

NORM Disposal Sites at the Closed Uranium Mine Žirovski Vrh

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ABSTRACT

The closed Žirovski vrh uranium mine is in Slovenia, in the Poljane valley south of the village Gorenja vas. The uranium mineralization is hosted within middle Permian clastics of the Gröden formation, and the deposit was classified as medium-sized based on its reserves. Uranium concentrate production was carried out from 1984 until June 1990, when operations were terminated by government decree. The Act on the Permanent Cessation of Uranium Ore Exploitation (1992) defined the legal framework for mine closure, facility decommissioning, and long-term environmental protection. The Jazbec and Boršt disposal sites form the core infrastructure for permanent decommissioning and long-term containment of mining and processing (milling) residues. Remediation combined slope stabilization, multi-layer engineered cover systems, and hydraulic control measures to limit radon exhalation and prevent radionuclide and heavy metal migration into surface and groundwater. The Boršt disposal facility is located on the northeastern slope of Boršt Hill (535–565 m a.s.l.), covers 4,2 ha, and contains 610.000 tonnes of hydrometallurgical tailings, 111.000 tonnes of mine waste rock, and 9.450 tonnes of radioactively contaminated material, with a total activity of 48,8 TBq. It is sealed by a 2,05 m multi-layer cover. Slope instability was identified due to a reactivated paleo-landslide; as a consequence, stabilisation works included construction of a rock-fill toe wall, a drainage tunnel and an array of sub-horizontal drainage boreholes. Residual movements are monitored by geodetic and GPS methods. The Jazbec disposal site lies in the Jazbec stream valley at elevations between 427,5 and 509 m a.s.l and contains 1,91 million tonnes of material, including 48.000 tonnes of Th-230 enriched red precipitate. The disposal body covers 6,6 ha, within a restricted area of 7,4 ha, with engineered slopes not exceeding 20° and a protective multi-layer cover of 1,95 m to limit erosion and water ingress. Following completion of remediation, both disposal facilities were designated as national infrastructure for long-term containment. The Agency for Radioactive Waste Management (ARAO) is responsible for their long-term institutional control, maintenance, and surveillance. Systematic monitoring ensures that effective dose contributions to the critical group do not exceed the regulatory limit of 0,3 mSv/year, and so far, results indicate that exposures in the vicinity of the sites remain below this threshold. This case provides a rare example of long-term management of uranium mill tailings in a geotechnically active environment, demonstrating the effectiveness of drainage-based stabilization combined with engineered cover systems and active institutional control.

Keywords: NORM Disposal sites, Žirovski vrh uranium mine, Monitoring, Agency for Radioactive Waste Management (ARAO)

1 INTRODUCTION

The closed Žirovski vrh uranium mine is located in western Slovenia, near the village of Todraž in the Municipality of Gorenja Vas–Poljane, approximately 45 km west of Ljubljana. The

Žirovski vrh uranium mine produced approximately 600.000 tonnes of uranium ore during its active years. Regular production of yellowcake was terminated in 1990. The legislative framework for the closure was established by the Act on the Permanent Cessation of Uranium Ore Exploitation (1992), which assigned the task of remediation and environmental protection to the public company Rudnik Žirovski vrh (RŽV).

The closure process involved the decommissioning of the processing plant at Todraž site and the remediation of two primary waste sites: Jazbec (mine waste rock) and Boršt (hydrometallurgical tailings). In 2015, following the successful completion of remediation and a transitional monitoring period, the Jazbec disposal site was officially closed and designated as a national infrastructure facility, with long-term management and surveillance assumed by the Agency for Radioactive Waste Management (ARAO). Subsequently, in 2025, after an extended transition period due to geotechnical stabilization requirements, the Boršt disposal site was also formally closed, transferred to ARAO, and granted the status of national infrastructure.

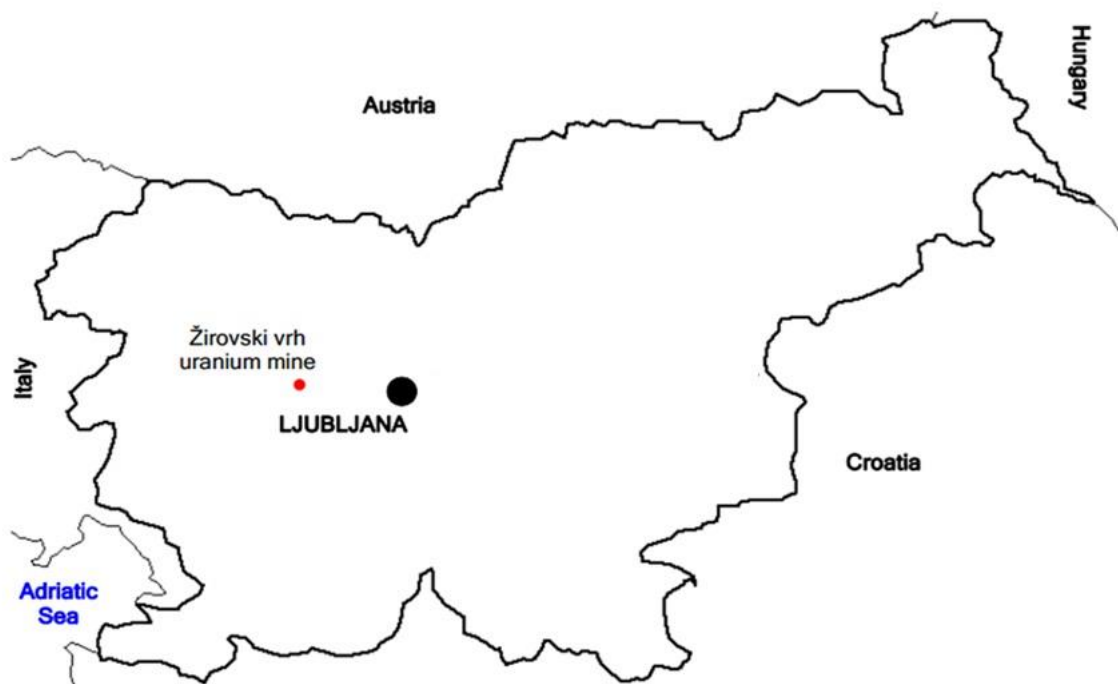


Figure 1: Location of the closed Žirovski vrh uranium mine

2 JAZBEC MINE WASTE DISPOSAL SITE

2.1 Inventory and Site Characteristics

The Jazbec disposal site is situated within the valley of the Jazbec stream, where the natural topography was utilized and subsequently modified to accommodate the disposal of mining and processing residues. The site contains approximately 1,91 million tonnes of material, including predominantly mine waste rock and low-grade ore. A key component of the inventory is approximately 48.000 tonnes of so-called red precipitate, a fine-grained sandy-silty residue generated during uranium hydrometallurgical processing. This material is characterized by elevated concentrations of Thorium-230 (typically 60–65 kBq/kg), representing a significant long-term radiological source term due to its decay into Radium-226. As a result, the Jazbec site is particularly

relevant from a long-term radiological perspective, as radionuclide activity is expected to evolve over time through decay chain ingrowth.

From a geotechnical and hydrogeological standpoint, the heterogeneous composition of the disposal body—combining coarse waste rock with finer processing residues—affects both permeability and water retention characteristics. These properties influence infiltration processes, seepage generation, and radionuclide transport behaviour, making effective hydraulic control and cover performance essential for long-term stability and environmental protection.



Figure 2: Jazbec mine waste disposal site

2.2 Engineered Cover System

The disposal body covers an area of approximately 6,6 hectares and is protected by a 1,95 m thick multi-layer engineered cover system designed in accordance with the multi-barrier concept.

The cover system integrates several functional layers that collectively provide:

- radon attenuation, through diffusion resistance of the sealing layer,
- infiltration control, reducing water ingress into the waste body,
- mechanical protection, safeguarding the underlying material from erosion, freeze–thaw effects, and surface degradation.

A key design principle was the use of locally available materials, which minimized environmental impacts associated with material transport and ensured compatibility with site-specific geotechnical conditions. The sealing layer, composed of low-permeability clayey-silty material, acts as the primary barrier against both water infiltration and radon migration.

The overlying granular layers function as protective and drainage elements, promoting lateral water flow and preventing the development of excess pore pressures within the cover system. The vegetated top layer provides erosion resistance and contributes to long-term surface stability.

The cover system at Jazbec represents a robust engineered solution that effectively limits both gaseous and liquid transport pathways, ensuring the long-term containment of radionuclides and compliance with environmental protection criteria.

Table 1: Composition of the Jazbec engineered cover

Layer	Material	Thickness	Function
Vegetation	Mixed grass	-	Erosion control
Vegetative layer	Humus/Local soil	0,25 m	Growth medium
Storage layer	Local sandy gravel	0,80 m	Protection/Water storage
Protective layer	Local sandy gravel	0,50 m	Freeze/thaw protection
Sealing layer	Clayey-silty sand (Jaka)	0,40 m	Radon/Water barrier

2.3 Hydraulic Engineering

Remediation of the Jazbec disposal site required extensive hydraulic intervention due to the inherently unfavourable hydrogeological conditions, including high precipitation rates, groundwater inflow from the upstream catchment, and the permeable nature of the waste rock material. The disposal body was originally constructed by backfilling the natural valley of the Jazbec stream, which necessitated complete reorganization of the local drainage system.

As part of the remediation, surface water from the Jazbec stream and adjacent runoff areas was diverted away from the disposal site into the Brdarčkovo ravine, thereby significantly reducing direct hydraulic loading and infiltration into the waste body. This measure was essential to limit leaching of radionuclides and to improve long-term geotechnical stability.

Beneath the disposal body, a concrete culvert constructed along the former valley bottom serves as the primary drainage structure. This culvert collects seepage water, intercepted surface runoff, and background groundwater, and safely conveys them downstream into the Brebovščica catchment. Similar drainage systems at Jazbec have been shown to effectively collect seepage waters and control contaminant transport.

The hydraulic management system—comprising surface water diversion, internal drainage, and controlled discharge—represents a critical component of the multi-barrier concept, as it reduces water ingress, limits contaminant mobilisation, and ensures the long-term performance of the engineered cover system.

3 BORŠT HYDROMETALLURGICAL TAILINGS DISPOSAL SITE

3.1 Inventory and Radiological Profile

Located at elevations between 535 and 565 m a.s.l., the Boršt disposal site contains approximately 610.000 tonnes of hydrometallurgical tailings (HMJ) and 111.000 tonnes of mine waste rock, covering an area of about 4,2 ha. Although smaller in total mass compared to the Jazbec disposal site, Boršt represents the dominant radiological source term within the Žirovski vrh system, with a total activity of approximately 48,8 TBq. This is primarily due to the concentration of Radium-226 in the fine-grained tailings, with typical activity levels around 8,6 kBq/kg. The hydrometallurgical tailings contain the majority (~95%) of the original Ra-226 inventory derived from uranium ore processing, while also retaining significant fractions of Th-230 and U-238.

From a radiological perspective, this results in:

- high radon generation potential (via decay of Ra-226),
- relatively homogeneous radionuclide distribution within the tailings matrix,
- increased importance of gaseous transport pathways compared to solid-phase migration.

In contrast to coarser waste rock deposits, the fine particle size and high moisture retention capacity of HMJ enhance radon emanation and diffusion, making Boršt the critical site in terms of atmospheric radiological impact.



Figure 3: Boršt disposal site

3.2 Engineered Cover System

Due to the elevated radon exhalation potential and the fine-grained nature of the hydrometallurgical tailings, the Boršt disposal site is equipped with a comparatively thicker engineered cover system, with a total thickness of approximately 2,05 m. The cover design follows a multi-layer barrier concept, specifically optimized for radon attenuation and hydraulic control. A key component is the sealing layer constructed from low-permeability clay, selected for its favourable geotechnical and diffusion properties.

The primary functions of the cover system are:

- radon flux reduction through diffusion resistance,
- minimization of water infiltration, thereby limiting leaching and pore pressure increase,
- mechanical protection of the tailings surface against erosion and climatic effects.

The increased thickness of the cover, compared to the Jazbec site, reflects the need to:

- compensate for higher Ra-226 activity concentrations,
- reduce radon exhalation rates from initial values in the range of 1–5 Bq/m²·s prior to remediation.

In addition, the granular protective layers above the sealing clay ensure:

- drainage of infiltrating water,
- prevention of desiccation cracking in the clay barrier,
- long-term structural stability of the cover system under variable climatic conditions.

The Boršt cover system represents a critical engineered barrier within the multi-barrier safety concept, effectively controlling both gaseous and liquid transport pathways and ensuring compliance with radiological protection criteria.

Table 2: Composition of the Jazbec engineered cover

Layer	Material	Thickness
Vegetative	Soil (external source)	0, 25 m
Storage/Protective	Crushed stone (Jaka)	1,30 m (in two layers)
Sealing (Radon barrier)	Imported Clay	0,50 m

4 GEOTECHNICAL CHALLENGES: THE BORŠT LANDSLIDE

4.1 The 1990 Event and Stabilization Works

A major deep-seated landslide was triggered in November 1990 following a period of intense and prolonged rainfall, mobilizing approximately 2,9 million m³ of material. The failure occurred along a pre-existing paleolandslide structure, with a slip surface extending to depths of approximately 50 m within the bedrock. The landslide mechanism was primarily governed by elevated pore water pressures and reduced shear strength along weak geological interfaces. The event highlighted the critical role of hydrogeological conditions in slope stability at the Boršt site and necessitated the implementation of a comprehensive stabilization programme focused on groundwater control rather than structural reinforcement.

The main stabilization measures included:

1. Drainage tunnel – A 354 m long drainage tunnel, constructed beneath the landslide body, serves as the principal element for reducing groundwater levels. The tunnel, completed in the mid-1990s, significantly decreased pore pressures and thus improved slope stability.

2. Drainage boreholes – A system of vertical wells and sub-horizontal boreholes (e.g., DV-1 with a length of approximately 160 m) was installed to enhance drainage efficiency. These boreholes intercept perched groundwater and channel it into the drainage tunnel, increasing the overall hydraulic conductivity of the slope mass.

3. Rock-fill toe buttress – A rock-fill structure was constructed at the toe of the landslide to provide passive resistance and improve global slope stability by increasing confining stress at the base of the sliding mass.

4. Surface drainage and crack sealing – Additional measures included diversion of surface runoff and sealing of tension cracks formed during the landslide event, further limiting water infiltration into the sliding mass.

The stabilization concept is based on hydro-mechanical control, where reduction of pore pressure is the dominant factor in increasing the factor of safety.

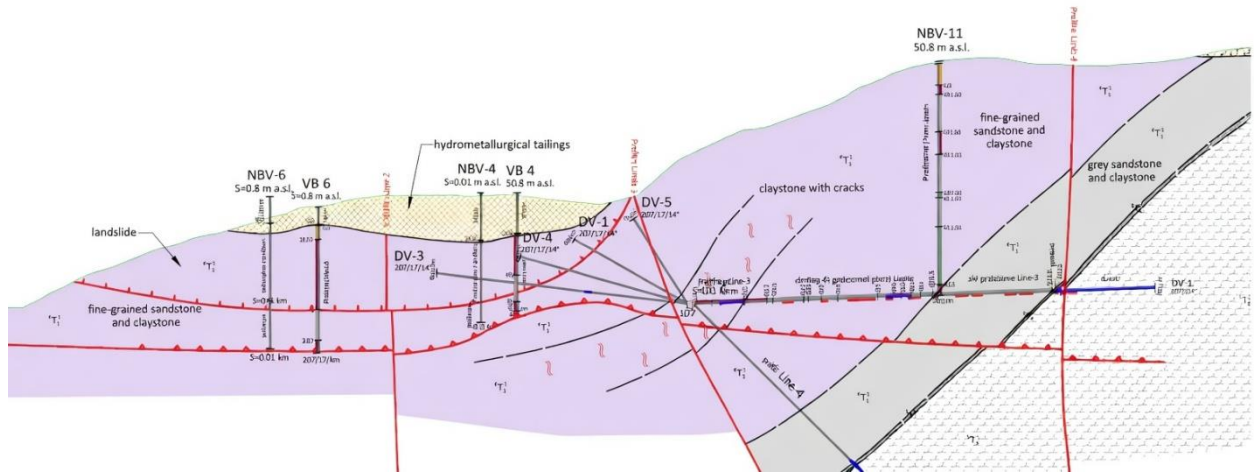


Figure 4: Cross-section of the Boršt landslide

4.2 Ongoing Monitoring and Residual Movements

Despite the extensive stabilization measures, the Boršt landslide remains an active but controlled geotechnical system. Long-term monitoring data indicate that the landslide is currently in a creep regime, characterized by slow and continuous displacements rather than rapid failure. The average horizontal displacement velocity is approximately 22 mm/year (based on 2023–2024 measurements), which is consistent with stabilized deep-seated landslides under effective drainage conditions.

The landslide behaviour is strongly influenced by hydrological conditions:

- Groundwater levels represent the primary controlling factor,
- precipitation events induce delayed responses in displacement due to infiltration and pore pressure increase (typically with a lag of 1–3 days).

Extreme weather events can temporarily accelerate movement. For example, the record rainfall event in August 2023 (219 mm within 24 hours) caused a noticeable increase in displacement rates, particularly at the lower, more deformable edge of the landslide body.

However, the absence of progressive acceleration or structural failure indicates that:

- the drainage system remains effective,
- the landslide is in a conditionally stable state,
- current movements represent long-term deformation rather than instability.

Continuous monitoring, including geodetic measurements, GPS observations, and in-tunnel instrumentation, is therefore essential to ensure early detection of any changes in behaviour and to support adaptive management of the site.

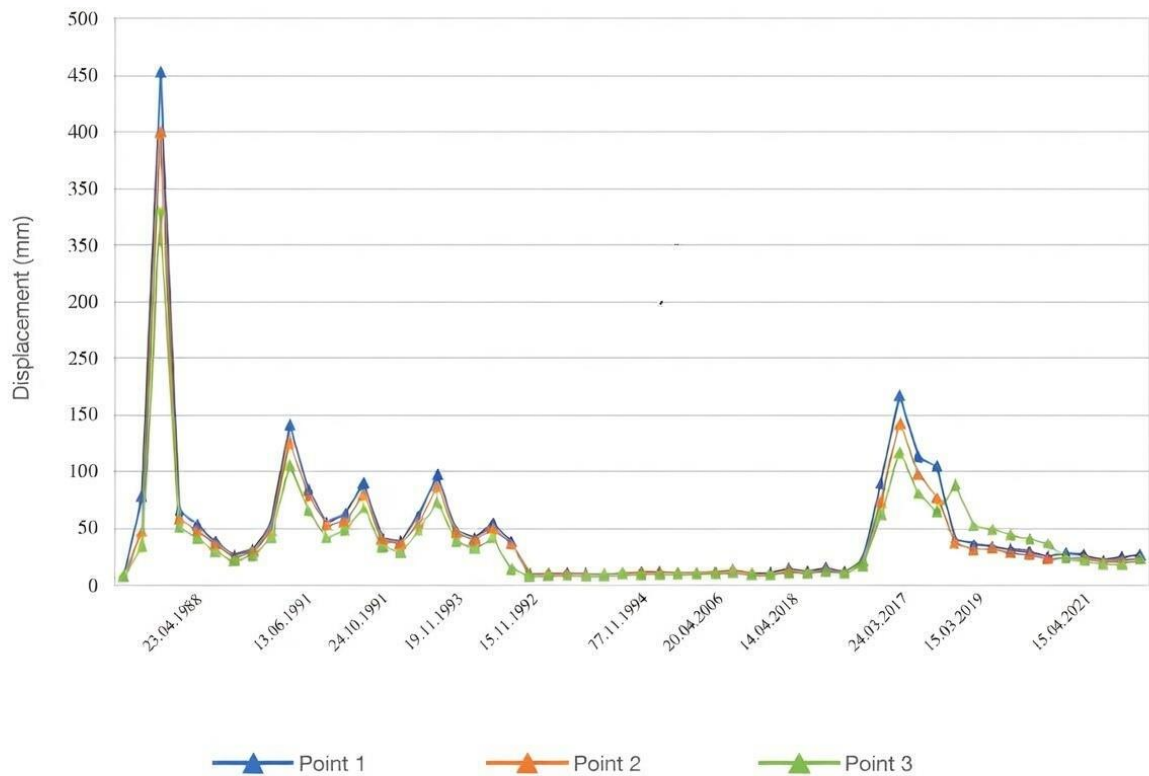


Figure 5: Horizontal displacement trends for Point 1, 2 and 3

5 RADIOLOGICAL SAFETY AND ENVIRONMENTAL IMPACT

5.1 Radon Exhalation and Concentration

The implementation of engineered multi-layer covers at both disposal sites resulted in a substantial reduction of radon exhalation from the underlying uranium mill tailings. Prior to remediation, radon release rates from exposed tailings were estimated to reach values on the order of up to 10 Bq/s (site-integrated flux), reflecting the high Ra-226 content and favourable emanation conditions in fine-grained materials.

Following the installation of low-permeability sealing layers, radon exhalation was reduced to levels approaching natural background conditions, with effective fluxes below 0,1 Bq/s. This corresponds to a reduction of more than two orders of magnitude and is consistent with international experience, where engineered covers reduce radon fluxes from tailings to values comparable to natural soil exhalation rates (typically on the order of $0,0002\text{--}0,07\text{ Bq}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$).

The effectiveness of the cover system is primarily governed by:

- the diffusion resistance of the clay sealing layer,
- moisture content and compaction state of the barrier,
- thickness of the cover relative to radon diffusion length.

Environmental monitoring in the surrounding area confirms the success of these measures. In the Todraščica valley, the average annual radon activity concentration in air was measured at $34 \pm 6\text{ Bq/m}^3$ over the period 2010–2023. This value lies within the range of typical natural background concentrations (approximately $27\text{--}88\text{ Bq/m}^3$ globally) and is significantly below internationally recommended reference levels for indoor radon ($100\text{--}300\text{ Bq/m}^3$).

These results indicate that the contribution of the disposal sites to ambient radon levels is negligible compared to natural sources.

5.2 Public Dose Assessment

The annual effective dose to the critical group, defined as residents in the Todrašćica and Brebovščica valleys, has consistently remained well below the regulatory limit of 0,3 mSv/year. The dominant exposure pathway is inhalation of radon and its progeny, while other pathways are negligible. Current dose estimates are on the order of a few $\mu\text{Sv}/\text{year}$, indicating that the radiological impact of the site is minimal and comparable to natural background variability. These results confirm the effectiveness of the implemented remediation measures and long-term containment system.

6 SAFETY ANALYSIS: WORST-CASE SCENARIOS

Safety assessments included conservative modelling of extreme, low-probability events to evaluate the long-term resilience of the Boršt disposal site. The bounding scenario assumes the simultaneous occurrence of a 1.000-year earthquake (peak ground acceleration up to 0,49 g) and extreme precipitation (380,5 mm in 24 hours).

Under such conditions, the model predicts up to 4,5 m of landslide displacement, leading to significant damage of the engineered cover system, including the formation of deep fissures and partial erosion of the tailings body. As a result, approximately 1.000 m³ of tailings could be mobilised and transported into the Todrašćica stream.

The associated radiological impact is estimated at up to 4,5 mSv/year for the most exposed individuals, primarily due to external gamma radiation from contaminated sediments deposited along the valley.

Although highly conservative, the analysis demonstrates that the main risk pathway is linked to sediment transport following mechanical failure, rather than gradual release processes. It also highlights the critical importance of maintaining cover integrity and ensuring the long-term functionality of drainage systems in limiting both geotechnical and radiological consequences.

7 TRANSITION TO INSTITUTIONAL CONTROL AND LONG-TERM SURVEILLANCE

7.1 ARAO Institutional Control (2016–present)

The transition from active remediation to institutional control represents a shift towards long-term active institutional control, in which engineered barriers are complemented by systematic monitoring and maintenance.

Institutional control of the disposal sites was implemented in a phased manner. The Jazbec disposal site was transferred to the Agency for Radioactive Waste Management (ARAO) in 2016, marking the beginning of its long-term management phase. In contrast, the Boršt disposal site was taken over by ARAO in 2025, following an extended transition period associated with geotechnical stabilization and final closure.

ARAO is responsible for ensuring the long-term safety and functionality of the disposal systems through:

- Geodetic monitoring, including quarterly GPS surveys and annual terrestrial measurements of the Plaz-2 network to track landslide displacements,
- Hydraulic maintenance, comprising regular inspection and cleaning of the drainage tunnel, culverts, and peripheral channels to maintain effective groundwater control,

- Cover system maintenance, including vegetation management and timely repair of any surface damage caused by ongoing ground movements.

These measures are essential for preserving the integrity of engineered barriers and mitigating the effects of long-term geotechnical processes.

7.2 Monitoring Programs

The long-term monitoring programme has been optimized to ensure both efficiency and a comprehensive assessment of potential environmental impacts, focusing on key environmental compartments and geotechnical parameters.

Monitoring of water systems includes regular sampling at multiple locations in streams and rivers surrounding the disposal sites. Both drainage waters originating from the disposal bodies and natural surface waters are systematically analysed to assess potential contaminant transport. In addition, groundwater monitoring is performed through a network of boreholes located within and beneath the disposal sites.

Water samples are analysed for key radionuclides, including U-238 and Ra-226, as well as for selected heavy metals associated with uranium ore processing. In parallel, the physico-chemical characteristics of water are determined, including pH, electrical conductivity, temperature, redox potential, and major ions. These parameters provide essential information on geochemical conditions controlling radionuclide mobility and enable early detection of any changes in water quality.

Air monitoring is carried out using semi-annual radon measurements with track detectors in the surrounding valleys, while geotechnical monitoring relies on continuous data acquisition from automated extensometers installed in the Boršt drainage tunnel.

Together, these monitoring activities provide an integrated evaluation of system performance, ensuring that any potential impacts on the environment are detected in a timely manner and remain within acceptable limits.

8 CONCLUSION

The environmental remediation of the Žirovski vrh uranium mine represents a successful application of modern principles for the long-term management and containment of NORM residues in a geotechnically complex environment. The implemented multi-barrier system, combining engineered covers, hydraulic control, and geotechnical stabilization, has proven effective in limiting radionuclide release and minimizing environmental impacts.

Although the Boršt landslide remains a persistent geotechnical constraint, its behaviour is currently controlled through drainage-based stabilization and continuous monitoring, resulting in a conditionally stable system. This confirms that even in dynamically evolving geological settings, long-term containment of uranium mill tailings can be achieved through integrated engineering and adaptive management approaches.

The transition to institutional control under ARAO ensures that both passive and active safety functions will be maintained over the long term. This is particularly important given that uranium tailings may pose potential environmental risks over extended timescales, requiring monitoring and maintenance for centuries.

The Žirovski vrh case demonstrates that effective remediation, supported by sustained institutional control and monitoring, can provide a robust framework for the long-term protection of the environment and the population.

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