DOI: https://doi.org/10.5592/CO/EUROENGEO.2024.245

DESIGN AND CONSTRUCTION FOR REHABILITATION OF EARTHQUAKE DAMAGED WATER PROTECTION LEVEES - METHODOLOGY AND SOLUTIONS

IVAN MIHALJEVIĆ[1], BERISLAV RUPČIĆ[1], MARKO KAIĆ[1], GORAN GRGET[1], LEO MATEŠIĆ[1]

[1] *Geokon-Zagreb d.d., Croatia, info@geokon.hr*

Abstract

After completing emergency measures for flood protection on the levees of the rivers Kupa, Sava and Petrinjčica, damaged by the earthquake, Croatian Waters Authorities (Hrvatske vode) assigned preparation of design documentation for rehabilitation. At each location, data on damage and from geotechnical investigations were collected. The damage included deep vertical cracks in the soil and embankments, in some cases with the expulsion of sandy material as a result of liquefaction, subsidence and loss of embankment integrity, and, in a smaller number of cases, landslides towards the riverbed. For each type of damage, its impact on the stability and safety of the levee was considered, and remedial measures were proposed. The measures to rehabilitate the foundation soil, culverts and embankments were then formed into complete solutions for the repair of damaged levees, taking into account the specifics of individual sections (state of construction and infrastructure, implemented intervention rehabilitation measures, etc.). The foundation soil under the embankment has increased its resistance to liquefaction, the embankments have been rehabilitated and strengthened against seismic load, while the damaged culverts have been replaced.

Key words

water protection levees, earthquake, liquefaction, emergency measures

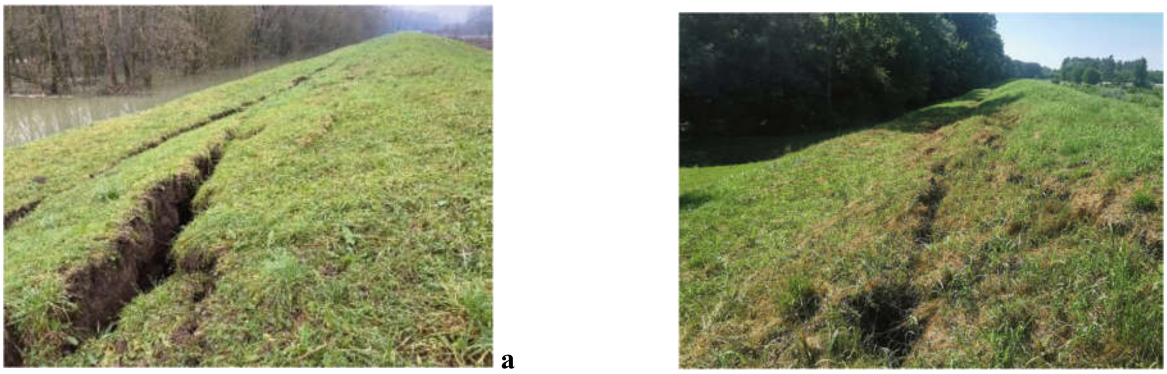
1 Introduction

Croatian Waters Authorities (Hrvatske vode) and licensed contractors companies have within less than two months after the disastrous Petrinja earthquake Mw 6.4 from December 2020, conducted expert examinations and emergency remedial measures for 14 critically damaged location of water protection levees. Using box barriers (gabion type, earth filled barriers), second line of defences were built in the locations of Galdovo (740 m), Palanjek (250 m), Krnjica (530 m), Stara Drenčina (580 m). In order to access the locations it was necessary to build new access roads in total length of about 9 km.
After the earthquake, the composition and characteristics of the underlying soil had to be investigated, as well as the mechanisms that are led to damage.

Contracts with designers were concluded six months after the earthquake. In order to gain insight into levee damage, recordings and observations carried out by experts and volunteers in the days immediately after the earthquake, when there are traces of liquefaction and cracks in the soil and levees were "fresh" (Fig. 1a), proved to be invaluable. Subsequently, many cracks in the soil self-healed, or were hidden with grass growth by the time of designing, while traces of liquefaction have been washed away (Fig. 1b).

For liquefaction and related damages there were no experiences in the recent history of Croatia and surroundings region, which also represented a challenge for permanent rehabilitation solutions.
Designing the rehabilitation of damage to levees was led by international guidelines (Seismic Design Guidelines for Dikes, 2014) and published professional works (Sasaki et al., 2004). Designers were

looking for technical solutions that would be simple to implement, robust in application and safe for the final state of the performed rehabilitation.



a b

Figure 1. Comparison of the levee crack: a) immediately after the earthquake and b) after 6 months

2 Geotechnical investigation works

At the locations of damaged levees, geotechnical investigation works were carried out, which consisted of geological and hydrogeological survey, geophysical field survey and exploratory drilling, as well as laboratory tests.

The geotechnical stratification of the underlying soil and the physical and mechanical parameters of the material were determined by exploratory boreholes. Special emphasis was placed on performing a larger number of static penetration tests (CPT), given that the determination of liquefaction potential relied on CPT tests (Boulanger and Idriss, 2014). Geophysical measurements were carried out with the aim of determining the thickness of the roof clay layer along the levee. Geophysical methods of seismic refraction, MASW (multichannel analysis of surface waves) and geoelectrical tomography were applied. In most locations, the composition of the foundation soil was determined, which consisted of roof clay layer and sand and gravel underneath (Figure 2).

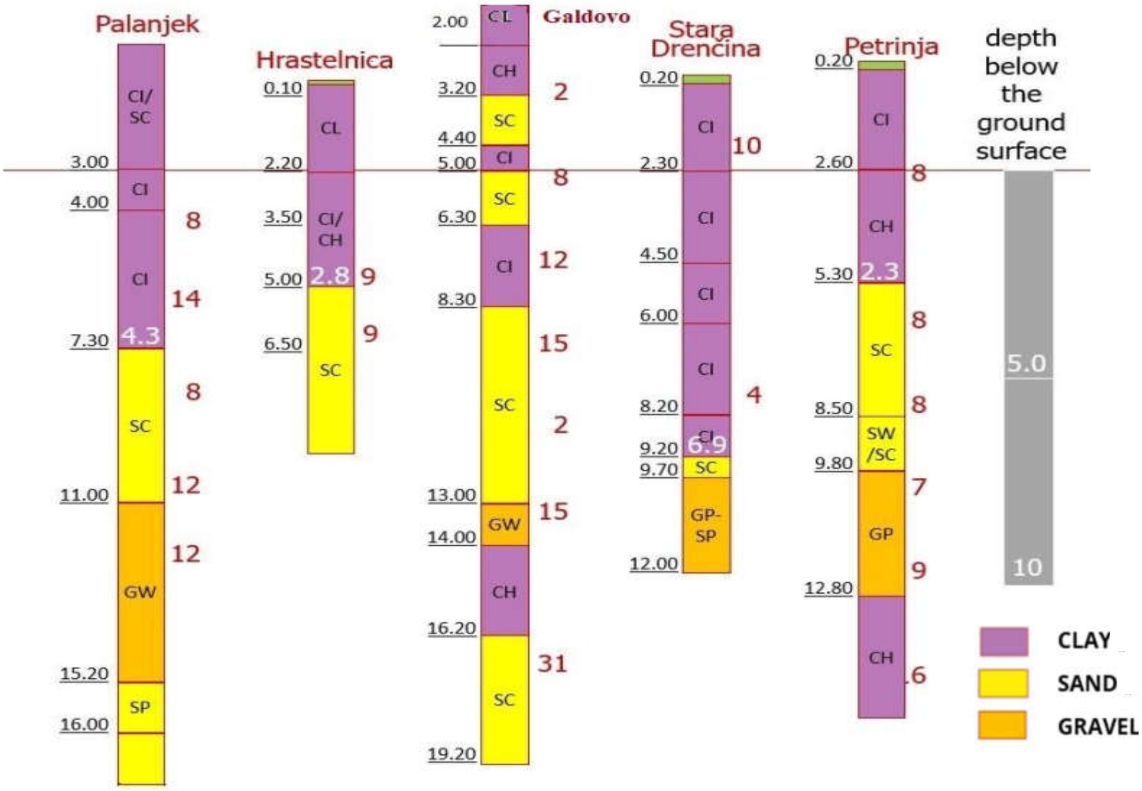


Figure 2. Geotechnical layering of embankment and subsoil by depth at damage locations with SPT values (according to Mihaljević and Zlatović, 2023)

Seismological data were analysed from the official seismological maps of the Republic of Croatia. But the designers considered that the peak accelerations of the return periods were underestimated compared to the past earthquake, so based on the data of the Seismological Service at the Geophysics Department of the Faculty of Science in Zagreb (2021), the maximum values were defined for further design magnitude M_w 6.5 and horizontal acceleration a = 0.2 g. The soil is classified as soil type C and S2.

3 Analysis of liquefaction potential

In practice, procedures based on field correlations of the appearance of liquefaction with the results of in situ experiments, SPT and CPT (Seed and Idriss, 1971) are used to assess the liquefaction potential, for which empirical liquefaction diagrams are used.

The basis of the evaluation of the liquefaction potential is the calculation of the cyclic resistance ratio (CRR) to define the resistance of the soil to cyclic loading, and the cyclic stress ratio (CSR). If CSR is CRR, it can be concluded that the analysed soil is subject to liquefaction. If the CRR value is higher, the probability of liquefaction occurrence is low.

According to EC8, the formula for the required safety factor against the occurrence of liquefaction is:

$$F_s = \frac{CRR_{7,5} \cdot CM}{CSR} > 1{,}25$$

where is:

- CSR is the calculated shear cyclic stress ratio for a given earthquake,
- CRR7.5 is the cyclic resistance ratio for an earthquake of magnitude M=7.5,
- CM is the magnitude adjustment factor. (Magnitude Scaling Factor).

The liquefaction safety factor can be determined continuously by depth for each individual CPT test result. Based on the methodology proposed by Juang et al. (2002) also calculated the probability of liquefaction according to the depth of each test. Chen and Juang (2000) proposed a soil classification with regard to liquefaction potential according to Table 1.

Table 1. Soil classes according to liquefaction probability

Probability of liquefaction	Class	Description
0.85 ≤ PL	5	The soil will almost certainly liquefy
0.65 ≤ PL < 0.85	4	It is very likely that the soil will liquefy
0.35 ≤ PL < 0.65	3	Liquefaction / non-liquefaction is equally likely
0.15 ≤ PL < 0.35	2	It is unlikely that the soil will liquefy
PL < 0.15	1	Almost certainly the soil will not liquefy

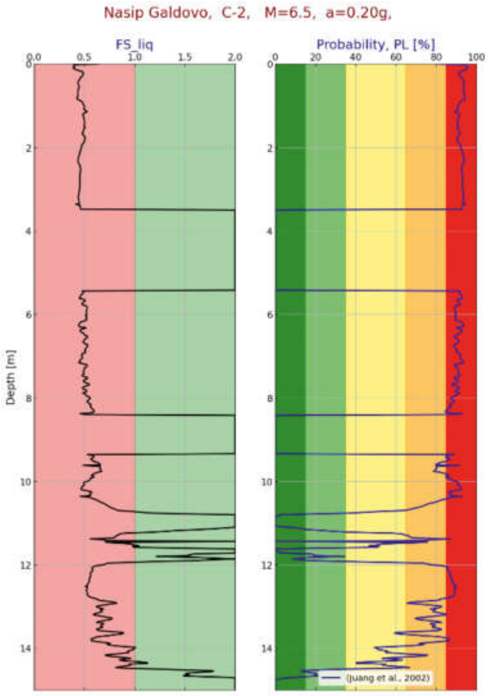


Figure 3. Safety factor against liquefaction and probability of liquefaction occurrence (Galdovo)

The analysis of the liquefaction potential at the locations of the damaged embankments was carried out according to the results of field CPTU tests, for an earthquake of magnitude M_w 6.5, with an assumed high level of underground water (Fig.3).

The results at the locations of most of the damaged embankments showed a high potential for the occurrence of liquefaction.

In addition to the appearance of liquefaction in the sandy layers of the foundation soil, the loss of strength under the seismic action was also observed in clays and silts under the name of cyclic softening. The phenomenon is caused by the increase of additional pore pressures, as a consequence of seismic action, which results in a temporary reduction or loss of strength in clays and silts. The phenomenon is comparable to the phenomenon of liquefaction in sands, except that there is no physical flow and movement of material, but instead large shear deformation occurs.

Taking that into account, high liquefaction potential in sands, or quasi-liquefaction potential, i.e. cyclic softening in clays and silts, is not surprising.

4. Rehabilitation methodology and solutions

Conceptualizing solutions for levee rehabilitation was approached by grouping according to the manifested type of damage, which is associated with the probable causes of its occurrence and the impact on the stability and safety of the levee.

4 main types of embankment damage were detected according to Table 2:

Table 2. Grouping types of levee damage with probable causes and impact on stability and safety

	Type of damage	Probable cause	Impact on the stability and safety
1)	Cracks in the levee that extend deep into the underlying soil	- Shear failure of clay soil layer caused by settlement, due to liquefaction of underlying sand layer	- Structural integrity of the levee body is compromised. - Open path for internal erosion and piping due to seepage.
2)	Settlement / sliding of the levee	- Liquefaction of sand layer in the foundation soil, accompanied with sand ejecta through cracks or in the watercourse.	- Loss of overflow height - possible overtopping - Questionable bearing capacity of foundation soil
3)	Cracks on the toe of the levee / with or without sand ejecta	- Shear failure of clay soil layer caused by seismic shaking - Shear failure of clay soil layer caused by settlement, due to liquefaction of underlying sand layer	- Open path for internal erosion and piping due to seepage. - Possible significant water flow on the protected side of the levee
4)	Structural damage of discharge pipe culverts in the levees	- Structural failure of pipes due to settlement	- Probable piping - Functionality of discharge pipes is compromised

Variants of remedial measures were considered for each type of damage. The levees of a single section most often included several types of damage, so priority was given to solutions that could meet the requirements of repairing several types of damage and at the same time meet the criteria of simplicity, robustness and safety.

The limiting factor in the projects was the investor's request that the rehabilitation be carried out within the geometry of the existing levee and in the width of the existing cadastral parcels of the levee.
The chosen solution for levee that developed cracks and deformations and lost their integrity consisted of partial or complete removal of the clay embankment body and its reconstruction in the geometry that existed before the earthquake, while reinforcing the levee body by installing layers of geogrids (Sasaki et al., 2004).

A special challenge was represented by longitudinal, deep cracks along the toe of the embankment, which partially collapsed and self-healed after a certain time after the earthquake. The question arose whether it is necessary to treat them and in what way. It was concluded that they represent a permanent problem as places of possible seepage and internal erosion under the levee, and that they must be rehabilitated in the zone immediately next to the toe of the levee.

The idea of filling with coherent or incoherent materials was abandoned due to the unreliability of such a method, as well as the idea of injecting cracks, which would create unnatural inclusions in the soil, of different stiffness and questionable durability.

It was decided to excavate the foundation soil in the areas of the cracks near the toe of the levee to a minimum depth of 1.5 m and to install the clay material in a controlled manner, in order to ensure continuation of the soil conditions and safety from the hydraulic uplift.

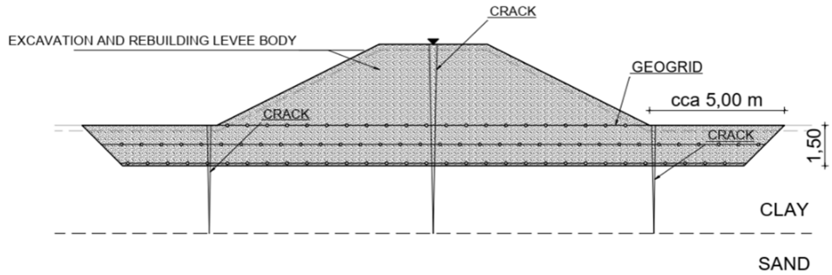


Figure 4. Solution for the repair of cracks and strengthening of levee against seismic loads

The results of the investigation showed that the underlying soil under the levee, even after the appearance of liquefaction in the past earthquake, is susceptible to liquefaction for new seismic actions and it is necessary to strengthen it.

On the parts of the levees that have experienced subsidence due to liquefaction, the foundation soil in the zone of the sand layer has been rehabilitated with a grid of jet-grouting columns, which have the role of increasing the resistance of the layer to seismic cyclic loading and, in the event of liquefaction, transfer the loads from the embankment and the overlying layer, as shown in Figure 5.

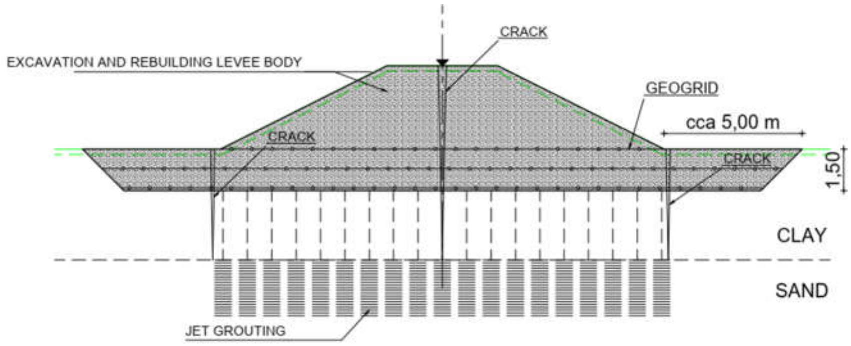


Figure 5. The solution for strengthening the sand layer under the levee with jet-grouting columns

In places of damaged pipe culverts, the solution consisted of excavation and removal of the culvert, improvement of the subsoil under the culvert with jet-grouting columns and construction of a new concrete culvert.

On the section of the damaged Sava levee near Galdovo, where the underlying soil is sandy, the improvement of the underlying soil by impulse compaction (rapid impact compaction - RIC) was chosen, as illustrated in Figure 6. With this improvement method the soil is compacted and brought to a denser state by a machine that strikes the surface of the foundation soil dozens of times per minute with a weight over a transfer plate. RIC was chosen because of its applicability to increase the density of granular soils and thereby reduce the likelihood of liquefaction.

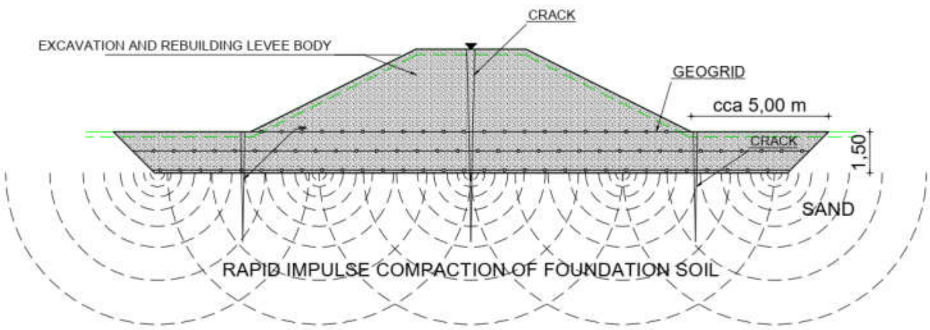


Figure 6. The solution of strengthening the sand layer under the levee by impulse compaction

Control of the improvement by pulse compaction in terms of resistance to liquefaction is carried out by CPTU tests before and after the reclamation of the base soil. Although some limiting factors occurred during rehabilitation works (high water levels of river Sava resulting in high ground water levels) results showed that liquefaction potential has been significantly reduced.

On two sections of the left Kupa levee, where sliding and translational movement of the levee towards the riverbed occurred, the levee was relocated inland and reinforced, as shown in Figure 7.

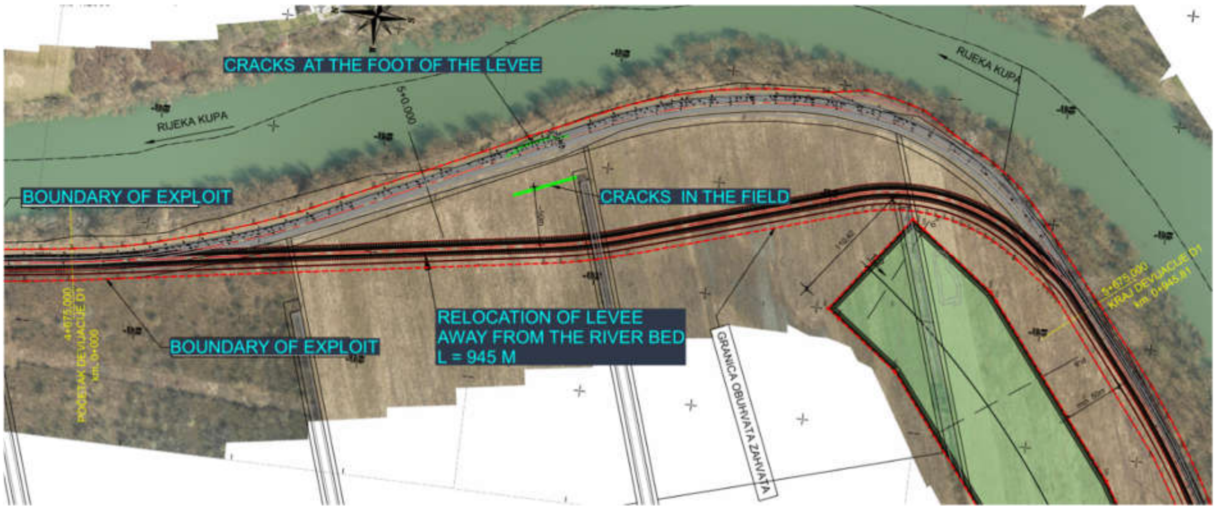


Figure 7. Relocation of the left Kupa levee damaged by sliding to the river bank (section Staro Pračno - Stara Drenčina), (*rijeka Kupa*= river Kupa)

5 Conclusion

For the permanent rehabilitation of levees damaged by the catastrophic Petrinja Mw 6.4 earthquake from 29.12.2020, geotechnical investigations were carried out and all available data on damage was collected. Damages were grouped according to type and probable causes, and their impact on the stability and safety of the levee was assessed.

Possible variants of rehabilitation measures by type of damage were considered. By combining the application of rehabilitation measures, complete solutions were formed that took into account the type of damage and the specifics of individual sections (state of construction and infrastructure, implemented interventional rehabilitation measures, etc.). Solutions were chosen that are easy to implement, robust in application and provide sufficient stability and security for design loads.

Table 3. Presentation of applied repair methods by type of damage

Type of damage	Rehabilitation measures
1), 3)	- Removal of the damaged levee, - Excavation of the foundation soil at the toe of the levee, - Reconstruction of the levee with geogrid reinforcement
2)	- Improvement of the sand layer of the soil with jet-grouting columns
2)	- Relocating the levee to a new location inland
2)	- Improvement of the sandy foundation soil by rapid impulse compaction
4)	- Removal of the damaged levee - Improvement of the foundation soil, - Removal of the damaged pipe culvert and construction of a new concrete culvert and building levee reinforced by geogrid

It is possible that in the upcoming period, under high water loads, residual damage which remained hidden, will manifest on unrehabilitated levee sections. Therefore, the importance of continuous levee inspections is emphasized and projects for levee modernization and strengthening should be launched over time.

References

Boulanger, R.W.; Idriss, I.M., CPT and SPT based liquefaction triggering procedures, *Report No. UCD/CGM-14/01, Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis, CA, 134 pp.*, 2014

Chen, C. J.; Juang, C. H., Calibration of SPT- and CPT-Based Liquefaction Evaluation Methods, *Innovations and Applications in Geotechnical Site Characterization, doi:10.1061/40505(285)4*, 2000

Geokon-Zagreb d.d., Geotehnički istražni radovi za izvanredno održavanje l.o. savskog nasipa od n.km.r. 101+200 do n.km.r. 102+000 u naselju Galdovo; *Geokon-Zagreb d.d., Br. E-061-21-01, Zagreb*, 2021a

Geokon-Zagreb d.d., Projekt izvanrednog održavanja lijevoobalni savski nasip od n.km 101+200 do n.km 102+000 u naselju Galdovo, Sisačko-moslavačka županija; *Geokon-Zagreb d.d., Br. E-061-21-02, Zagreb*, 2021b

Juang, C.H., Jiang, T.; Andrus, R.D., Assessing probability-based methods for liquefaction evaluation, *Journal of Geotechnical and Geoenvironmental Engineering*, 128 (7), pp. 580-589, 2002

Mihaljević, I.; Zlatović, S. (), Embankments Damaged in the Magnitude Mw 6.4 Petrinja Earthquake and Remediation. *Geosciences 2023*, 13, 48. https://doi.org/10.3390/geosciences13020048, 2023

Ministry of Forests, Lands, and Natural Resource Operations – Flood Safety Division, *Seismic Design Guidelines for Dikes*, 2nd Edition, BC, Canada, 2014

Mihaljević, I., Zlatović, S., Čičak, M.: Croatian experience on urgent measures and remediation of levees after earthquake Mw 6.4 on December 2020, Proceedings from 13th Conference on Water Economy and Hydrotechnics, MACOLD 2023, Skopje, pp 59-68, ISBN 978-608-4953-02-9

Sasaki, Y.; Fukuwatari, T.; Tsuji, T.; Kano, S.; Sawada, S.; Uekuma, H., A Study on the Performance of a Reinforced Dike Section With Geogrid During the Tottori-Ken Seibu Earthquake, *International Conference on Case Histories in Geotechnical Engineering*. 36., 2004

Seed, H.B.; Idriss, I.M., Simplified procedure for evaluating soil Liquefaction Potential, *Journal of the Soil Mechanics and Foundation Division*, 97, pp. 1249-1273., 1971

Seizmološka služba, Preliminarni rezultati serije potresa kod Petrinje od 28. prosinca 2020. do 28. siječnja 2021., https://www.pmf.unizg.hr/geof/seizmoloska_sluzba/ mjesec_dana_od_glavnog_petrinjskog_potresa, 2021