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RESEARCH ON THE LIQUEFACTION POTENTIAL OF THE TERRAIN ALONG THE MONTENEGRIN COAST

Abstract

After the catastrophic 1979 earthquake, a classification according to the degree of damage was carried out on about 40,000 buildings in the area of six municipalities along the coast of Montenegro. The results showed that a significant number of commercial, residential and hotel buildings were destroyed or heavily damaged as a result of liquefaction or ground subsidence of the terrain. The results were systematized in overview maps of liquefaction potential at a scale of 1:5000, which was used as a basis for the adoption of urban plans of coastal municipalities. This paper aims to raise the general level of information among planners and civil engineers about the existence of a high risk of liquefaction in these areas.

Keywords: seismic hazard, deformation, liquefaction, SPT test, urban plans

ИСТРАЖИВАЊЕ ПОТЕНЦИЈАЛА ЛИКВЕФАКЦИЈЕ ТЕРЕНА ДУЖ ЦРНОГОРСКЕ ОБАЛЕ

Сажетак

Након катастрофалног земљотреса 1979 године извршена је класификација према степену оштећења на око 40 000 објеката на подручју шест општина дуж црногорског приморја. Резултати су показали да је значајан број пословних, стамбених и хотелских објеката срушен или тешко оштећен као посљедица ликвефакције или слијегања терена. Резултати су систематизовани у прегледне карте потенцијала ликвефакције у размјери 1:5000 које су коришћене као основ за доношење урбанистичких планова приморских општина. Овај рад има за циљ подизање општег нивоа информисаности међу пројектантима и грађевинским инжењерима о постојању високог ризика од појаве ликвефакције на овим просторима.

Кључне ријечи: Сеизмички хазард, деформације, ликвефакција СПТ-test, урбанистички план

1. INTRODUCTION

As a consequence of geodynamic processes, most of the southern Adriatic has a high degree of seismic hazard. In Montenegro, the seismic hazard is expressed along the coastal belt, where, in addition to the seismic risk, there are also risks of activating large landslides, rock falls, and soil liquefaction during earthquakes. During the 1979 earthquake, in several locations in the Lake Skadar area as well as along the Montenegrin coast, liquefaction phenomena were registered. After this earthquake, a classification according to the degree of damage was carried out on about 40,000 buildings in the area of six municipalities along the coast of Montenegro. Figure 1 shows the markings on the buildings after the classification of the level of damage, the markings were on the buildings that need to be demolished or constructively rehabilitated.

Figure 1. Markings on buildings after the 1979 earthquake classification indicating demolition or constructively rehabilitated

The results indicated that a significant number of commercial residential and hotel buildings that were built according to the principles of earthquake engineering were demolished or heavily damaged as a result of liquefaction or large ground subsidence of the terrain. Locations, where the appearance of liquefaction was documented, were 35 to 70 km from the epicentral area in the settlements, Kumbor, Baošići, Bjela, Tivat, Kotor, Bar, and Ulcinj.

The liquefaction was accompanied by cracks in the ground, from smaller cracks to trenches over one meter wide, vertical subsidence, horizontal movements, sinking parts of the coast, etc. There were numerous occurrences of the eruption of fine-grained sand on the surface, followed by the eruption of water in jets. Large amounts of sand covered the entire surface next to the newly formed trenches and in several cases, the floors of the houses were covered with layers of sand. Such manifestations in the soil and on the surface caused a large settlement and horizontal movement of the foundation, Figure 2.

Figure 2. Subsidence of the terrain under the warehouse in the port of Zelenika, left picture;Heavy damage to Hotel Fjord – Kotor city, right picture

Liquefaction, as one of the most difficult forms of dynamic soil instability, directly threatened the general stability of any object on the surface, causing significant damage. After the 1979 earthquake, it was clear that it was necessary to identify terrain areas with high liquefaction potential. The research was conducted by the Institute for Earthquake Engineering and Engineering Seismology from Skopje and was based on identifying the structure of the terrain, determining their granulometric composition, the degree of their compaction as well as the level of underground water. The results of the research were published in 1981 during the revision of the general urban plans of the municipality along the Montenegrin coast, on liquefaction potential maps, scale R=1:5000.

2. LIQUEFACTION PHENOMENON

In non-coherent soil with a weak possibility of draining underground water, during oscillations caused by the earthquake, the tendency to change the volume cannot be realized, which leads to an increase in pore pressures. An increase in pore pressures leads to a decrease in initial effective stresses in the soil and a weakening of intergranular connections. An increase in pore pressures can be of such a value that it reaches the values of the initial effective stresses in the soil. In such cases, the dynamic shear modulus is close to zero, and the soil loses its shear strength and transforms into a heavy fluid. This condition in the soil is defined as the beginning of liquefaction.

Liquefaction was one of the specific manifestations during a large number of strong earthquakes, however, certain dynamic and geotechnical conditions are required for its occurrence. Liquefaction occurs in earthquakes with a magnitude greater than 5 degrees, also a long duration of the earthquake is required. Also, the soil must be constructed of poorly compacted fine-grained non-coherent materials that have a low filtration coefficient and a high level of groundwater. Liquefaction occurs most often in fine-grained uniform sands.

Determining the liquefaction zone is done by identifying the terrain in which there are geotechnical conditions for the occurrence of liquefaction. Such terrains are marked as areas with a high risk of liquefaction in dynamic conditions, and they can be marked at the stage of creating urban plans, which is of great importance. Buildings can be protected from liquefaction by deep foundations, however, there is a whole series of infrastructural objects that cannot be protected, such as sewage, water supply networks, etc. Figure 3 shows the sewage manhole in the Japanese city of Abiko, which broke out on the surface due to the liquefaction.

Figure 3. Sewage manhole that broke out on the surface due to the liquefaction, Abiko city in Japan

The most effective way to prevent the negative effects of liquefaction is to create a map of the liquefaction potential of the terrain and then limit construction in areas with a high risk of liquefaction in the planning documentation phase. Exactly this approach was applied in Montenegro after the 1979 earthquake when the Institute for Earthquake Engineering and Engineering Seismology from Skopje conducted research that resulted in liquefaction potential maps, scale R=1:5000 for all municipalities of the Montenegrin coast.

3. DETERMINATION OF SOIL LIQUEFACTION POTENTIAL

The first necessary condition for liquefaction is the potential of dynamic oscillation, experience and research results show that liquefaction is caused only by earthquakes of large magnitude. To intensively increase pore pressure, it is necessary to generate oscillations not only of high amplitude but also of long duration. Figure 4 shows the oscillations and the duration of the 2011 earthquake in eastern Japan. For the occurrence of liquefaction, the duration of this earthquake was more than 90 seconds (red zone). Based on the historically recorded earthquakes, we can state that this condition is satisfied in the territory of Montenegro, especially along its coastal belt.

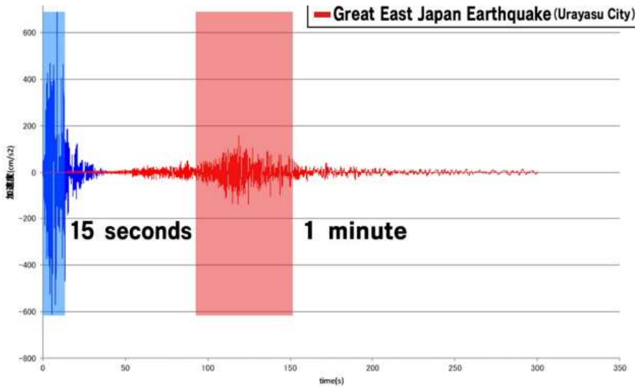

Figure 4. Earthquake duration and oscillations during the 2011 East Japan earthquake (Japan Meteorological Agency)

Another necessary condition is that liquefaction is induced only in certain types of soils with high groundwater levels. A type of soil susceptible to liquefaction is one in which resistance to deformation is mobilized by friction between grains. If other factors such as grain shape, uniformity coefficient, and relative compaction are equal, frictional resistance decreases with decreasing soil grain size. Based on the analysis of the granulometric composition of various alluvial sediments in which liquefaction was registered, Tscuhida proposed granulometric curves that indicate soils subject to liquefaction, Figure 5.

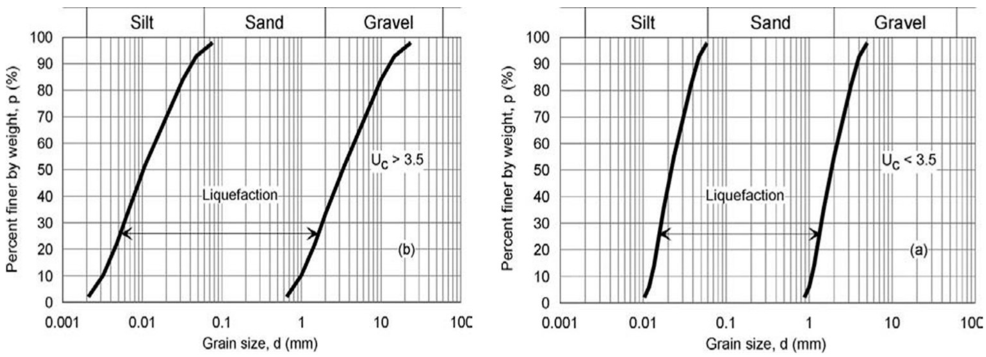

Figure 5. Granulometric curves of materials with high and low uniformity coefficients in which liquefaction was registered, (Tscuchida, 1970)

The area between the two inner curves represents sandy and dusty sands, which have the lowest resistance to liquefaction, also uniformly granulated material is more suitable for liquefaction than well-granulated material. Liquefaction can also occur in soils with a higher content of gravel, or clay fractions, however, these soils mobilize greater shear strength.

If the soil has a favorable granulometric composition, this still does not mean that liquefaction will occur in it, namely, compaction is the basic parameter that determines the risk of liquefaction. Greater compaction will result in less vertical deformation (settlement) under dynamic loading conditions. Liquefaction usually occurs in saturated clean sand and dusty sand when compaction is less than 50%. In compacted sand, dilation can occur during cyclic loading, which generates negative pore pressures and thus increases shear stress resistance.

Soil liquefaction potential is a quantitative expression of the possibility of soil liquefaction. It is defined as the relationship between the dynamic excitations that can be received by a certain geotechnical environment and the dynamic excitations that cause liquefaction in that environment. The safety factor for liquefaction is given by the expression:

$$F_s = \frac{CRR}{CSR} \geq 1.0 \tag{1}$$

where:
Fs-factor of safety for liquefaction;
CRR-coefficient of cyclic loading required to cause liquefaction;
CSR-coefficient of cyclic loading induced by an earthquake.

If the liquefaction resistance is greater than the expected earthquake effect, Fs will be greater than unity, otherwise, liquefaction is expected to occur. The earthquake-induced cyclic loading coefficient (CSR), is usually determined as equivalent of 65% of the maximum cyclic shear stress, by the expression:

$$CSR_{M,\sigma'v} = 0.65\ \frac{\sigma v}{\sigma\prime v}\frac{amax}{g}rd \tag{2}$$

where:
σv (kPa)-vertical overburden stress,
σ′v (kPa)-effective vertical overburden stress,
a_{max} (m/s^2)-peak ground acceleration,
g (m/s^2)-acceleration due to gravity,
rd-stress reduction factor accounting for the flexibility of the soil profile.

The coefficient of cyclic load required to cause liquefaction (CRR) can be calculated using the cone penetration test (CPT), through the correlation given by Juang et al. (2005), however most often cyclic load required is calculated based on parameters obtained by performing a standard penetration test (SPT), using the corrected blow count value:

$$(N1)\_60 = Cn \cdot Ce \cdot Cr \cdot Cb \cdot Cs \cdot Nspt \tag{3}$$

Cn-overburden correction factor,
Ce-energy correction factor,
Cr-rod length correction factor,
Cb -hole diameter correction factor,
Cs-correction factor for sampling method,
Nspt-measured number of blows in field test.

The correlation for a magnitude 7.5 earthquake to calculating the CRR from the SPT as a function of the percentage of smaller particles in the soil (FC), is given in Figure 6.

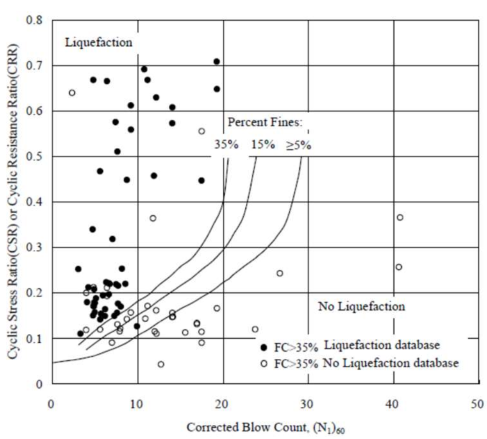

Figure 6. Liquefaction diagram based on standard penetration tests (SPT) for magnitude 7.5 earthquakes (Seed et al. 1985)

4. TERRAIN ZONING BASED ON LIQUEFACTION POTENTIAL

During the creation of liquefaction potential maps after the 1979 earthquake, the focus of analysis was on defining the type of soil, its geological age, granulometric properties, compaction, and underground water level. Based on such an analysis and a global assessment of the liquefaction potential, the area was zoned into four zones with different degrees of liquefaction occurrence.

The main characteristic of the then separated zones with a high liquefaction potential is the presence of surface layers of sand 15-20m deep, which rest on flysch or over layers of silty debris, rarely clay. Granulometric curves from zones with high liquefaction potential are very typical for their occurrence. Standard Penetration Tests (SPT) performed in zones with high liquefaction potential also show that the soil is in a state of compaction very typical for the occurrence of liquefaction. Figure 7 shows the liquefaction potential map of the municipality of Ulcinj, created as part of the revision of the urban plans. We can see that four zones of liquefaction potential have been identified and that large parts of the terrain as marked as high risk zones.

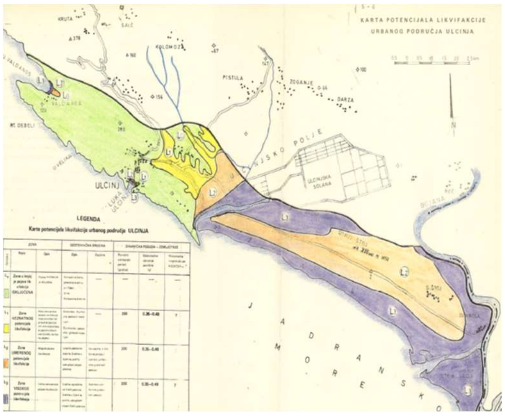

Figure 7. Liquefaction potential map of Ulcinj municipality (Institute of Earthquake Engineering and Engineering Seismology, Skoplje 1981)

The main goal of creating liquefaction potential maps after the 1979 earthquake was to estimate the global probability, however, today's liquefaction potential map uses the liquefaction potential index (LPI) as the main criteria. Liquefaction procedures predict that the soil will liquefy at a specific depth, but they do not predict the liquefaction strength at the ground surface. To fill this gap, Iwasaki et al. (1982) proposed the following assumptions in formulating the liquefaction potential index (LPI) to estimate the potential for liquefaction damage:

- The strength of liquefaction is proportional to the thickness of the liquefied layer,
- The strength of liquefaction is proportional to the proximity of the liquefied layer to the ground surface;
- The strength of liquefaction is related to the factor of safety (FS) against the initiation of liquefaction, but only the soils with FS < 1 contribute to the strength of liquefaction.

Moreover, the effect of liquefaction at depths greater than 20m is assumed to be negligible, since surface effects of liquefaction at such depths have not been reported. Due to all of the above, the criterion of liquefaction based on the LPI index is considered more appropriate, and it is given by the expression:

$$LPI = \int_{0}^{20m} F\, w(z)\, dz \tag{4}$$

w (z) = 10 – 0.5z depth weighting factor,

z (m) depth;

z = 0 weighting factor is 10 and decreased linearly to 0 at z = 20 m.

The variable F is defined as follows: F = 1 – FS, for FS ≤ 1; and F = 0 for FS > 1, Fs-factor of safety for liquefaction.

A liquefaction Potential Index was developed to predict the potential of liquefaction to cause foundation damage at a site, as follows: There is no risk of liquefaction if LPI = 0; risk is low if 0 < LPI ≤ 5; high if 5< LPI ≤ 15; and very high if LPI > 15.

5. CONCLUSION

Liquefaction potential maps created by the Institute for Earthquake Engineering and Engineering Seismology from Skopje were used as a basis for adopting urban planning plans for the coastal municipalities of Montenegro.These maps, created in 1981, recognize the risk of liquefaction in a wider area along the Montenegrin coast.

The liquefaction potential is closely related to the geotechnical properties of the surface layers, which are highly variable from one micro-location to another, so when adopting new urban plans for municipalities along the Montenegrin coast, it would be necessary to conduct research that would more closely define the potential for liquefaction.

Unfortunately, in Montenegro there are no plans to create new liquefaction potential maps of the coastal area, and we can say that even the existing liquefaction potential maps are not used, which certainly significantly increases the risk of a future earthquake.Today, the current criteria for evaluating liquefaction based on the LPI index are significantly different from the criteria that were used 45 years ago when the existing liquefaction potential maps were created for the Montenegrin coastal belt.

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