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Original Contribution

SYSTEMATIC APPROACH TO THE CONSIDERATION OF ENGINEERING AND TECHNICAL FACILITIES IN VIEW OF THEIR FUNCTIONAL, RISK AND TERRITORIAL CHARACTERISTICS, FOCUSING ON MONITORING AND PREVENTION THROUGH GNSS TECHNOLOGIES

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ABSTRACT: *This report aims to propose a systematic approach to the examination of engineering facilities, taking into account their functional, risk and territorial characteristics, with a focus on the possibilities for monitoring and prevention through GNSS technologies.*

KEY WORDS: *GNSS technologies, Engineering facilities, Monitoring, Prevention, Territorial vulnerability, Critical infrastructure, Sensor monitoring.*

1. Introduction

In the context of increasing climate change, urbanization and the increasing complexity of technical infrastructure, engineering and technical facilities (ITS) are increasingly facing serious challenges related to natural disasters, man-made incidents and complex risk scenarios. Damage or failure of critical facilities – such as dams, bridges, tunnels, energy and transport systems – can lead to serious economic, environmental and social consequences.

A systematic approach to the risk assessment and management of ITS, based on their functional, territorial and risk characteristics, is essential for sustainable development and the security of society. In this context, Global Navigation Satellite Systems (GNSS) are establishing themselves as a key tool for spatial monitoring and early warning, thanks to their high accuracy, continuity and compatibility with other geoinformation technologies.

The integration of GNSS into ITS monitoring systems allows for real-time tracking of deformations, displacements and other indicators of potential malfunction. This makes timely intervention and the implementation of preventive measures possible, while improving the adaptive capacity of institutions responsible for infrastructure and risk management.

Therefore, looking at ITS through the prism of systematic analysis and the use of GNSS technologies for monitoring and prevention is a scientific and practical challenge of high relevance and strategic importance.

Scientific justification, classification and analysis

In the scientific literature, the term "engineering facilities" (ITS) is used depending on the context and industry. In the regulatory framework, European directives and national standards, the concept is defined specifically and often related to critical infrastructure are sites with a high risk to public safety.

The criteria for designating a facility as "critical" are:

• **Functional significance** – what role does it play in the normal functioning of society;

• **Degree of dependency** – other systems/sectors depend on it;

• **Risk profile** – opportunities for accidents, natural disasters or malicious actions;

• **Difficulty to replace or repair** – the time and resources needed to recover from a breakdown;

• **Potential for cascading effect** – the collapse of this facility can cause chain crises.

The main categories of classification based on their role in functional significance, economy and national security:

- **Energy**
  - Electricity production facilities (nuclear power plants, thermal power plants, hydroelectric power plants, etc.)
    - Risks: floods, earthquakes, landslides, fires, tsunamis (in some regions).
    - Example: Fukushima nuclear power plant in Japan, which suffered from a tsunami after an earthquake in 2011.
      - Electricity transmission and distribution network
      - Gas, oil pipelines and storage facilities
    - Risks: floods, earthquakes, hurricanes, fires.
    - Consequences: toxic spills, pollution of water sources, explosions.
      - Liquefied gas refineries and terminals
- **Water supply and sewerage**
      - Reservoirs, dams, water supply stations
    - Risks: pollution from floods, damage from earthquakes.
    - Consequences: critical for the health and hygiene of the population.
      - Wastewater treatment plants
      - Sewerage systems and drainage
      -

- **Transport infrastructure**
    - Highways, bridges, tunnels
    - Railway infrastructure and stations
    - Airports, ports
    - Metros and mass public transport
- **Communications and Information Technology (ICT)**
    - Data centers and servers
    - Mobile and fixed telecommunication networks
    - Satellite and navigation systems (incl. GNSS)
    - Cybersecurity and network infrastructure
- **Healthcare**
    - Hospitals and emergency centers
    - Centers for Public Health and Epidemiological Control
    - Manufacturing facilities and distribution of medicines
- **Food and Agriculture**
    - Food warehouses and logistics networks
    - Food processing centers
    - Agricultural facilities of national importance

In recent decades, there has been an increasing vulnerability of engineering and technical facilities (ITS) to a wide range of natural and man-made threats. This trend is due to both the increasing climatic conditions and the increase in loads, the obsolescence of infrastructure and the insufficient modernization of existing risk control and management systems.

In Bulgaria, a significant part of the ITS systems were built in the second half of the 20th century and need systematic monitoring, maintenance and adaptation to modern requirements for safety, sustainability and digitalization. This highlights the need for innovative solutions for their management and monitoring – among which GNSS-based technologies for precise monitoring and early detection of deviations from normal operation stand out.

Table 1 presents the classification characteristic by degree of vulnerability (high, medium, low) based on the frequency of impact and severity of potential consequences:

Table 1 Classification table by vulnerability, frequency of exposure

	Тип съоръжение	**Примери**	**Честота на въздействие**	**Тежест на последиците**	**Степен на уязвимост**
1	Nuclear power plants	Kozloduy NPP, Fukushima NPP	Low-medium (geographically dependent)	Very high (nuclear risk, pollution, evacuations)	⚫ High
2	Dams and hydroelectric power plants	"Tsankov Kamak", "Ivaylovgrad"	Medium-high (in case of landslides and heavy rains)	High (massive flooding, power failure)	⚫ High
3	Chemical and Oil Plants	Devnya, Burgas, Plovdiv	Medium (region-dependent)	High (toxic pollution, fires, explosions)	⚫ High
4	Power grid and substations	CEZ, EVN, NEK facilities	High (storms, ice, fires)	Medium–high (power outage)	🟠 Medium
5	Gas and heat pipelines	Balkan Stream, TPP Sofia	Medium	Medium (leakage, explosion risk)	🟠 Medium
6	Water supply and sewerage systems	Water supply and sewerage facilities, WWTP	High (floods, pollution)	Medium (health risks, local crises)	🟠 Medium
7	Transport infrastructure	Bridges, tunnels, highways	High (landslides, earthquakes, snowstorms)	Medium (logistics disruption, evacuation)	🟠 Medium
8	Telecommunication facilities	Base Stations, Server Centers	Medium	Low–medium (backup available)	🟢 Low
9	Administrative buildings	Hospitals, Ministry of Interior, municipalities	Medium	Medium (if not functioning in a crisis)	🟢 Low
10	RES facilities (photovoltaics, wind farms)	Solar power plants, RES parks	Medium–high (storms, fires, ice)	Low–medium (smaller capacity)	🟢 Low

Legend:

⚫ High vulnerability – combines a rare but destructive impact with catastrophic consequences.

🟠 Medium vulnerability – frequent impact, but with moderately recoverable consequences.

🟢 Low vulnerability – good resilience, redundancy and damage control capabilities.

In this regard, the need for preventive monitoring and early warning puts at the forefront the potential of modern geoinformation technologies, including global navigation satellite systems (GNSS). They allow for precise, continuous, and automated monitoring of micro-movements and deformations in critical facilities, while providing a reliable basis for making timely management decisions.

Part of GNSS Technologies in Monitoring

Global Navigation Satellite Systems (GNSS), including GPS, Galileo, GLONASS and BeiDou, provide high accuracy in tracking movements and deformations of the earth's surface. The application of GNSS technologies in the monitoring of critical engineering and technical facilities (KITS) in environmental threats includes:

- Continuous monitoring – real-time monitoring of micro-deformations – using high-frequency GNSS measurements to track micro-deformations and structural movements in real time, in order to detect potential risks to critical infrastructure early.
- Integration with other technologies – sensors, drones, GIS systems;

The integration of GNSS with networks of structural health sensors, drones (drones) and geographic information systems (GIS) provides a multidisciplinary approach to monitoring. This achieves increased spatial and temporal accuracy when observing deformations, displacements or other anomalies in the state of the KITS. Drones equipped with GNSS receivers and high-resolution cameras can be used to quickly and accurately capture hard-to-reach objects. Sensor networks contribute to continuous real-time data collection, while GIS platforms allow for analysis, visualization, and integration of data in spatial contexts. This technological synergy significantly improves early warning and decision-making processes in situations of natural disasters or man-made accidents [1].

- Automated alarm systems – when critical thresholds are reached
  Automated alarm systems related to GNSS and sensor data can trigger early warning signals in case of deviations from permissible structural or geodynamic parameters. This allows for a timely response and minimization of damage to the population, infrastructure and the environment [2].
- Preventive planning and risk assessment – by accumulating spatio-temporal data.

Systematic approach to the assessment of engineering facilities: functional, risk and territorial characteristics

For the effective management and prevention of incidents related to engineering and technical facilities (ITS), a systematic approach is needed that integrates multi-layered aspects of their nature and operating environment. In this regard, the proposed methodology covers three main groups of characteristics: functional, risk and territorial, which together form a comprehensive assessment of the facilities.

1. Functional characteristics

This component includes an analysis of:

1.1 The importance and role of the facility in the economy and society (e.g. transport corridor, water supply system, energy infrastructure).

ITS perform key functions without which modern society and economy cannot function sustainably. Depending on their specifics, these facilities can be classified by purpose, and each type plays an essential role in maintaining vital processes:

Transport infrastructure (roads, bridges, tunnels, railways) that provide mobility of people and goods, connectivity between settlements, trade flows and logistics. Disruption leads to economic losses, delays in deliveries, limited access to services and potential humanitarian difficulties in the event of disasters.

Water supply and sanitation infrastructure – provides access to clean drinking water and sanitation services – essential for health and social stability, and in case of failure, hygiene, public health and ecological balance are threatened.

Energy infrastructure (power lines, substations, hydroelectric power plants, thermal power plants, renewable energy sources) – Guarantees the production, transmission and distribution of electricity – the basis of all other economic sectors. An outage or failure can block hospitals, communications, manufacturing, transportation, etc.

Natural Resource Management Facilities (Dams, Irrigation Systems, Protective Dikes) – Regulates water flows, protects agricultural land, provides flood protection. Defects or poor maintenance at these sites can lead to large-scale accidents.

The importance and functional role of engineering and technical facilities determine the level of their criticality. Therefore, in a systematic approach to assessment and management, it is essential to differentiate the significance of each site, in view of the socio-economic consequences of its failure or failure.

1.2 Capacity and load that the facility bears in normal and emergency mode.

The capacity of an engineering facility determines the maximum volume of load that it can safely and efficiently absorb during its service life. This includes both permanent load (dead load) and temporary load (live loads, traffic, water pressure, vibrations, etc.).

Exceeding the designed parameters leads to accelerated wear, the appearance of deformations or even structural damage. Therefore, the real workload follows to be monitored in real time, especially in critical facilities, through monitoring systems – including GNSS, strain sensors, strain gauges and other IoT-based technologies.

1.3 The design features and technical parameters determining stability and operational reliability.

Each type of facility has a specific engineering logic of construction, which determines its resistance to external loads.

Different design solutions predetermine different vulnerability to risks such as earthquakes, landslides, thermal expansion or chemical influences (e.g. corrosion).

1.4 Age and current condition of the structure based on inspection and monitoring data.

The condition of an engineering facility is a dynamic indicator that is influenced by multiple factors such as operational loads, environmental impacts, seismic activity, geotechnical conditions, technological and structural defects, the presence of accidents or extreme events, lack of maintenance and monitoring (through GNSS – monitoring of micro-deformations or horizontal movements).

It is important to maintain a documented "passport" of the facility, which reflects all structural changes, repairs, measurements and analyses. This is the basis for an objective risk assessment and for engineering decisions regarding prolongation or decommissioning.

Functional characteristics represent the first pillar in the systematic approach to the evaluation of engineering and technical facilities. They allow not only classification by importance, but also quantification of the effect of a possible failure, which is critical in the prioritization of sites for monitoring, prevention and investment.

2. Risk characteristics

In this aspect, the factors that threaten the facility are assessed:

Natural risks: earthquakes, landslides, floods, extreme weather conditions.

2.1 Technogenic risks: accidents, explosions, fires, human errors and sabotage.

2.2 Probability and potential consequences of risk occurrence – vulnerability and operational impact analysis.

2.3 Historical and empirical data – archives of earthquakes, earthquakes, floods, data from monitoring GNSS systems for previous deformations, as well as engineering-geological, hydrological and geodetic maps.

Risk characteristics are the second key element of the systemic approach, and their accurate identification and quantitative assessment is the basis for predictive monitoring, infrastructure risk management and optimal allocation of prevention resources.

3. Territorial characteristics

The territorial context of an engineering facility (ITS) has a direct impact on its operation, vulnerability and the need for monitoring and prevention. These characteristics consider the geographical, administrative, infrastructural and environmental environment in which the site is located.

3.1 Geographical location and topographical features – the geographical location and topography of the area in which the facility is located play a decisive role in its stability and sustainability.

3.2 Geological stability – includes assessment of the rock and soil composition, the presence of tectonic faults and seismic activity in the area. Facilities located on unstable terrain are more vulnerable to deformations, cracks and structural damage.

3.3 Landslide and subsidence – the risk of activation of landslide processes, erosion or uneven subsidence of the base, especially at high groundwater or after significant precipitation, is assessed.

3.4 Environment – proximity to sensitive areas, such as settlements, protected areas, water bodies, areas with intensive land use or industrial sites, is analyzed. This has implications for both environmental safety and the potential consequences of an accident.

3.5 Accessibility and possibilities for emergency intervention – the analysis of the infrastructure for access to the site – roads, paths, logistics routes – as well as the ability to respond quickly in a crisis situation (e.g. with the intervention of emergency teams or fire-fighting equipment) is important.

Analysis

For the purposes of the report, the Ticha Dam, located in the Shumen region, is examined. "Ticha" old name: "Vinitsa" (Fig. 1) is a dam on the Golyama Kamchia River in northeastern Bulgaria. It is located in the river valley before the Preslav Gorge [4].

The facility is a critical infrastructure of national importance, serving several key functions:

- water supply to the cities of Shumen, Targovishte and Veliki Preslav;
- maintaining the hydrobalance of the Kamchia River;
- flood protection in adjacent areas;
- power generation potential.

Fig. 1.

The dam was designed and put into operation in 1973, with a maximum volume of about 311 million cubic meters. m³, which makes it one of the largest dams in the country [5].

The choice of this site is determined by:

- Its strategic role in the regional water supply system;
- Increased vulnerability to natural risks related to geological features of the area (including landslides and subsidence);
- Hydrological variability in recent years, including periods of extreme rainfall and droughts;
- Potential risks of a man-made nature, including aging infrastructure, lack of modern monitoring systems and limited access to real-time data.

These characteristics make Ticha Dam a suitable site for applying a systematic approach to risk assessment and for demonstrating the capabilities of GNSS-based spatial monitoring and analysis.

In order to achieve a more complete and reliable assessment of the condition and dynamics of the Ticha Dam, additional sensor measurements are integrated into the GNSS data, which provide valuable information for various aspects of monitoring:

- **Inclinometers** — used to measure angular deviations and slopes of the structure and adjacent land masses, allowing early detection of landslides, subsidence or other deformations.
- **Geodetic control** – regular ground measurements with total stations and laser scanners, which serve both for calibration and verification of GNSS data, as well as for monitoring changes in the relief and position of key points of the facility.

- **Hydrometric stations** – monitoring of the level and flow of water in the dam valley and river basin, which is essential for assessing hydrodynamic influences and changes in dam loading.

Combining these different types of data into a common information system allows a multidisciplinary and integrated approach to monitoring, increasing the reliability of the analysis and supporting the making of timely decisions on exploitation and prevention.

The risk analysis is based on quantifying the probability of occurrence of critical events and assessing their potential consequences on infrastructure and population in adjacent areas.

Dam vulnerability is addressed by assessing the structural integrity, operational condition of the water dike, and control and monitoring systems. Particular attention is paid to areas with potential defects and deformations that could compromise the stability of the dam under extreme loads.

For effective risk management and prevention of emergency situations related to the Ticha dam, it is necessary to adopt an integrated approach, including both technical and organizational measures.

- Improvement of monitoring systems: Installation and maintenance of highly accurate GNSS stations for constant monitoring of deformations and movements of the dam structure. In addition, integration of structural control sensors (accelerometers, deformation sensors) and weather stations for early warning in adverse weather conditions is recommended.
- Regular inspections and technical support: Conduct systematic surveying and technical inspections to identify early signs of wear, cracks or erosion. Timely removal of identified defects is key to accident prevention.
- Development of forecasting models: Use of modern hydrological, geological and structural analysis models to support the simulation of the impacts of extreme natural phenomena and assess dam vulnerability in different scenarios.
- Emergency action training and planning: Provide training to risk and emergency management personnel, and develop and regularly update contingency plans, including evacuation and coordination with local authorities.
- Information campaign and interaction with society: Raising the awareness of the local population about the risks associated with the dam and safety measures, as well as creating channels for rapid communication in case of potential crises.

Conclusion

The systematic approach to the analysis of engineering and technical facilities, which integrates functional, risk and territorial parameters, allows the construction of a complex assessment of their operational condition and potential emergency scenarios. This approach requires detailed mapping of structural characteristics, load dynamics and environmental impacts, as well as identification of critical vulnerability points based on geotechnical, hydrological and climatic factors.

The application of GNSS technologies provides high-precision measurements of deformations, slopes and dislocations with accuracy in the centimeter and millimeter range, which is key to the early detection of structural changes, precursors of potential accidents. The integration of GNSS data with numerical models for the simulation of mechanical behavior and hydrodynamic processes allows quantitative prediction of risk scenarios and optimization of preventive interventions.

Real-time monitoring, supported by automated platforms for large data processing and analysis (Big Data), enables effective risk management through a timely alarm system and support for decision-making processes. This integrated approach minimizes the likelihood of catastrophic events and increases the operational reliability of facilities, while taking into account the specific territorial conditions that affect the behavior of structures.

In conclusion, the systematic consideration of engineering and technical facilities with an emphasis on functional and risk parameters, supported by precise GNSS measurements and modern forecasting models, is critical to achieving infrastructure sustainability and safety in conditions of a dynamic and unpredictable environment.

Given the increased need for sustainable and proactive management of critical hydrotechnical facilities, such as the „Ticha“ dam, future research efforts should focus on the development of integrated and reliable monitoring systems based on Global Navigation Satellite Systems (GNSS). Based on the present study, the following priority directions can be outlined:

1. **Optimizing the GNSS monitoring network**

The deployment of additional GNSS stations in the dam area, including on the dam wall and in critical sections of the adjacent territory, will contribute to more precise detection of microdeformations and early identification of potential risks related to the structural stability of the facility.

2. **Multidisciplinary integration of sensor technologies**

Combining GNSS observations with inclinometric, hydrogeological and meteorological data will enable the creation of a complex behaviour pattern of the dam and its environment under different loads. Such integration would improve the accuracy of analysis and prediction of critical events.

3. Simulation modelling of emergency scenarios

By using empirical GNSS data and numerical modelling, scenarios for possible dam failures or partial failures should be developed. Such models would have direct application in the planning of actions to mitigate consequences and optimize the emergency response.

4. Development of a localized early warning system

Based on continuous GNSS monitoring and automated real-time data processing, an early warning system adapted to the specific geographical and technical features of the „Ticha“ dam can be created. This would significantly increase the readiness of institutions to react when critical conditions arise.

5. Long-term analysis and assessment of climate impacts

The accumulation and analysis of GNSS data over a prolonged time horizon would contribute to identifying trends associated with deformations influenced by climatic and seasonal fluctuations. This is particularly important in the context of changing climate dynamics and the frequency of extreme weather events.

6. Creation of interactive platforms for visualization and analysis

The development of dedicated mobile and web-based GNSS data visualization platforms and the real-time status of the dam would facilitate access to information and management decision-making by expert and operational structures.

7. Development of a normative and methodological framework

Based on the results derived, recommendations can be formulated to include GNSS monitoring as a mandatory element in the national regulation and standardization of monitoring of dams and similar critical facilities.

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