opposed to the relatively lower ones on Awaji. This difference is considered one of the basic reasons for the discrepancy in the intensity maxima. Besides, the Doppler-Fiseau effect led to significantly longer periods on Awaji, so that the low, short-natural-period buildings did not suffer so great damage as the ones in Kobe, where because of the same effect, the periods were significantly shorter and the short-natural-period buildings were severely damaged.

1 Introduction

The earthquake of 17 January, 1995 in Kobe (Southwestern Japan), also known as Hanshin or Hyogo-ken Nanbu earthquake had immense consequences. According to the official data, more than 5,300 people lost their lives, 30,000 were wounded and 300,000 remained homeless. In addition, more than 110,000 buildings collapsed, or were damaged beyond repair; the immediate financial cost amounted to 7 trillion yen, with the long-term impact being much higher, because of the destruction of major industrial units, highways, infrastructure and lifelines.

The recording of the damage carried out showed that this had a linear development, along a general NE-SW direction for a distance of 25 km approximately, coinciding with the trace of the reactivated fault zone. The linear distribution is located both in the urban complex of Kobe and on the nearby Awaji island (Awajishima); however there was considerable differentiation in the amount of damage along this zone. In the following paragraphs, and after the basic elements that constitute the geologic/neotectonic setting of the area and certain data pertaining to the shock of 17 Jan 1995 are given, an attempt for interpretation of the unequal distribution of the damage along the zone of maximum intensities will be made.

2 Geodynamic - Seismotectonic Setting

The greater area of Kobe, as the Japanese territory is known in its entirety, is characterized 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. This complex geodynamic setting determines the prevailing geological procedures and structures both on a regional and local level. These are characterized by a general EW compression, giving rise to local transpressional structures (Ishibashi, [1]).

The greater area is characterized by the presence of such a structure, namely a first order fault zone (Median Tectonic Line), of pure dextral strike-slip (RGAFJ, [2]; [3]). This E-W trending zone runs south of Awaji Island and Gulf of Osaka. 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 echelon) 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 (Fig. 1).

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 (Itihara, [4]; Itihara *et al.* [5]).

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 Mountain 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 main shock of January 1995, and the seismic sequence in general, resulted in the reactivating of certain faults comprising the fault zone. The main

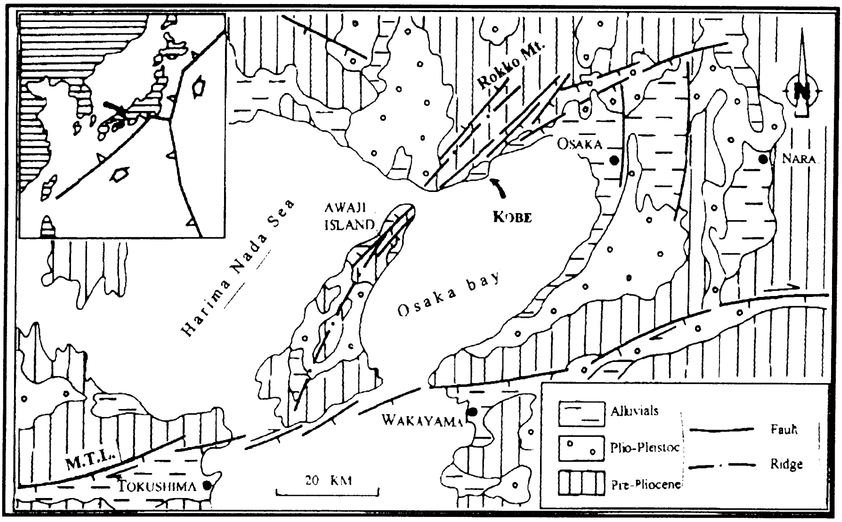

Figure 1. Geological sketch map of Osaka Bay and environs, modified after Itihara *et al.* [5].

Figure 2. Close-up photo of the reactivated portion of Nojima fault on Awaji island.

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° and dips 75° - 80° towards the NE and had a maximum horizontal offset of 1.7 m. and a maximum vertical slip of 1.3 m.. The survey showed that the fault had been reactivated for a length of approximately 9 km; its continuation in the Akashi Straits, through Plio - Pleistocene and alluvial formations and was planar for sections of up to 200 m in length. Locally, it was in a step-like (en echelon) arrangement, a fact that was in accordance with the dextral-slip sense (Fig. 2) of the seismogenic fault (Lekkas *et al.*, [6]).

3 The Hanshin Earthquake

On 17 January 1995 at 05:46 (local time) an earthquake of magnitude M=7.2 occurred. Two foreshocks preceded the main event by approximately 12 hours and they both originated in the same fault zone. The aftershock sequence included about 6.000 events, the largest of which was of magnitude M=4.9 and took place two hours after the main shock (Fig. 3).

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.

The focal mechanism analysis of the earthquake yielded a N229°striking fault, with a dip of 77°, slip of 713° and fault area of 40 x 10 km^2; the stress drop was 100 - 200 bar, the relative displacement was 2.1 m, the duration of the main rupture was 11 seconds and had a seismic moment of 3 x 10^{19} as of Sato *et al.* [7]), reporting Kikuchi [8], who also showed that the main shock was generated by three sub-events (Fig. 4) based on the source inversion method using teleseismic body wave (Sato *et al.*, [7]; Kikuchi [8]). That is, the main shock can be broken into three partial ruptures, each one measuring 6.8, 6.3 and 6.4, respectively, on the M_w scale. The first (M_w=6.8) rupture was located beneath the northeastern tip of Awajishima. The second one (M_w= 6.3) occurred 9 km to the northeast of the first one, and the third (M_w= 6.4) occurred 4 km further to the Northeast, under the city of Kobe. In all, what actually happened was a migration of the ruptures towards the NE along a 13-km-long plane, in a total time of 11 seconds.

4 Distribution Of Damage

As already mentioned, the earthquake of 17 January 1995 had tremendous impact on human and material loss. The vast majority of the collapsed buildings (or the ones that were damaged beyond repair) lay at an elongated,

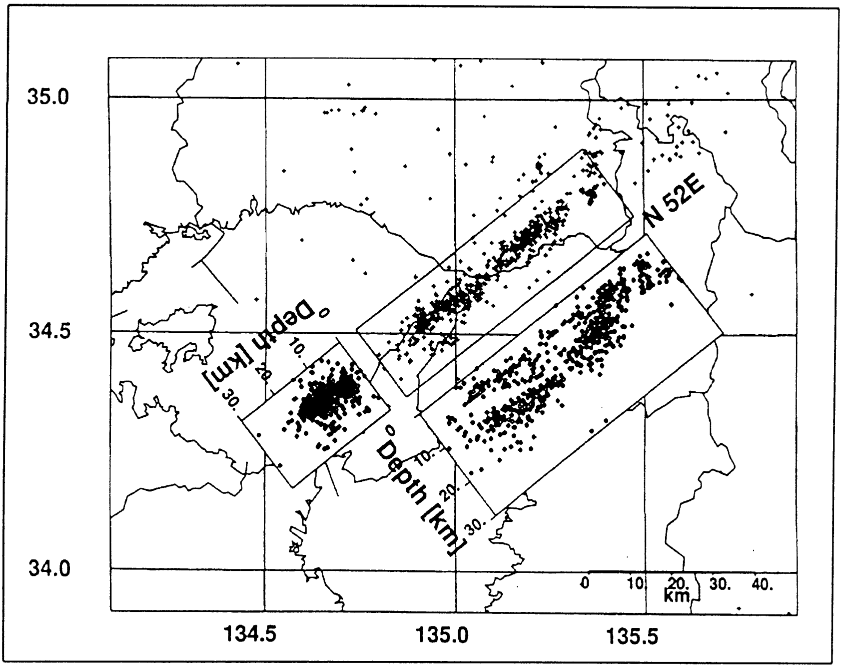

Figure 3. Epicentral distribution of aftershocks.

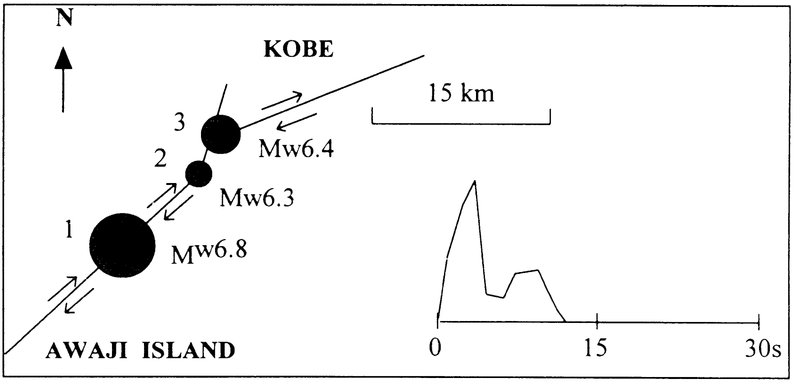

Figure 4. The mechanism of the Hyogo-ken Nanbu earthquake (after Sato *et al.* [7]).

25km-long zone of northeastern direction, which comprises the northeastern part of Awajishima and a portion of the Kobe urban complex. It also coincides both with the trace of the reactivated fault zone and the aftershock distribution.

The recording of the damage was done in a number of methods, that is to say, in situ estimation of the type and magnitude of damage of each building, the evaluation of the earthquake report forms compiled by the local authorities, as well as communication with other fellow researchers and research institutions.

The collection of data was followed by an attempt for evaluation of amage based on a new intensity scale, the European Macroseismic Scale 1992 (E.M.S.-92) (Grünthal [9]). The results of this procedure have already been presented in recent papers (Lekkas *et al.*[6]; [10]; Lekkas & Kranis [11]) and has, in general, as follows (Fig. 5):

The maximum intensities inside the urban complex locally reached the XI grade, while over extended areas the intensity was X. The X grade isoseismals developed linearly, for at least 20 km in length and 1-2 km in width. The smaller (VII, IX) isoseismals surrounded accordingly the larger ones. On Awajishima the maximum E.M.S.-1992 intensity was VIII and the equivalent contour was also elongated, about 5 km long by less than 1 km wide.

Apart from the observation that there was a discrepancy in the maximum intensities between Kobe and Awajishima, there is also another fact that deserves attention, and has to do with the extent and magnitude of damage in buildings of the same type. That is to say, as for the wooden structures (and generally one- or two-storey houses), there was significant differentiation in the destruction: such structures in Kobe collapsed, totally or partially, or suffered severe damage, with only a small percentage suffering light or no damage. According to the official data, 80% of these structures fall into the first category and only 20% in the second. On the other hand, the corresponding percentages were 40% and 60%, respectively (Fig. 6).

As for the other types of structures, no such correlation could be made, due to the fact that in Kobe a large variety of building types exists (multi-storey buildings, made of reinforced concrete or steel ones), which is not the case on Awajishima, where the wooden houses prevail.

Finally, it should be mentioned that the geologic and geotechnical features of the foundation formations in the maximum intensity zones in Kobe and Awajishima are almost identical. The formations comprise alluvial deposits, (max. thickness 10 m.), overlying Plio-Pleistocene clay, sand and gravel. This is due to the fact that the pleistoseismal area develops parallel to the regional neotectonic structures (the horst of Mt. Rokko and the graben). There is some differentiation locally in the geotechnical profile of the formations, though not that striking to account for such discrepancy in the maximum intensities. It should also mentioned that the damage caused by surficial earthquake effects (liquefaction, landslides, etc.), as well as the destruction by fires were not taken into account in the compilation of the E.M.S.-1992 intensities.

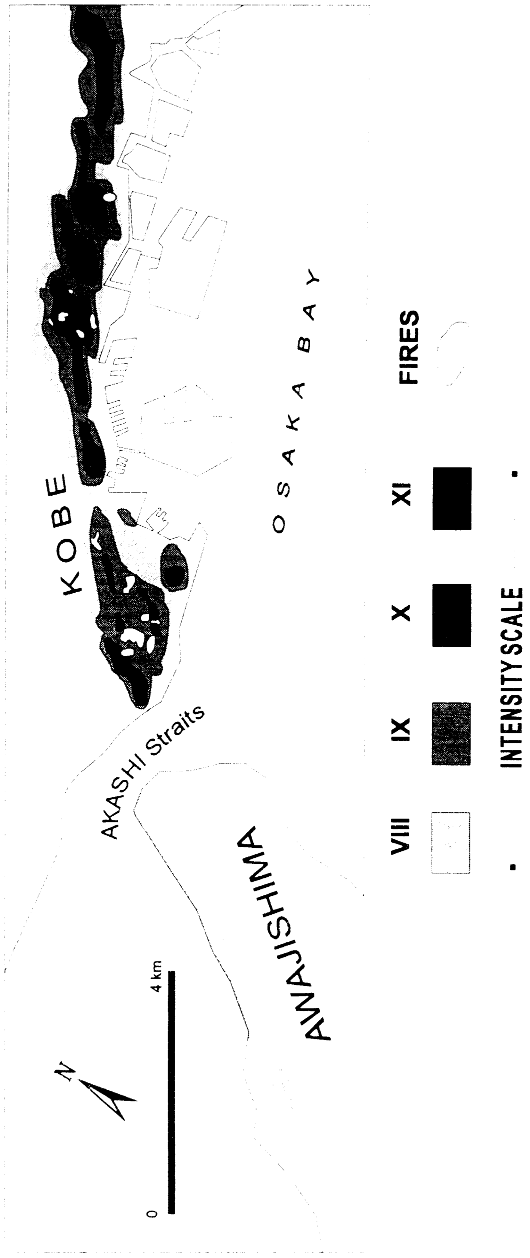

Figure 5. E.M.S.-92 intensity distribution.

Figure 6. Destroyed wooden houses in Kobe.

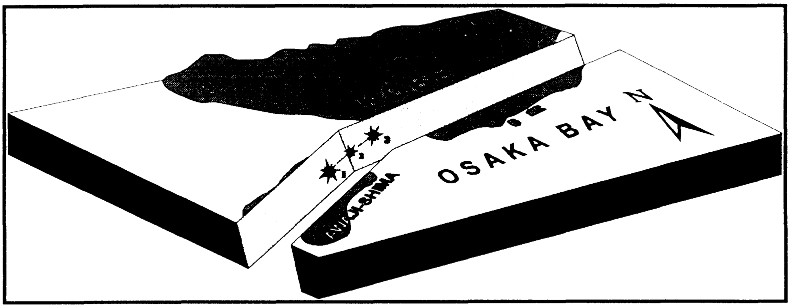

Figure 7. Schematic stereogram (not to scale) of the rupture process.

5 Doppler-Fiseau effect and correlation to damage distribution

The migration of the rupture process during the main shock from the SW to the NE (Fig. 7) gave rise to the Doppler-Fiseau effect, which accounts for the transposition of the spectrum, with higher frequencies towards the NE and lower ones to the SW. At the same time, the wave periods were shorter in the northeastern direction and longer in the southwestern one. Besides, a high acceleration pulse developed towards the NE, with the opposite happening in the opposite direction.

All these can be directly correlated to the damage, as described in the previous section. Thus, the high acceleration towards the northeastern portion of the reactivated fault, a fact also confirmed by instrumental data (RCEP - DPRI [12] led to the amplification of damage along he fault as compared to other locations, and mainly to the southwestern part the elongated maximum intensity area. There was a difference of at least two grades in the maximum intensities between the northeastern and the southwestern part.

In addition, due to the fact that the low (and generally the one- or two-storey wooden houses) structures have a short natural period, the conditions were more unfavourable in Kobe (northeastern section) than on Awaji (southwestern section) as the Doppler - Fiseau effect led to shorter wave periods in the city complex. Thus, there was a matching of the natural periods of the structures and the earthquake wave periods, causing about 40% more damage in Kobe than on Awajishima.

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