ANALYSIS OF SOIL LIQUEFACTION DURING 1979 MONTENEGRO EARTHQUAKE

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SUMMARY

The presented details and the results obtained by analysis of the soil liquefaction during the Monte Negro earthquake of April 14, 1979 are aimed at explanation of the character of this phenomenon and the geotechnical conditions and excitation potential inducing it. In order to realize the scale and the properties of the phenomenon, distribution of the locations with manifestations likely to have been induced by soil liquefaction, as observed on the ground surface and on civil engineering structures, has been given and described. To idnetify the presence of conditions inducing soil liquefaction the geotachnical soil properties for several typical locations have been analysed. Analysis of the characteristic ground surface horizontal acceleration records obtained by the earthquake from the aspect of their potential to cause liquefaction have been also carried out. To determine the liquefaction potential of the considered earthquake detailed analysis of a typical geotechnical model of a site have been performed.

DESCRIPTION OF LIQUEFACTION

Soil liquefaction was one of the characteristic phenomenon induced by the April 14, 1979 Monte Negro earthquake. Visible manifestations on the ground surface and in structures, probable to have been caused by liquefaction, have been observed at several places within the Boka Kotorska bay area and along the Bojana river in Ulcinj. It is characteristic that liquefaction was found within relatively limited areas, particularly in the Boka Kotorska bay area, where a narrow belt of sand deposits along the sea coast was found. Liquefaction cases along the Bojana river in Ulcinj have been also observed within a smaller limited area while the major part of the Ulcinj valley, characterized by thick sand deposits, did not exhibit considerable ground manifestations of liquefaction. However, no visible cases of soil liquefaction have been observed in the 100 km long coastal belt from Ulcinj, in the south, to Boka Kotorska, in the north.

The sites with typical and very intensive soil liquefaction, as observed on the ground surface, are shown in Fig. 1. Ground surface faulting, ranging from slight cracks to trentches of over 1 metre width, vertical settlements and warping deformations, sinking of parts of the coastal belt under the sea water and similar phenomena have been observed on the ground surface at these locations. There were frequent cases of outbursts of fine uniform sand with high water jets from the ground. Large quantities of sand covered the areas along new-formed trenches, while traces of water were obvious on the walls of some structures. The ground floors of some buildings were covered with sand.

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These processes in the ground itself and on the ground surface had direct influence to structures and induced settlement and horizontal displacement of foundations which combined with rotation caused structural damage of diverse intensity ranging from cracks to collapse. There were several cases of sinking of structures for several centimetres.

Typical examples of liquefaction manifestations in the ground and on structures are illustrated in Figs. 2, 3, 4 and 5.

ANALYSIS OF GEOTECHNICAL PROPERTIES OF THE SITES

Soil liquefaction was identified based on ground surface manifestations observed at the sites. These manifestations point to the high probability to have been caused by soil liquefaction. To explain them it is necessary to define the geotechnical properties of the soil at the considered site, since soil properties and the seismic force potential are the basic factors constituting the conditions for liquefaction occurence. The lack of detailed pre-earthquake information obtained by geotechnical investigation of the considered locations did not allow definition of the geotechnical soil properties. On the other hand, due to their volume, the required post earthquake geotechnical investigations were not possible to be complited within a short time. Therefore, the presented geotechnical soil property analysis cannot be considered as a complete one, and covers only several locations. It has been carried out according to the results from previous investigations, field observations, laboratory test analysis of soil samples taken from the sites and outbursted during the earthquake, as well as on the basis of investigation of the soil profile after the earthquake.

Three characteristic sites, specially marked in Fig. 1 have been analysed The analysis showed their soils to be of quarternary sediments with average depth of 15 to 20 meters and frequent uniformly granulated sand layers. These sediments are overlaying flysh, or marlstone rocks. Underground water level is rather high, from 0.5 to 1.5 meters of the ground level, and equal to the sea level, since all the sites are in the vicinity of the sea coast.

The grain size distribution of the samples taken from the three sites is presented in Fig. 6. Analyses could show that they are uniformly granulated sands with coefficients of non-uniformity (D_{60}/D_{10}) from 2.5 to 3.0 and average diametre (D_{50}) from 0.15 to 0.45 mm.

These grain size characteristics classify them in the cathegory of sands typical for soil liqefaction. More intensive geotechnical investigations have been performed after the earthquake for one of the considered sites. A typical geotechnical soil profile, determined by geotechnical boreholes in the zone of intensive liquefaction manifestations is presented in Fig. 7. The grain size distribution in the sand layer up to 13,7 m depth complies with the sands shown in Fig.6 but the coefficient of non-uniformity is somewhat higher. The blow counts of standard penetration have shown that the major part of the layer is loose with average relative density (Dr) from about30% to about 50%. It should be mentioned that the presented results correspond to the post earthquake state and due to lack of pre-earthquake information no comparison was possible to be performed. The results obtained by several bore holes in the surrounding area are similar to those shown in Fig. 7.

Considering the results of the geotechnical soil property analysis it can be concluded that in view to soil properties the required conditions for soil liquefaction occurence existed.

ANALYSIS OF EARTHQUAKE DYNAMIC EXCITATION

The Monte Negro April 14, 1979 earthquake had magnitude of 7.0 degree. The ground acceleration due to the earthquake was recorded by five three-componental instruments for recording of strong earthquakes installed at various sites of the coastal area. Fig. 1 shows the instrument locations.

The basic data on the instrument locations and the horizontal component records are shown in Table 1. By comparison of the data from Fig. 1 and Table 1 it can be concluded that the records in the Table 1, numerated 1, 2 and 5, correspond mostly to the sites with the most expressive surface soil liquefaction manifestations. Table 1 also shows the results of the preliminary analysis of the number of different peak values (αa_{max}) as compared to the maximum acceleration (a_{max}) of each record. The analysis was aimed at evaluation of the earthquake excitation from the viewpoint of its potential to induce liquefaction. In determination of the excitation potential by record analysis, especially for the records under 2 and 5, it should be taken into account that they are obtained on bedrock, thus when converted to sites where soil liquefaction was observed some amplification of their peak values due to site soil influence should be considered.

To present the excitation potential expressed by the records in a form suitable for comparison with excitations applicable in laboratory testing of soil liquefaction conditions the records have been converted to equivalent uniform cyclic series. Conversion was performed based upon the results from Table 1 and a wide range of laboratory results obtained by many investigators, as shown in Fig. 8. In the range of results illustrated in Fig. 8 are also the results obtained by dynamic three-axial testing of sand samples taken from the considered sites. The conversion results are presented in Table 2.

In summary of the performed analysis it can be concluded that the excitation potential of each component was sufficient to induce soil liquefaction under adequate geotechnical conditions. If both components are taken simultaneously, which is a logical step, especially considering their close peak values, the excitation potential even increases.

ESTIMATION OF LIQUEFACTION POTENTIAL OF THE SITE

A simplified analysis of the estimation of the soil liquefaction potential in the post earthquake conditions was performed for the site with geotechnical profile shown in Fig. 7. The geotechnical profile characteristics were considered to be the same during the earthquake.

Estimation of the soil liquefaction potential was performed by comparison of the equivalent cyclic shear stresses due to the earthquake and the estimated cyclic shear stresses which could induce soil liquefaction along the profile. Earthquake stresses are taken according to the record obtained at Herceg Novi (No. 5) which is closest to the site, without amplification, and with 20% amplification. Two cases were analysed: excitation due to only one component, and excitation due to both components. In the both cases conversion to an equivalent number of uniform cycles N=10 have been carried out. Cyclic stresses which could induce liquefaction in 10 cycles are obtained applying the values in Fig. 8 and they correspond to the relative density of the sample with D_R equal approximately 50%. For analysis convinience the density of the sand layer up to 14 m depth was taken to be uniform and equal to 50%.

The results obtained from estimation of the soil liquefaction potential are presented in Fig. 9. By their analysis it can be concluded that for the major part of the soil profile the cyclic shear stresses induced by even only one non-amplified record exceed the stress potential which could induce soil liquefaction, i.e. that soil liquefaction is higher than 1. Considering the fact that the geotechnical properties of the profile refer to the post earthquake condition it is clear that the soil even at present has the same liquefaction potential for similar earthquake excitation. Assuming that certain soil densification might have occured, as compared to the pre earthquake state, it can be further concluded that the liquefaction potential could have been even higher during the earthquake.

CONCLUSIONS

The analysis of the geotechnical soil properties of the considered sites, and the dynamic excitation potential induced by the earthquake proved soil liquefaction conditions to exist in them. It further means that the manifestations observed on the ground surface at the sites were caused by liquefaction.

The results obtained by detailed analysis of liquefaction potential of the characteristic site showed satisfactory correlation with soil behaviour during the earthquake and thus proved the suitability for application of this method of analysis.

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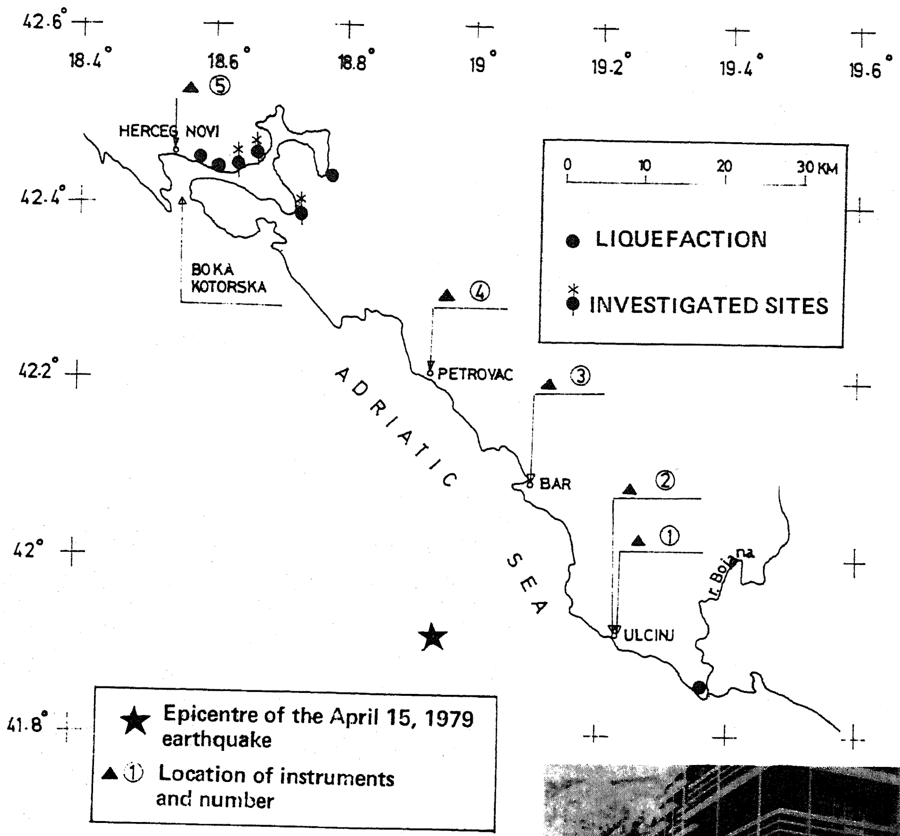

Fig. 1 Locations with liquefaction cases

Fig. 2 Typical ground surface manifestations of soil liquefaction

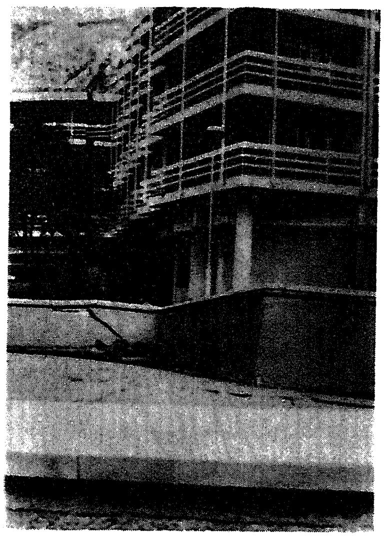

Fig. 3 Soil liquefaction consequencies observed on the hotel and swimming pool structures

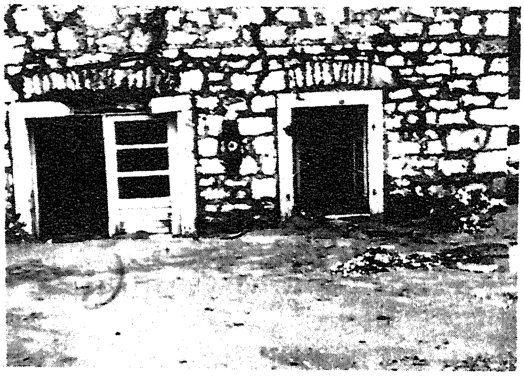

Fig. 4 Damage due to liquefaction: sinking of house and soil, house floor and its surrounding covered with outbursted sand, cracks in the walls

Fig. 5 Damage due to liquefaction: cracks in the soil and the concrete platform, sand outbursts, rotated lighthouse

Fig. 6 Grain size distribution for 6 types of sand taken from three investigated sites, as outbursted during the earthquake

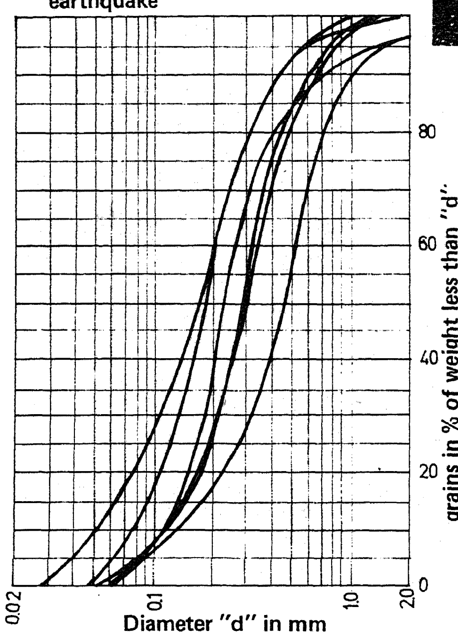

Fig. 7 Typical soil profile of sites investigated after the earthquake

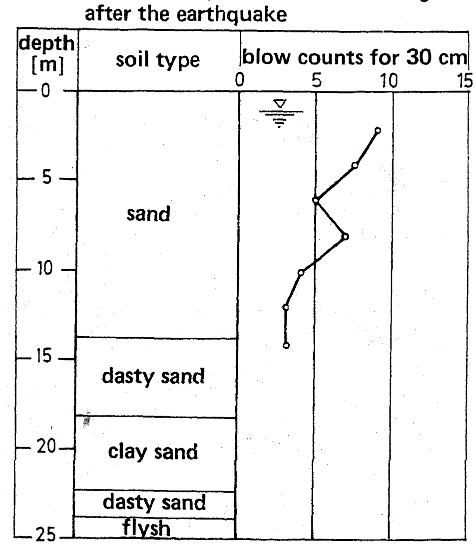

TABLE 1: LOKATION OF INSTRUMENTS AND DATA ON THE RECORDS

No.	Location of instrument	Geotechnical medium	Component	Max.Acc. a_{max} (g)	Number of peak values α a_{max}													
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					1.00	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35
1	Olimpic Ulcinj	Deposit	N–S	0.29	1	–	2	1	–	1	2	7	7	4	5	6	7	6
			W–E	0.24	1	–	–	–	1	3	3	5	3	–	5	3	7	9
2	Albatros Ulcinj	Rock	N–S	0.19	1	1	1	2	4	3	2	5	4	9	5	7	7	9
			W–S	0.25	1	1	–	–	3	–	2	–	3	1	4	5	3	6
3	Bar	Deposit	N–S	0.37	1	–	1	1	–	–	1	–	1	–	–	5	2	7
			W–E	0.37	1	1	1	–	–	3	1	1	3	3	1	4	8	8
4	Oliva Petrovac	Deposit	N–S	0.46	2	–	2	1	2	1	4	–	3	3	4	3	7	3
			W–E	0.30	1	1	3	1	2	1	3	1	4	4	3	2	10	4
5	Hreceg Novi	Rock	N–S	0.23	1	1	–	–	3	2	1	1	–	3	4	5	6	3
			W–S	0.26	1	1	–	–	1	–	–	–	1	2	1	2	9	6

TABLE 2: RESULST OF THE ANALYSIS OF RECORDS: EQUIVALENT NUMBER OF CYCLES WITH AMPLITUDE 0.65 a_{max}

No.	Location of instrument	Geotechnical medium	Komponent	Max.Acc. a_{max} (g)	a_e 0.65. a_{max} (g)	Equialent number of cycles Ne	Mean value of the number of cycles Ne
1	Olimpic Ulcinj	Deposit	N–S	0.29	0.19	14.6	11
			W–E	0.24	0.16	10.7	
2	Albatros Ulcinj	Rock	N–S	0.19	0.12	19.6	
			W–E	0.25	0.16	8.6	
3	Bar	Deposit	N–S	0.37	0.24	5.0	
			W–E	0.37	0.24	9.4	
4.	Oliva Petrovac	Deposit	N–S	0.46	0.30	13.6	
			W–E	0.30	0.19	15.0	
5	Herceg Novi	Rock	N–S	0.23	0.15	8.5	
			W–E	0.26	0.17	49	

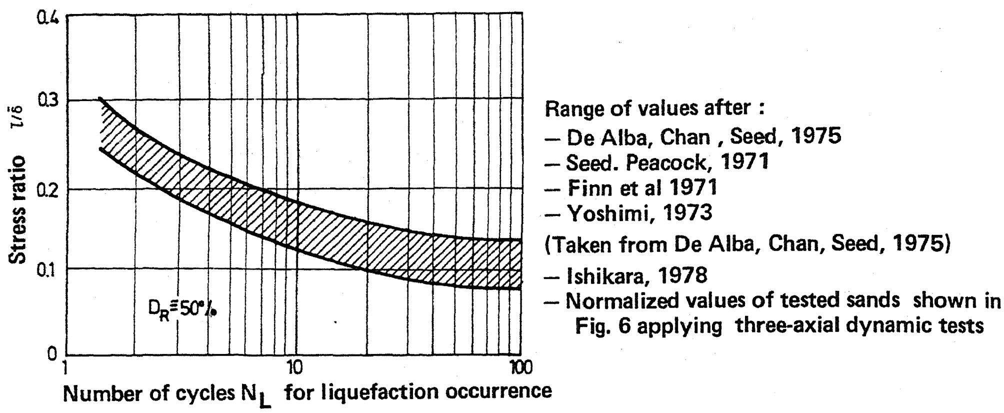

Fig. 8 Range of values for soil liquefaction occurrence, as obtained by laboratory testing

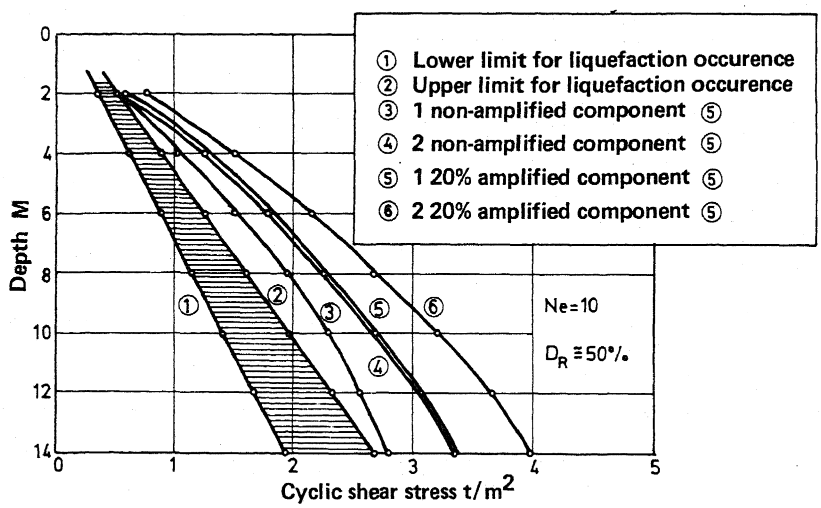

Fig. 9 Results from the analysis of the profile in Fig. 7 to assess liquefaction potential