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Numerical Modelling of Changes in Local Seismic Site Response During Progressive Tailings Dam Raising

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SUMMARY

The seismic safety of tailings storage facilities becomes increasingly important as these structures are progressively raised during operation. Continuous embankment construction modifies the engineering geological conditions and surface topography, which may significantly affect local seismic site response and, consequently, the design seismic loading. This study investigates the influence of progressive tailings dam raising on seismic site conditions using numerical modelling. The methodology integrates a digital geological model, engineering geological and geophysical investigation data, and three-dimensional models of the natural and projected topography. The spatial distribution of technogenic deposit thickness was determined from the difference between the natural and design ground surfaces. Local seismic site response was evaluated using one-dimensional equivalent-linear soil response modelling and two-dimensional finite-difference simulations to account for topographic effects. Site-specific synthetic accelerograms and corresponding response spectra were generated for different stages of tailings dam raising. The modelling results demonstrate that increasing the thickness of technogenic deposits and the development of pronounced technogenic relief significantly modify local seismic response by changing the frequency characteristics and amplifying earthquake ground motion. The greatest amplification occurs in areas with substantial elevation differences and steep relief gradients, resulting in increased design seismic loading. The proposed approach provides an effective framework for evaluating the evolution of local seismic hazard throughout the operational life of tailings storage facilities. The results demonstrate that progressive changes in engineering geological conditions should be explicitly considered in seismic hazard assessment and in the development of site-specific design seismic loading for tailings dams.

Keywords: Tailings storage facility; Local seismic site response; Numerical modelling; Seismic hazard assessment; Technogenic deposits; Response spectra; Synthetic accelerograms.

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Introduction

Tailings storage facilities (TSFs) of large mining and processing enterprises belong to the highest consequence class of engineering structures, where failure may result in severe environmental, social, and economic impacts. One of the key factors controlling their safety is seismic loading associated with both natural tectonic earthquakes and mining-induced seismicity (Kendzera et al., 2021). TSFs represent large-scale anthropogenic geological systems whose long-term operation modifies the engineering geological, hydrogeological, and geomorphological conditions of the site. Progressive dam raising and continuous deposition of tailings form thick technogenic soil deposits with specific physical, mechanical, and dynamic properties, influencing seismic wave propagation, the frequency characteristics of ground motion, and local seismic site response. Temporal changes in these properties during long-term operation directly affect the design seismic loading and therefore should be considered in seismic hazard assessment (ICOLD, 2016; Ministry for Communities and Territories Development of Ukraine, 2025).

According to the requirements of the Ukrainian Building Code DBN V.1.1-12:2025 (Ministry for Communities and Territories Development of Ukraine, 2025), seismic resistance of consequence class CC3 structures shall be evaluated using the direct dynamic method, in which seismic loading is represented by digital ground-motion records (accelerograms). The frequency content of seismic ground motion is one of the governing parameters controlling resonance effects and the stress–strain behaviour of retaining dams. Progressive dam raising and the associated changes in technogenic soil properties modify the dynamic site response and the spectral characteristics of ground motion, thereby affecting the design seismic loading parameters (Dejphumee et al., 2026; Labanda et al., 2021). The aim of this study is to apply numerical modelling to predict changes in the seismic hazard of tailings during progressive dam raising, investigate the transformation of earthquake ground motion, and generate site-specific design accelerograms accounting for the evolving engineering geological conditions of the technogenic massif.

Method and Theory

In engineering seismology, the design seismic loading at a site is determined by the combined effect of the regional seismic hazard and local site conditions. According to the conventional Ukrainian regulatory approach, the design seismic intensity is evaluated as the sum of the normative seismic intensity (I_n) and the increment of seismic intensity (ΔI) caused by local ground conditions. Within the Kryvyi Rih Iron Ore Basin, the seismic hazard affecting tailings storage facilities is primarily associated with strong earthquakes originating from the Carpathian seismic region (Vrancea zone), the Crimean–Black Sea seismic region, the Dobruja seismic source area, and local earthquakes of the Ukrainian Shield. These seismic and seismotectonic characteristics were incorporated by the S.I. Subbotin Institute of Geophysics of the National Academy of Sciences of Ukraine in the General Seismic Zoning Map of Ukraine (GSZ-2004) (Ministry for Communities and Territories Development of Ukraine, 2025).

Modern approaches to seismic microzonation based on numerical modelling require the development of a digital structural-parametric model of the geological environment. For engineering seismological investigations, a physical-geological model is developed as a structural representation of the geological environment parameterized by the physical properties of geological formations, primarily seismic wave velocities and density. The structural model is constructed using all available geological exploration and engineering geological data, whereas the velocity and density characteristics are determined from shallow seismic surveys and engineering geological investigations.

A considerable amount of geological exploration and engineering geological information has been accumulated for the study area. Since a significant part of these data is available only in analogue form, the construction of a digital structural model requires vectorization and digitization using modern geographic information system (GIS) technologies. Particular attention is paid to structural elements characterized by significant elevation changes within the tailings storage facility, including the natural ground surface, the design technogenic relief, and the thickness of technogenic deposits.

The influence of natural sedimentary sequences and technogenic soils on earthquake ground motion is evaluated by one-dimensional site response modelling from the top of the crystalline basement to the ground surface using the SHAKE software package (Stewart et al., 2022). The influence of the projected technogenic relief on seismic intensity increment is analysed using the two-dimensional full-wave modelling package Tesseral-2D, which simulates seismic wave propagation by solving the elastic wave equation with the finite-difference method.

Results and Conclusions

The proposed methodology was validated using one of the prospective tailings storage facilities in the Kryvyi Rih Iron Ore Basin. Based on the design documentation, digital models of the natural topography and the projected technogenic relief were developed (Figure 1). These models served as the basis for determining the spatial distribution of technogenic deposit thickness (Figure 2).

The resulting digital models, together with geological exploration, engineering geological, and shallow seismic survey data, were used to develop the numerical models for evaluating the influence of local site conditions on earthquake ground motion. Figure 3 illustrates the relationship between seismic intensity increment and the thickness of technogenic deposits. The modelling results demonstrate that progressive raising of the tailings storage facility leads to significant changes in the frequency characteristics of seismic ground motion, as reflected in the corresponding response spectra (Figure 4). The technogenic relief has a pronounced effect on seismic wave amplification. For elevation differences exceeding 20–30 m and relief gradients greater than 0.12–0.15 m/m, the amplification factor may exceed 1.5, corresponding to an increase in seismic intensity of more than 0.5 intensity points.

The results demonstrate that progressive tailings dam raising should be explicitly considered in seismic hazard assessment and in the development of design seismic loading for tailings storage facilities. Neglecting changes in the engineering geological structure and technogenic relief may lead to an underestimation of local site amplification and, consequently, to unconservative estimates of seismic loading acting on retaining dams. An important aspect is the assessment of the potential liquefaction of technogenic soils during earthquakes (Viktosenko & Dovbnich, 2025).

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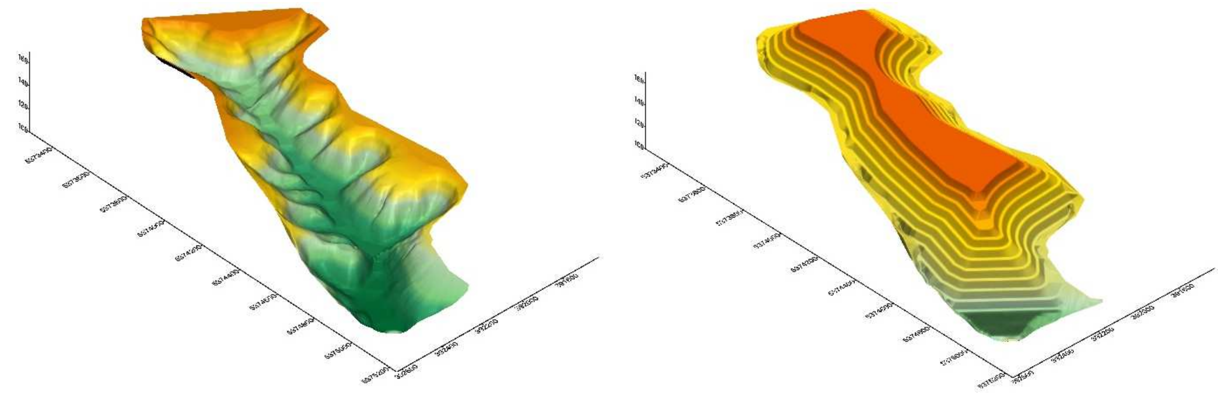

(a) (b)

***Figure 1**. 3D models of the natural (a) and projected technogenic (b) ground surface topography according to the tailings storage facility design (vertical scale exaggerated five times relative to the horizontal scale)*

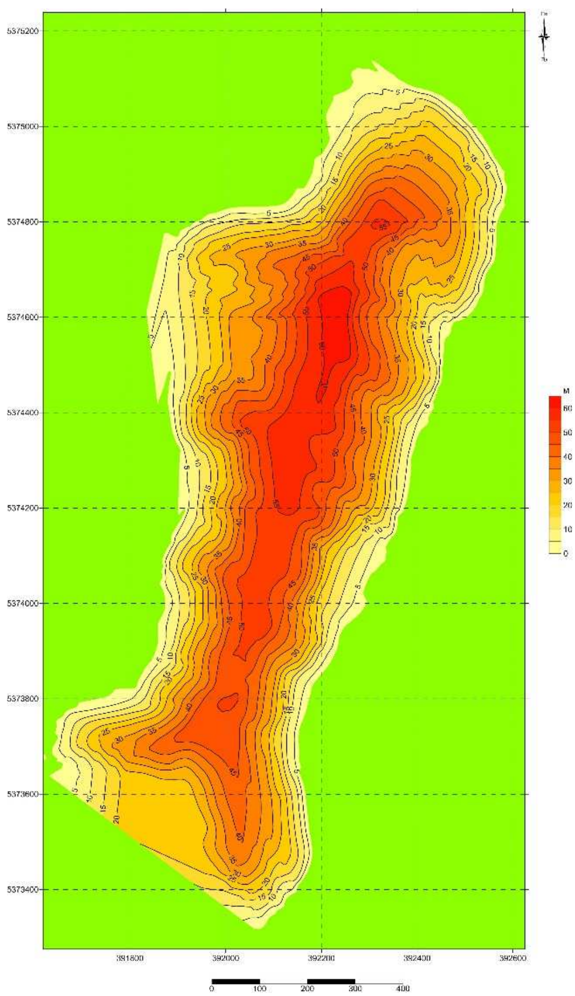

***Figure 2.** Isopach scheme of technogenic deposits accounting for the progressive raising of the tailings storage facility to the design elevation*

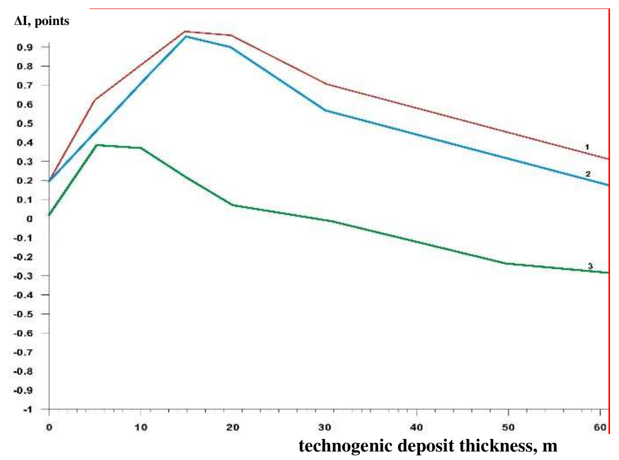

***Figure 3.** Seismic intensity increment as a function of technogenic deposit thickness: (1) long-period, (2) intermediate-period, and (3) short-period seismic excitation*

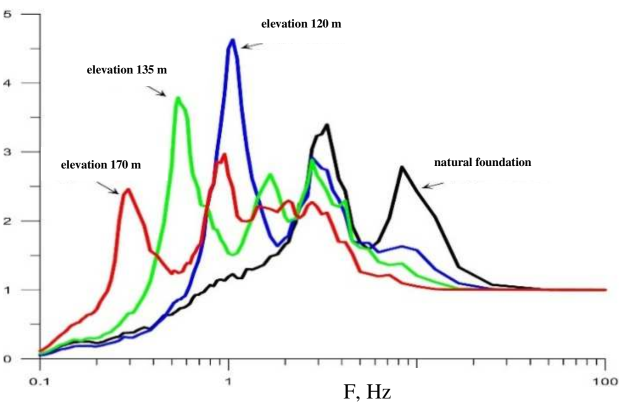

***Figure 4.** Comparison of the response spectra of synthetic accelerograms expressed as dynamic amplification factor (β, 5% damping) spectra for different stages of tailings storage facility raising*

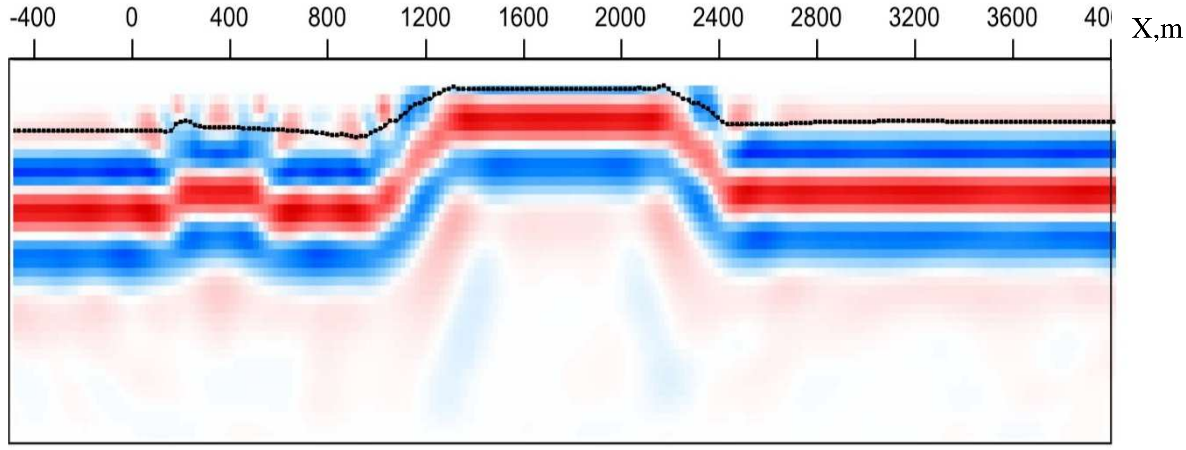

Figure 5. *Example of seismic wave propagation modelling in the presence of technogenic topography*

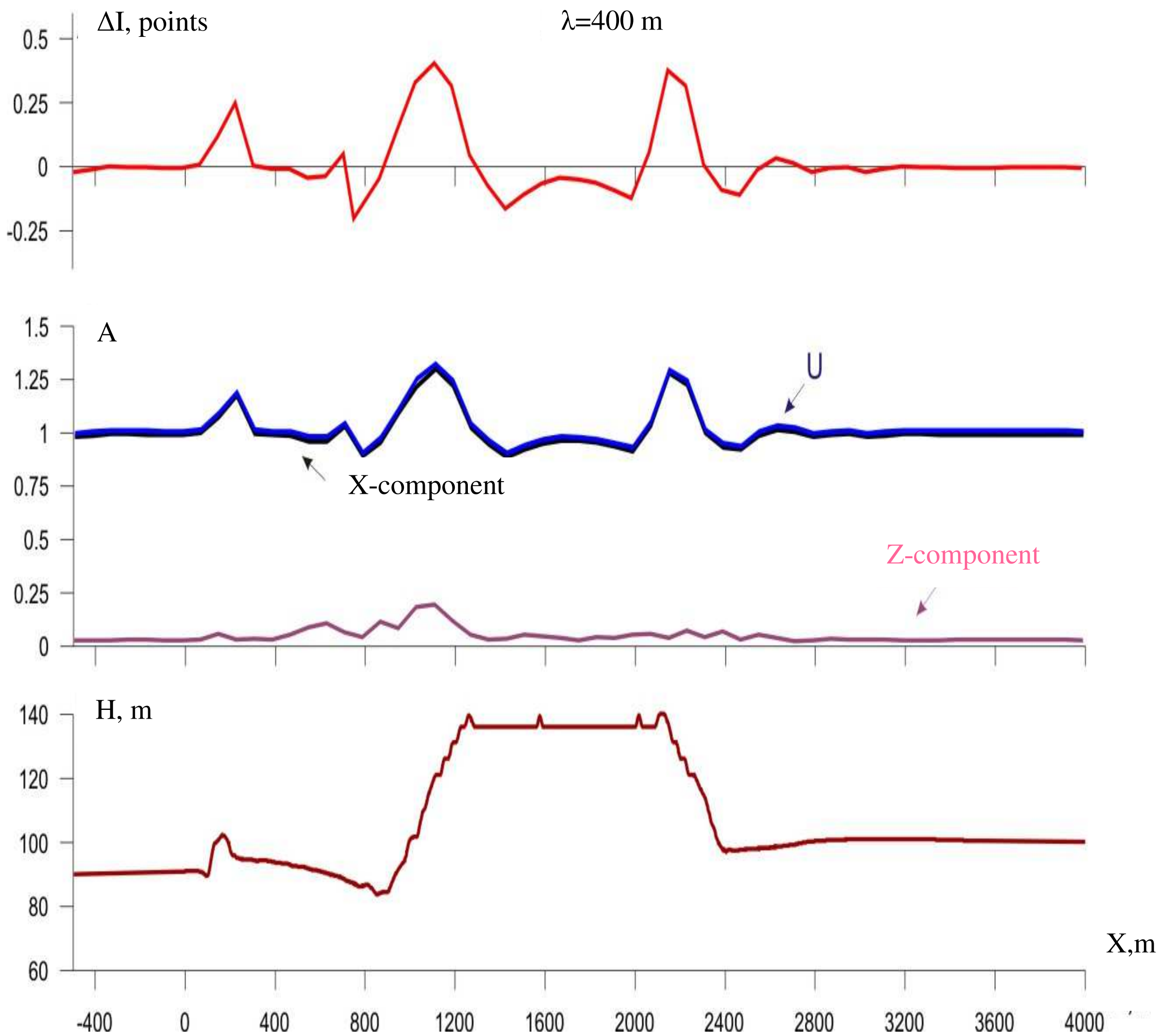

Figure 6. *Example of ground motion amplification and seismic intensity increment induced by technogenic topography*