Sexto Congreso Nacional y Conferencia Internacional de

Geología Ambiental y Ordenación del Territorio

Riesgos Naturales, Ordenación del Territorio y Medio Ambiente

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LIQUEFACTION PHENOMENA CAUSED BY THE KOBE EARTHQUAKE (JAPAN)

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ABSTRACT

The liquefaction phenomena that occurred during the Hanshin earthquake (Jan. 17, 1995, Kobe Japan) are described in this paper. In the beginning the geological-geotechnical conditions of the greater area of Kobe are outlined and three liquefaction types are distinguished. The affected localities were either covered by alluvial formations or coastal deposits, or were reclaimed land areas, such as the Rokko and Port islands. The type of damage caused is given and finally, the geotechnical characteristics of the liquefied materials are described and a correlation between the reactivated fault zone and the liquefied sites is made.

Key words: Liquefaction, Hanshin earthquake, Kobe, Japan.

RESUMEN

En este trabajo se describen los fenómenos de licuefación que tuvieron lugar durante el terremoto de Hanshin (17 de Enero de 1995, Kobe, Japón). Inicialmente, se describen las condiciones geológico-geotécnicas del entorno de Kobe de modo que se distinguen tres tipos de licuefacción. Las localidades afectadas estaban cubiertas bien por formaciones aluviales o depósitos costeros, o bien eran terrenos ganados al mar, tales como las islas Rokko y Port. Se indica asimismo el tipo de daños causados y, finalmente, se describen las características geotécnicas de los materiales licuefactados y se realiza una correlación entre la zona de falla reactivada y los lugares donde se produjo licuefacción

Palabras clave: Kobe, Japón, licuefacción, terremoto de Hanshin.

INTRODUCTION

The earthquake of January 17, 1995 (M_b=7.2 R) that hit the city of Kobe-Nishinomiya, also known as Kobe-Awaji or Hanshin earthquake, caused a great number of victims and huge material loss. The initial estimations on the financial cost of the earthquake were about 7 trillion yen, while the long-term impact is certain to be considerably higher.

One of the main long-term impacts of the earthquake was the destruction of the port of Kobe which is one of the principal export outlets of Japan, together with major damage to the access routes to it. This is mostly attributed to the occurrence of a number of concomitant to the earthquake geodynamic phenomena, the most prominent of which was the liquefaction both in the port and the vicinity.

As a matter of fact, areas larger than in equivalent seismic events were liquefied during the main tremor, whose epicentre lay offshore, in the Akashi Straits, between Kobe and Awaji island (Awajishima). The liquefaction caused considerable damage both directly to the constructions and indirectly through the flooding of extended areas by liquefied material, rendering them inaccessible. In the following sections and after an outline of the local geological setting has been given, the extent and types of liquefaction will be analysed. Then, the kinds of damage caused to the constructions will be described. Finally, certain features pertaining to the reasons for the manifestations of liquefaction phenomena, their geographical distribution and development will be focused on.

THE TECTONIC SETTING OF THE AREA

The city of Kobe-Nishinomiya develops in linear fashion in a northeastern-southwestern trend, at the southwestern foot of mountain Rokko, which is 900 m. high and also presents an elongated NE-SW development. The urban area, which covers the narrow zone between the mountain and the shoreline, is densely populated and also contains several manufacturing plants. Besides, it is the terrestrial link between northern and southern Japan.

This geomorphological arrangement is the result of the regional tectonic setting (Fig. 1) that comprises an uplifting tectonic block (horst), which is mount Rokko and a downthrown block (graben), the city of Kobe. The horst consists of pre-Pliocene formations, mainly igneous ones - granites and dykes. On the other hand, the graben is filled for several hundreds of meters, with mainly sedimentary formations (Itihara 1966, Ishibashi, 1986) of Pliocene-Holocene and its largest part is occupied by the Kobe-Nishinomiya megalopolis. The juxtaposition between the horst and the graben is achieved through numerous active faults of an average NE-SW trend. In this transitory zone certain sedimentary formations of Pliocene-Holocene age outcrop (Itihara, 1966).

The earthquake of Jan. 17, M_b=7.2, whose epicentre lay offshore in the Akashi straits, between Kobe and Awaji island, as well as the ensuing seismic sequence was the result of the reactivation of certain faults that consist the fault zone, a fact confirmed by the coincidence of the fault traces and the epicentres of the tremors (RCEP - DPRI 1995, RGAFJ, 1980, 1991). The most prominent surficial expression of the earthquake faulting was the Nojima fault which runs in NE-SW direction on Awaji island. Besides other features, some of them of considerable length were observed in the area of Kobe-Nishinomiya.

The liquefied area is covered with alluvial formations and coastal deposits that occur along the coastal zone for a width of 200m to 2km. In addition, liquefaction occurred at reclaimed land areas, which were constructed either to accommodate for the extension of the urban area towards the sea or for the artificial quays and islets at Kobe port (Koshien-hama, Rokko and Port islands).

No other formation that occurs in the graben was liquefied. Besides, no liquefied phenomena were observed either to the west (Himeji) or to the east (Osaka) at the port of Kobe, despite the fact that the same formations outcrop and similar man-made interventions have been made. As a matter of fact, the manifestation of liquefaction phenomena is closely interrelated with the neighbouring reactivated faults, which strike NE-SW in average and lay at a distance of approximately 5km.

DESCRIPTION OF THE LIQUEFACTION PHENOMENA

The manifestation of ground liquefaction has been a quite common concomitant geotechnical by-product of strong earthquake events (Mariolakos et al., 1990, Papanikolaou et al., 1992, Lekkas 1994, Lekkas 1995).

Soon after the main temblor of January 17, an attempt for the mapping of the

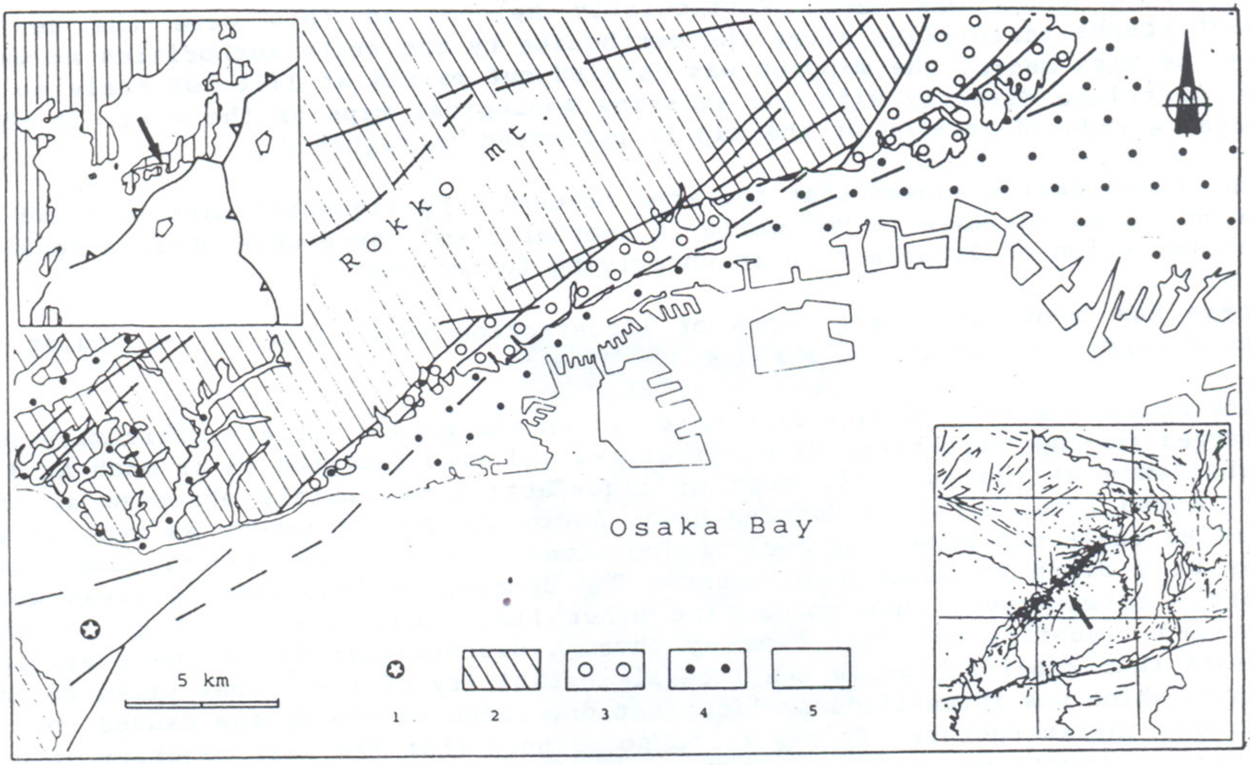


Figure 1. Simplified geological map of Kobe area. 1. Earthquake epicentre, 2. Pre-Pliocene formations, 3. Plio-Pleistocene formations, 4. Alluvials, 5. Reclaimed land areas. Insets: Tectonic setting of Japan (upper left) and the seismic sequence (lower right).

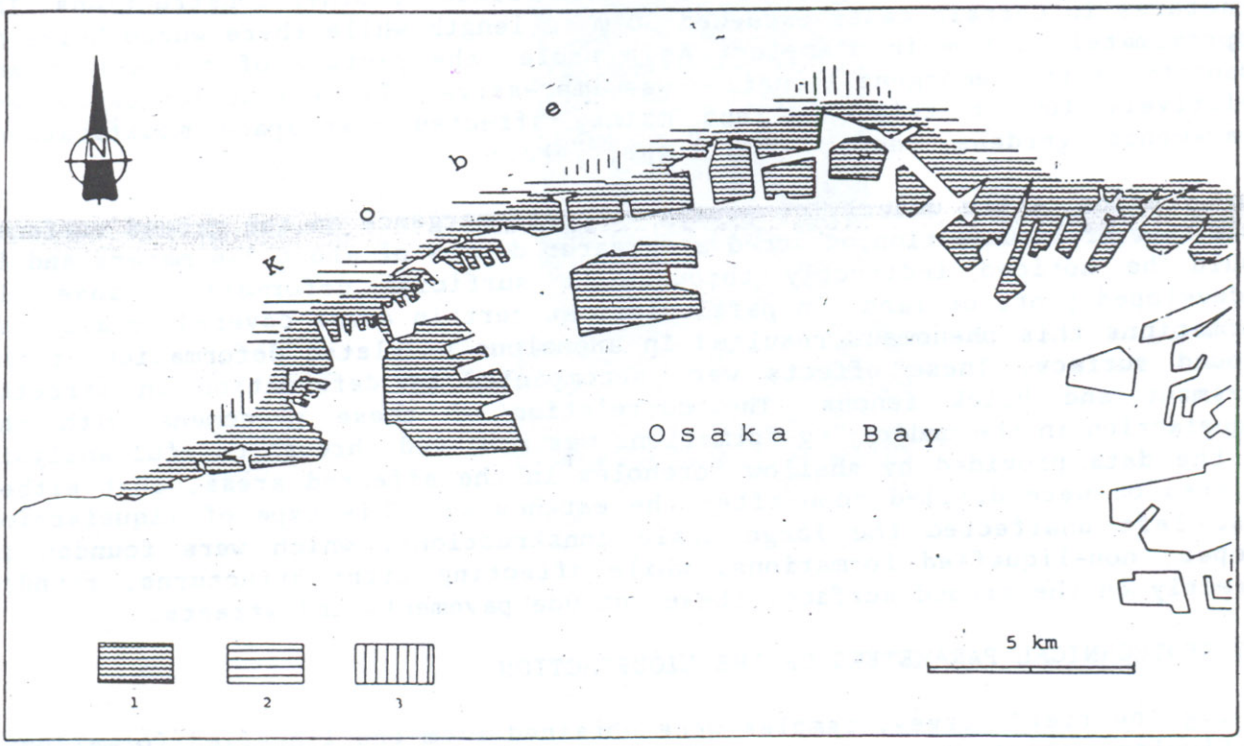


Figure 2. The liquefied areas and the liquefaction types. 1. Surficial outflow in reclaimed land areas, 2. Liquefaction through ground fissures, 3. Liquefaction without emergence of the liquefied material that resulted in surficial undulation.

liquefied areas was made. Particularly helpful in this were the aerial photographs taken right after the earthquake by the state authorities as well as the mass media. The mapping was carried out mainly at 1/10.000 scale so as to correlate directly with the existing geological maps of the area. In this paper a reduced version of the map is presented in figure 2.

The investigation showed that the area covered with liquefied materials had an extent of approximate 15 km^2 while in another 3 km^2 there were obvious results manifestation of liquefaction in underlying formations.

There has been three main types of liquefaction that occurred, according to their impact on the ground surface:

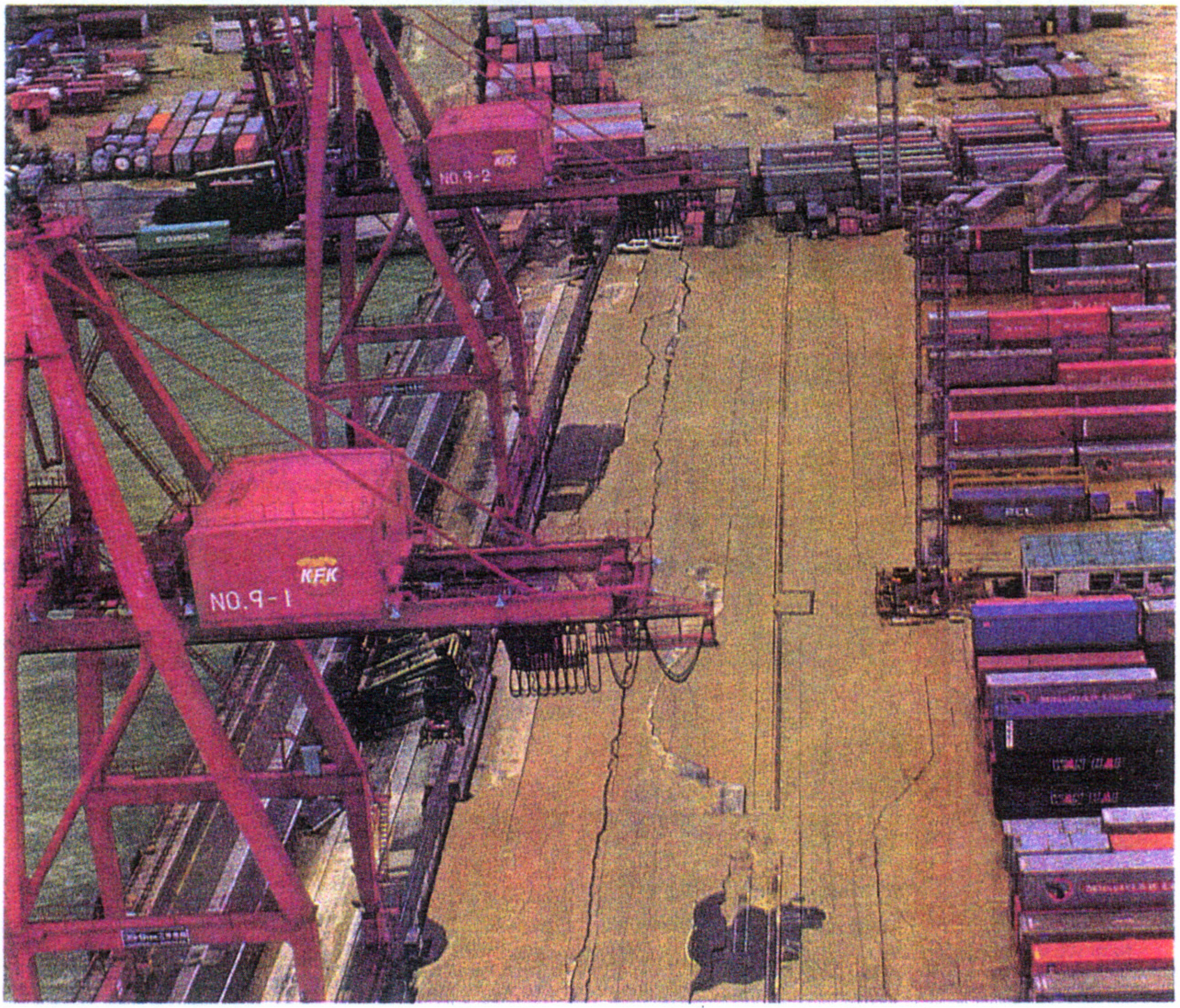
Wide-spread ejection of liquefied material on the ground surface. This material emerged through structural discontinuities and also resulted in as much as 3 m subsidence at places. This type of liquefaction was mainly observed at the reclaimed land islets of Koshien-hama, Rokko and Port islands, as well as at smaller scale man-made land reclamation sites (Fig. 3). The liquefied material lay at a depth of about 1-10 meters. The damaged by liquefaction areas were mostly tarmac-paved open spaces and other light constructions (Fig. 3). The emerged liquefied material came up through discontinuities in the overlying strata that subsided, while the lateral instability of the corner piles of the quays, which was intensified by liquefaction, added to the damage caused to the harbour infrastructure. It has to be noted here that the vast majority of the large constructions (bridges, multistory buildings, silos, etc.) which are in the area suffered little if no damage as their foundations had been laid in deeper formations that were not liquefied.

Sand blows and ejection at liquefied material through isolated cracks, holes or fracture sets. These occurred in coastal deposits and alluvials close to the shoreline. These strata were not paved with tarmac or other constructions. The fractures in certain cases exceeded 50 m in length while there where holes of approximately 0.5 m in diameter. As a whole, the picture of the extent and quantity of this emergent liquefied was impressive. The destruction caused was relatively low in this case and mainly affected open-space modifications (pavements, gardens, recreational areas, etc.).

Liquefaction of the underlying strata without emergence on the ground surface. This type of liquefaction occurred at greater depths of about 3-6 meters and it could be noticed indirectly through the surficial deformation caused in undeveloped plots of land. In particular, at certain areas covered by alluvial formations this phenomena resulted in anomalous undulated deformation at the ground surface. These effects were accompanied by deformation in streets, pavement and brick fences. The correlation of these phenomena with the liquefaction in the underlying formations was achieved through careful analysis of the data provided by shallow boreholes in the affected areas, that either existed or were drilled soon after the earthquake. This type of liquefaction also left unaffected the large scale constructions, which were founded in deeper, non-liquefied formations, while affecting light structures, founded directly on the ground surface; these include pavements and streets.

THE GEOTECHNICAL PARAMETERS OF THE LIQUEFACTION

During the field survey, samples were obtained from the liquefied formations. Particular attention was paid on the samples being representative of the liquefied formations. The subsequent granulometric analysis confirmed that these formations belong to the high liquefaction susceptibility zone, according to the Japanese standards (Fig. 4).



Surficial deformation resulted from liquefaction in the underlying formations (up) and liquefied material that covered Rokko island (down).

Liquefaction phenomena caused by the Kobe earthquake (Japan).

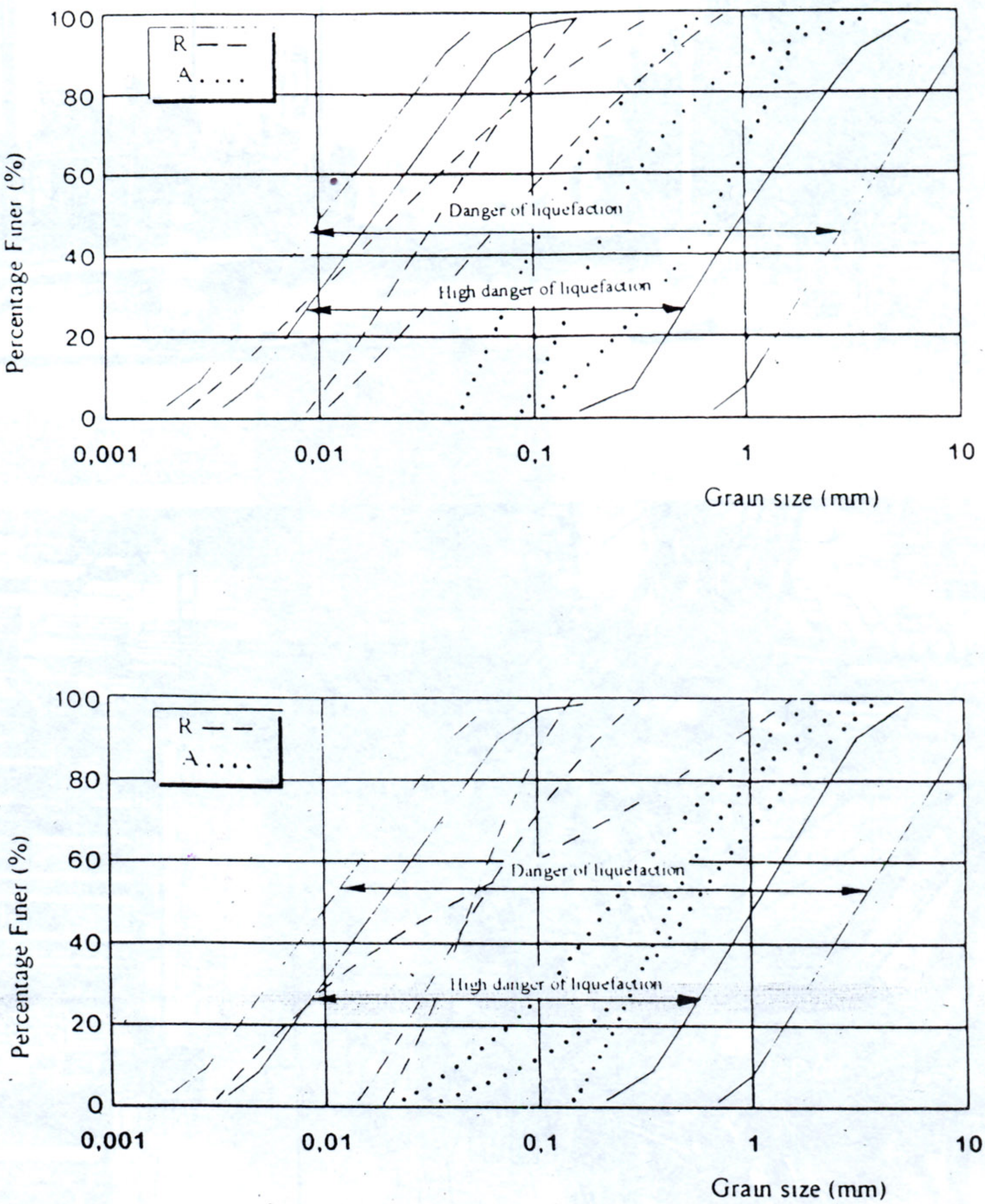


Figure 4. Grain analysis of samples obtained from the liquefied formations (up) and non-liquefied ones (down). The curves correspond to alluvials (A) and landfill material (R). Note that despite the apparent similarity in the composition of the material, the liquefied formations were the ones that lay close to the reactivated fault zone.

There is also however, substantial differentiation among the various sample locations, as far as the granulometric composition is concerned. In particular, a number of samples obtained from alluvial formations that where liquefied, showed coarser composition, in contrast to other ones taken from artificial landfills where the composition curve is shifted to finer increments.

In order to classify the conditions in similar formations and reclaimed land areas that were not liquefied, more samples were obtained from those locations. The results of the analysis on those samples are presented in figure 4. These areas either to the west or east of Kobe, in the direction of Himeji and Osaka, respectively. The analysis showed that despite the fact that the material was of the same granulometric composition and have been deposited and still are under the same or similar geological (alluvial, coastal deposits) and "artificial" (landfills) regime, they were not liquefied. This is a particularly important thing to mention, since it shows the determing effect of the fault zone that runs parallel to the port of Kobe on the manifestation of liquefaction. Besides, along this very fault zone the highest ground acceleration values were recorded and the maximum damage to the constructions took place (Lekkas et al, 1995). Thus, summing up, it has to be said that the elongated development of the liquefied zone and the reactivated fault zone lie in parallel with each other.

CONCLUSIONS

The earthquake of January 17, 1995 in Kobe caused a greater number of victims and huge damage. In addition to this a certain series of concomitant geodynamic phenomena were induced by it, the most representative case being the one of liquefaction.

Ground liquefaction was caused side along the reactivated fault zone that strikes NE-SW and runs through the city of Kobe-Nishinomiya. Certain faults that compose this fault zone were reactivated during the temblor. The liquefied material either belonged to alluvial formations and coastal deposits or to reclaimed land areas. The liquefactions caused were distinguished into three categories, namely (i) liquefaction in formations whose material emerged on the surface through structural discontinuities, (ii) liquefaction that occurred in alluvial and coastal deposits, where the liquefied material emerged through existing or earthquake-induced fractures and holes and (iii) liquefaction without emergence on the surface of the liquefied material that led to surficial deformation and damage to light constructions. According to the type of liquefaction, various kinds of damage were caused, which have been classified either as important or secondary.

Finally it is confirmed through the comparative study of certain geotechnical parameters that there is direct relationship between the manifestation of liquefaction phenomena in Kobe port and the neighbouring fault zone which was aroused during the seismic sequence.

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