The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)

GIS-based assessment of liquefaction potential for selected earthquake scenarios

J. Bojadjieva, V. Sheshov, K. Edip, J. Chaneva, T. Kitanovski & D. Ivanovski
Ss Cyril and Methodius University, Institute of Earthquake Engineering and Engineering Seismology – IZIIS, Skopje, Macedonia

ABSTRACT: The liquefaction phenomena is a complex condition in saturated cohesionless soils caused by dynamic loads i.e. earthquakes that can cause significant damage to structures and infrastructures. The focus of the research of this paper is to define the potential of liquefaction using in-situ methods, particulary SPT investigations for a characteristic location - Ohrid city, Republic of Macedonia. Being on the Coast of Ohrid Lake, the soils of this location are with near surface water tables, and are also characterized by layers of relatively loose saturated sand, with low to high content of fines. A liquefaction potential assessment by means of an Fs (factor of safety) and PL (probability of liquefaction), was carried out for a number of locations with available results from geotechnical investigations, using the deterministic and probabilistic relations proposed by Boulanger & Idriss. The dynamic inputs for deriving the CSR (cyclic stress ratio) were parameters of PGA and Mw for two selected seismic scenarios, in accordance with the seismic hazard for the selected location. The results served as a basis for deriving a methodology for local zoning of this type of hazard, using the GIS software. The final product are 4 maps of factor of safety against liquefaction and probability map of liquefaction for the two analyzed scenario, which refer to the critical layer with potential of liquefaction. The results led to several conclusions related to the soil conditions and characteristics, the advantages of the in-situ methods, the need for additional terrain investigations as well as comparison between deterministic and probabilistic approaches. Also, they highlight the necessity for this type of investigations as a preventative measure for urban planning.

1 INTRODUCTION

In-situ methods (SPT, CPT) for liquefaction assessment can be considered as most popular approach to define the liquefaction potential for several reasons. Namely is practical, it has an advantage over the difficulties and costs associated with high-quality undisturbed sampling for high-quality laboratory testing. Moreover, the same factors that affect SPT, CPT resistance also affect the liquefaction resistance (i.e., overconsolidation, non-uniformity, density, fines content etc.). As a methodology it has been analyzed by several authors (Youd et al. 2001, Cetin et al. 2004, Idriss and Boulanger 2006, 2010, 2014) and it relies and is based on selected case histories.

The liquefaction potential can be expressed by the factor of safety (Fs) or as probability for liquefaction (PL). The probabilistic liquefaction triggering models are crucial for developing the relatively new framework for evaluating liquefaction hazards - the performance-based liquefaction assessment procedure (Kramer et al., 2006).

The relationships obtained by the probabilistic approach are to some extent recent, and their development is needed for the purpose of more representative evaluation of locations of moderate seismicity for which the deterministic relationships have proved to be a kind of an upper bound (Ulmer, 2015).

Namely, the results obtained from deterministic methods for locations of a moderate hazard considerably over predict the liquefaction hazard (Ulmer, 2015) – the safety coefficients are around 1, which points to a liquefaction potential, but still, that value of the safety coefficient is associated with relatively small probabilities for liquefaction occurrence.

So far, in the R. Macedonia, several investigations have been carried out for definition of the liquefaction potential by application of field methods and use of the deterministic approach (Cubrinovska, 2009, Sesov et al. 2012, Bojadjieva et al. 2013, Bojadjieva et al. 2016, Chaneva, 2018). Considering the fact that R. Macedonia is a country characterized by moderate to high seismicity, the extension of knowledge and investigations in the field of these methods where the probability for occurrence of liquefaction is included would be of an extraordinary importance for further application in a number of additional activities and investigations for more detailed definition of the liquefaction hazard. Namely, recent history has seen a number of earthquakes with a magnitude greater than 5 in the territory of R Macedonia, without recorded cases of liquefaction occurrence. It is exactly at this point that a question is posed as to the probability for occurrence of such type of soil instability in the case of different magnitudes, i.e., earthquakes with different return periods.

SPT is the most frequently applied field investigation in the engineering practice in R. Macedonia. This and the fact that the methods for evaluation of the liquefaction potential based on these investigations have continuously been developed and updated in literature and the fact that they have been "favored" in EUROCODE 8 has made them the subject of the investigation presented in this paper.

2 STUDY AREA

The location used as a case study is in Ohrid, as a specific area with high underground water table, complex geological conditions and moderate level of seismicity. The liquefaction potential was computed for all layers of the selected soil profile. The city of Ohrid is in southwest Macedonia, in the northeastern part of the Ohrid Lake.

The available results from geological investigations and maps show that the soil in and around the city generally consists of surface Quaternary and deep Pliocene sediments (Figure 1).

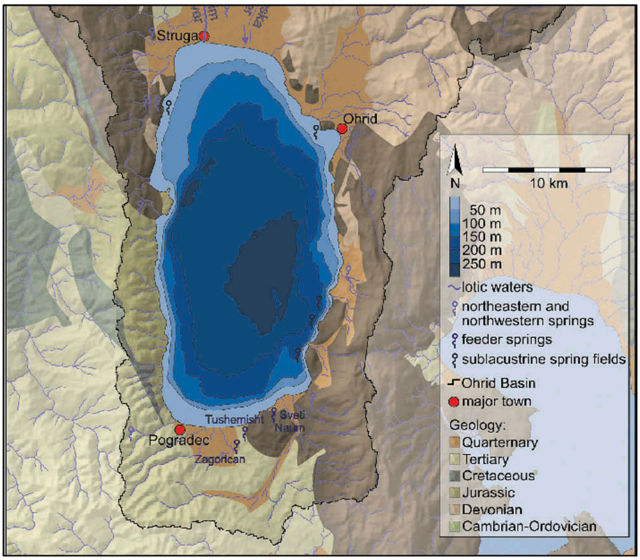

Figure 1. Map of the Ohrid basin showing major hydrological and geological features. (Hauffe et al. (2011)).

The Quaternary sediments are composed of silty-lacustrine materials composed of fine gravel and sand as well as organic clays and silty sand. The thickness of the Quaternary sediments reaches down to the depth of 20 m. These sediments are of a heterogeneous nature and are characterized by unfavourable physical-mechanical characteristics. The Pliocene sediments are composed of clays, sands and gravels characterized by much better physical-mechanical characteristics than those of the Quaternary sediments. The thickness of these sediments reaches down to the depth of 100 m. The underground water level is generally high in most of the investigated locations due to the vicinity of the Ohrid Lake.

As far as seismicity is concerned, the wider region of the Ohrid Lake is associated mainly with two epicentral areas: Ohrid – Struga and South part of the Ohrid Lake – Peshtani – Korcha.

On 18 June 2017, a series of tectonic earthquakes of a slight to moderate intensity started in the epicentral area Peshtani – Ohrid – Struga. The strongest of these took place on 3 July 2017, at 11:18 h according to local time, with a magnitude of M_L=4.9 (Seismic opbservatory UKIM PMF). The epicenter of this earthquake was at 10 km east from the city of Ohrid, in the immediate vicinity of the village Skrebatno. These earthquakes resulted in some non-structural damages to structures, but no liquefaction was recorded.

At this point, the question was posed about the probability for occurrence of liquefaction for a region with moderate to high seismicity as is the Ohrid region and this question initiated the investigations presented in this paper.

For the selected area, 16 locations (Figure 2) for which results from geotechnical investigations within SPT investigations were made available by the geotechnical company GEING Krebs und Kiefer International, Skopje, were analyzed.

These are in different parts of the city of Ohrid, but most of them lie along the lake coast, i.e., in the part where the underground water table is the highest. All 16 locations were analyzed in respect to their susceptibility and the liquefaction potential was assessed.

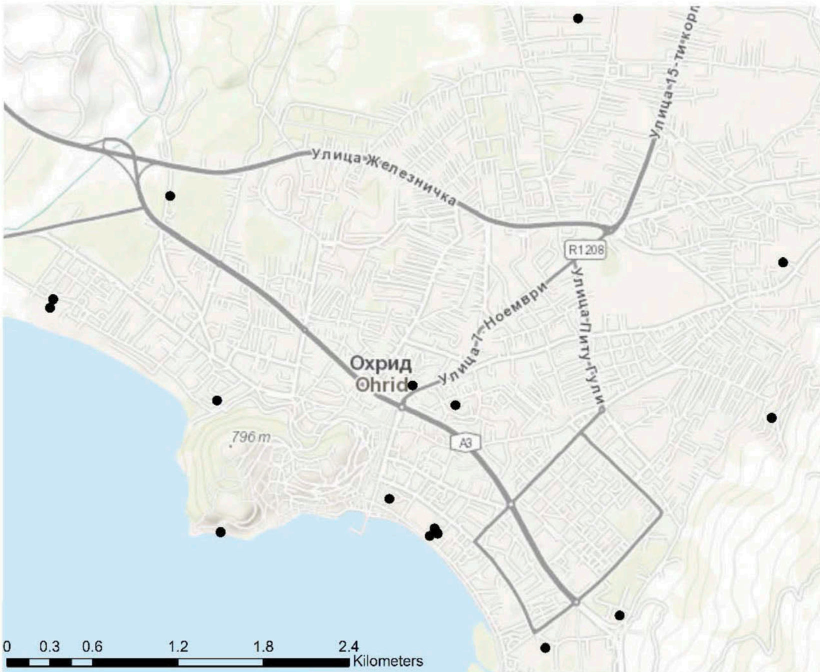

Figure 2. Presentation of the position of the sites involved in the SPT investigations

3 ASSESSMENT OF THE LIQUEFACTION POTENTIAL

3.1 *Appplied methodology for zonation*

Figure 3 shows the proposed methodology based on the investigations performed within the frames of this project from which a map of liquefaction potential for R. Macedonia could be elaborated. The systematization of the necessary data bases and parameters of the liquefaction potential will enable a good basis for further definition, zonation and raising of the awareness about the liquefaction hazard in the Republic of Macedonia.

The evaluation of liquefaction potential has three major steps (Figure 5):

1. Calculating the liquefaction resistance (CRR)
2. Calculation of the cyclic stress (CSR)
3. Calculation of safety against liquefaction (FSL)

Deterministic relations include CRR and CSR equations for deriving an Fs (factor of safety), eq. (1), which if smaller than 1, indicates that liquefaction of the selected susceptible soil would occur:

$$Fs = \frac{CRR}{CSR} \tag{1}$$

This approach basically locates a line between soils that liquefy and soils that don't liquefy – the triggering model is a curve relation of the CRR (cyclic resistance ratio), of the soil with its

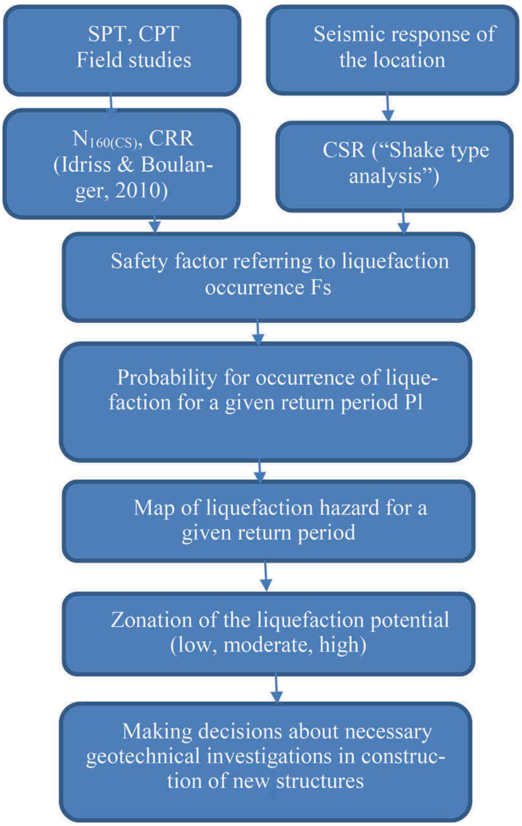

Figure 3. Proposed methodology of creation of liquefaction hazard maps

SPT – $(N_1)_{60sc}$ value. It is an interpolated curve between selected case histories of liquefaction/ no liquefaction occurrence. The CRR = f ($(N_1)_{60cs}$) empirical equation is given below (eq. 2):

$$CRR_{M=7.5,\sigma'=1atm} = \exp\left(\frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8\right) \quad (2)$$

Deterministic relations give a relatively strict yes or no answer regarding the liquefaction of a susceptible layer. The scatter of the data is more reasonably incorporated in the probabilistic relations that are developed using modern statistical tools.

The CRR deterministic equation is modified by a probabilistic Normal Distribution Function, so that it now corresponds to a certain probability of liquefaction (PL) (eq. 3):

$$CRR_{M=7.5,\sigma'=1atm} = \exp\left(\frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.67 + \sigma_{\ln(R)} * \phi^{-1}(P_L)\right) \quad (3)$$

As presented above, the CRR (cyclic resistance ratio) for a certain soil layer, using the Boulanger-Idriss proposition can be calculated using the $(N_1)_{60cs}$, value. This is the SPT clean sand equivalent N value, which is a function of FC (fines content) (Idriss, Boulanger, (2010)) eq. (4).

$$(N_1)_{60cs} = f[(N_1)_{60}; FC] \quad (4)$$

Regarding the, calculation of CSR (cyclic stress ratio), at the sites where geophysical measurements were available, SHAKE type analysis was performed to obtain the maximum acceleration through depth. For the other sites, the equation suggested by Idriss was used, which depends on the PGA, Mw and total and effective stresses of the soil layer eq. (6).

$$CSR = 0.65\frac{\sigma_v}{\sigma'_v}\frac{a_{\max}}{g}r_d \quad (6)$$

Where,

a_{max} – maximum acceleration at surface,
r_d – shear stress reduction factor that accounts for the dynamic response of the soil profiles.

3.2 *Comments on the calculations within the SPT methodology based on Boulanger and Idriss triggering model (2010)*

Regarding the considered soil profiles, a number of conclusions can be drawn in respect to the geotechnical characteristics of the soil in the considered area:

- The soil was expressively heterogeneous, with loose and soft layers present even at greater depths.
- Generally, the location is characterized by low bearing capacity soil with low compactness of the soil layers, which is evident from the described characteristics and even more from the small values of the N-measured number of SPT.
- The bedrock is located relatively deep, which together with the low bearing capacity characteristics results in large amplification of the input seismic excitation. This affects the liquefaction potential very unfavourably.

Yet, sandy, water saturated layers of considerable thickness that are very slightly granulated are relatively scarce in the considered sites. The percentage of fine particles in the sandy layers of the greater number of soil profiles is high. In addition, clayey, silty and layers with organic intercalations are very much present, which is favourable from the aspect of susceptibility to liquefaction. Generally, those sandy layers that have a small percentage of fine particles are well granulated, as well. All this affected the evaluation of the susceptibility to liquefaction for which a large number of layers of the considered soil profiles were excluded in further analysis.

It is important to note that finally there was only one critical layer susceptible to liquefaction per each analyzed site. The average depth from the ground level of the critical layers at the location was around 4.5m. The range of the global thickness of the liquefiable layers is from 2 meters up to 7 meters. Therefore it was decided to present maps of factor of safety and probability for the critical layer at the analyzed location instead of liquefaction potential index map (LPI) or Liquefaction severity number map (LSN).

During the investigation it has been identified that further extension of the assessment of the liquefaction potential based on the CPT – field test should be performed for the study area. The CPT method has extensively been used for assessment of the liquefaction potential and zoning (positive ex. van Ballegooy, S. et al. (2015)) and is considered more precise and less susceptible to improvisations in practice.

3.3 *Created GIS maps for selected seismic scenarios*

In Table 1 classification of zones for maps with presentation of the coefficient of safety against liquefaction occurrence (Fs) is presented. The proposed classification is done according to the recommendations given in EUROCODE 8 (EN 1998-5-2004 (E)) Article 4.1.2.: *The liquefaction potential is small and no improvement of the soil for safety coefficient Fs > 1.25 is necessary.* Table 2 represents the classes for zonation of the probability maps.

It is necessary to comment that, due to the fact that the maps are created by interpolation among the values of the parameters (Fs и PL), their exactness for the areas for which there are no available geotechnical reports or the available ones refer to a greater distance, can be increased by updating the database of the maps, i.e., increasing the number of geotechnical investigations whose results are used as basic documentation. It is important to mention that used scale for mapping would be more accurate with higher density of the data. Further investigation are ongoing in order to enlarge the database and perform more accurate results.

In addition to the basic information taken from the geotechnical reports, during the interpolation, care was taken that these basic information has sense for the areas of known soil, for example – the rocky hill overlooking the Kaneo beach.

Also, it should be mentioned that the results completely depended on the results from the geotechnical investigations that were not thoroughly unified, i.e., at some positions,

Table 1. Zonation of the factor of safety for liquefaction potential

Fs ≤ 1	Locations with very high liquefaction potential	(Red zone)
1.01 ≤ Fs ≤ 1.25	Locations with moderately high liquefaction potential	(Yellow zone)
Fs ≥ 1.25	Locations with low liquefaction potential	(Green zone)

Table 2. Zonation of the probability for liquefaction (Pl)

Probability [%]	Safety coefficient	Zoning
PL < 10	Fs < 1,03	
10,01 - 50	1,03 – 0,87	
50,01<PL<70	0,87 – 0, 82	
70,01<PL<95	0,82 – 0,70	
95,01<PL<100	0,70 – 0,50	

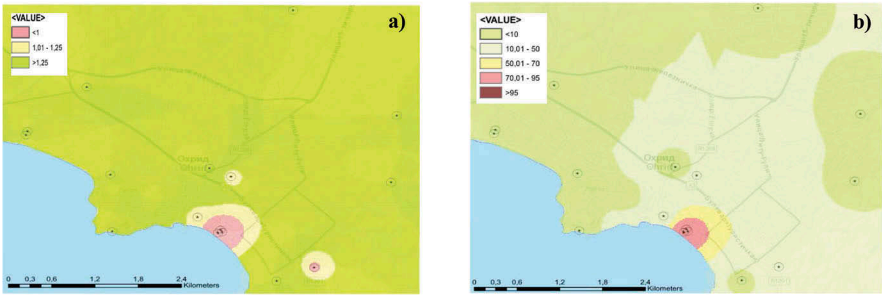

Figure 4. (a) Factor of safety against liquefaction map (b) Probability of liquefaction map for Ohrid, Macedonia for seismic scenario Mw=5, ag=0.15g

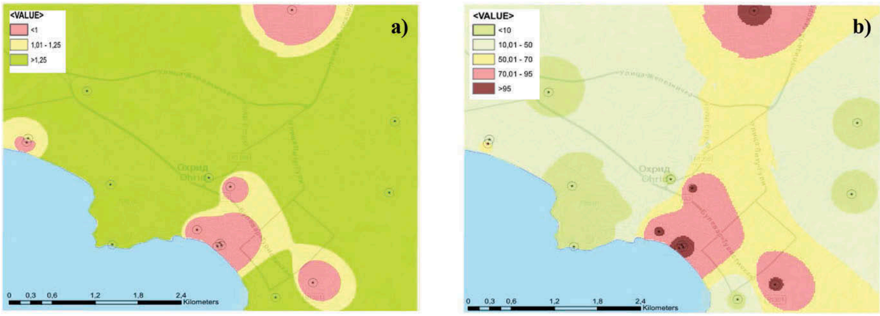

Figure 5. (a) Factor of safety against liquefaction map (b)Pprobability of liquefaction map for Ohrid, Macedonia for seismic scenario Mw=6, ag=0.25g

parameters for greater depths were available or there was a more precise classification of layers compared to other positions.

Another point is that the probabilistic triggering model does not cover site characterization uncertainties. Still, Ohrid is a location where, magnitudes around Mw = 5, are most typical, and there is no liquefaction case yet registered. This goes in favour of the results from the probabilistic triggering models.

As final product from the analysis 4 maps were created which are presented in Figure 4 and 5:

1. Fs (against liquefaction) of the critical layer for seismic scenario – Mw = 5, a0 = 0.15g;
2. Fs (against liquefaction) of the critical layer for seismic scenario – Mw = 6, a0 = 0.25g;
3. PL (probability of liquefaction) for seismic scenario – Mw = 5, a0 = 0.15g;
4. PL (probability of liquefaction) for seismic scenario – Mw = 6, a0 = 0.25g.

4 CONCLUSIONS

Based on the investigations presented in this paper the following conclusions can be made:

So far, in several case studies in R. Macedonia where field methods for evaluation of liquefaction potential were used, the analyses were done by use of the deterministic approach, i.e., through coefficient of safety against liquefaction occurrence.

The probabilistic models include a probability factor in the analysis where Fs < 1.2. In other words, they perform a new classification of zones per percentage [%] of probability where the deterministic ones indicate a red zone. This has been the main motivation for the performance of such an evaluation of a site that has recently been affected by a series of earthquakes among which an earthquake with a magnitude of Mw=5.2, with no record of liquefaction occurrence.

The results show that, for some locations that are in the red zone, according to Fs map, the probability for liquefaction occurrence in compliance with the Boulanger & Idriss model is very low to moderate. Thus, the probabilistic approach give improved insight to the real associated risk of liquefaction damage to a certain site.

Generally, this type of maps should serve as indicators of the red zones of liquefaction potential. For further decision, additional laboratory and numerical analyses of the critical soil layers for greater accuracy in evaluating the potential of liquefaction and the possible consequences are recommended.

REFERENCES

Bojadjieva J., Sesov V., Edip K. and Gjorgjiev I., 2013 "Evaluation of the Liquefaction Potential in Complex Geological Conditions" 15th International Symposium of Macedonian Association of Structural Engineers (MASE) 18–21, Struga, Macedonia.

Bojadjieva J., V. Sesov, K. Edip. 2016. "A Case Study of Liquefaction Assessment for Business Center in City of Skopje" ACUUS, Ss. Petersburg, Russia, 2016.

Bojadjieva J., Skopje 2015 "Dynamic Behaviour of Saturated Cohesionless Soils Based on Element and 1-G Experiments", doctoral dissertation.

Boulanger R. W., Idriss I.M. (2014), "CPT and SPT Based Liquefaction Triggering Procedures", Report no. UCD/CGM-14/01, University of California at Davis.

Cetin K.O., Seed R. B., Der Kiureghian A., Tokimatsu K., Harder Jr. L. F., Kayen R. E., Moss R.E.S., "Standard Penetration Test-Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Potential".

Chaneva, J., Bojadjieva, J., Sheshov, V., Edip, K. and Kitanovski, T. (2018), Application of deterministic and probabilistic - SPT based liquefaction assessment triggering models. ce/papers, 2: 603–608. doi:10.1002/cepa.736.

Cubrinovska, E., (2009), "Foundation of Structures in Urban Media with Liquefaction Potential", (in Macedonian), master thesis, UKIM-IZIIS.

Chubrinovski M., September (2013),"Liquefaction-Induced Damage in the 2010-2011 Christchurch (New Zealand) Earthquakes", 18th Int. Conf. ISSMGE.

Chubrinovski M., McManus K., Anderson K., (2013), "Earthquake Geotechnical Engineering Practice, Module 3: Identification Assessment and Mitigation of Liquefaction Hazards", New Zealand Geotechnical Society and Ministry of Business Innovation Employment Earthquake Geotechnical Engineering.

Idriss I. M., Boulanger R. W., December 2010, "SPT-BASED LIQUEFACTION TRIGGERING PROCEDURES" Report no. UCD/CGM-10/02 University of California at Davis.

Kramer, S. L., Mayfield, R. T., & Huang, Y. M. (2006). Performance-based liquefaction potential: a step toward more uniform design requirements. In *Proceedings of the US-Japan workshop on seismic design of bridges. Bellevue, WA*.

Sesov, V. et al., (2012), "Analysis of Stability and Technical Solution for Strengthening (Partially Strengthened) Structural System of the Structure of Surgical, Gynecological-Obstetrics and ORL Clinics", (in Macedonian), Public Health Institute – General Hospital – Ohrid - Evaluation of Seismic Parameters and Geophysical Field Studies, IZIIS Report 2012-02

Sesov V., Edip K., Cvetanovska J., September, 2012, "Evaluation Of The Liquefaction Potential by In-Situ Tests And Laboratory Experiments in Complex Geological Conditions", 15th World Conference on Earthquake Engineering, Lisbon, Portugal, 24–228.

Talaganov K., Petrovski J., Mihailov D., 1981, "Soil Liquefaction Seismic Risk Analysis Based on Post 1979 Earthquake Observations in Montenegro", First International Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics, Missouri University of Science and Technology.

Ulmer K. J., (2015), "Development of a simplified performance based procedure for Assessment of liquefaction triggering using liquefaction loading maps", Master thesis Brigham Young University.

Van Ballegooy, S., Wentz, F., & Boulanger, R. W. (2015). Evaluation of CPT-based liquefaction procedures at regional scale. *Soil Dynamics and Earthquake Engineering*, *79*, 315–334.

Youd et. al., April 2001 – "Liquefaction Resistance of Soils: Summary Report from 1996 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils", Journal of Geotechnical and Geoenviromental Engineering.