The potential of 4IR technologies to mitigate risk in mine residue management

by G.M. Rohde, C. Bester

Affiliation:
Department of Industrial Engineering, Stellenbosch University, South Africa

Correspondence to:
G.M. Rohde

Email:
rohdegustav1@gmail.com

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ORCiD:
G.M. Rohde
http://orcid.org/0009-0005-6174-5369
C. Bester
http://orcid.org/0000-0001-8967-050X

Abstract

A major challenge in the mining sector is the responsible management and efficient storage of mine residue. Over recent years numerous tailings dams have experienced unintended spills and failures, with severe consequences for the mining industry, the environment, local communities, and the regional economy.

The fourth industrial revolution (4IR) is impacting society due to increased interconnectivity, processing speed, and automated technologies. This paper explores whether 4IR technologies have the potential to mitigate risks associated with tailings dams.

Experts in the field of tailings dam operational management were surveyed to determine their view on the risks associated with tailings dams and the potential of 4IR technologies to mitigate these risks. The survey found that a majority of experts believe that certain 4IR technologies have the potential to reduce the risks associated with tailings dam failures.

Keywords

risk mitigation, 4IR technologies, tailings dam failures, tailings disasters

Introduction

The mining process is essential to produce goods, infrastructure, services, and to improve quality of life. Mines boost the economy in rural areas and provide job opportunities for the local communities; it contributes to the tax revenue required to support local municipalities and governments. Mining also has an immense impact on the environment. Estimates by Jawadand and Randive (2021) indicate that the production of 1 tonne of useable coal produces 0.4 tonnes of waste, and 1 tonne of useable copper generates 110 tonnes of waste.

A major challenge in the mining sector is the responsible management and efficient storage of waste resulting from the mining process (Aznar-Sánchez et al., 2018). In mining, tailings are the materials left behind after separating a valuable commodity from the uneconomical fraction (gangue) of the ore. Wet tailings are a sludge-like waste, comprising a mixture of water, chemicals, and fine gangue particles. This study focuses on wet tailings, which are commonly deposited in tailings dams. In the history of mining numerous tailings dams have collapsed with catastrophic monetary and human loss consequences (Owen et al., 2020).

Tailings dams represent some of the largest earth-fill structures in the world (Clarkson et al., 2021). There are an estimated 3 500 active tailings dam structures globally. An average of 2–5 major tailings dam failures and 35 minor failures occur per year (Caldwell et al., 2011). According to the literature, tailings dams fail significantly more than other constructed dams, such as water retention dams (Rana et al., 2022).

The fourth industrial revolution (4IR) is transforming many aspects of society (Schwab, 2017). The significant progression in interconnectivity and smart automation offers potential to improve the monitoring and management of tailings dams (Lumbroso et al., 2019). This could potentially improve tailings dam safety.

Tailings dam failures and associated risks

Traditionally tailings dams have been constructed based on design principles of water retention dams. Prior to the implementation of modern standards, tailings dams were designed less conservatively due to cost considerations (Vermeulen, 2001). The current practice in industry is to treat all aspects of operational management as site-specific (Vick, 1990; Dladla, Ramsamy, 2022). The cumulative tailings dam failure rate is as high as ~4.4%, which is much higher than the predicted failure rate of ~1.2% for normal water retention dams (Rana et al., 2022). A research study by Bowker and Chambers (2015) indicated that the number of general tailings dam failures decreased from the 1990s, but unfortunately the severity and number of fatalities increased (Bowker, Chambers, 2015).

As stated earlier, all tailings dam facilities are unique. Hence, the risks associated with each facility are site-specific, which makes risks difficult to generalise. However, the main ultimate failure mechanisms that have caused most failures, according to research studies, are overtopping, seepage, seismicity, and foundation failure (Bowker, Chambers, 2015; WISE, 2022; Piciullo et al., 2022), while others argue that overtopping and erosion are deemed the main failure modes (Mwanza et al., 2024). Extreme climatic events, mismanagement, and insufficient early detection may also be the root cause of dam failures. These issues are discussed in more detail in Table 1.

The 4IR and associated technologies

According to Klaus Schwab, the fourth industrial revolution (4IR) impacts industries, practices, and economies. It challenges and changes the way people think, operate, and make decisions. The revolution is characterised by a new era of digital driven technologies in the biological, digital, and physical world (Schwab, 2017).

Hermann et al (2016) summarised the fourth industrial revolution as a system that satisfies six design dimensions; these include visualisation, decentralisation, interoperability, real-time capability, modularity, as well as service orientation (Hermann et al., 2016). The 4IR further depends on a digital network and connections and includes Artificial Intelligence (AI), big data, Internet of Things (IoT), and machine learning (ML).

The 4IR includes numerous concepts and technologies, not all applicable to tailings dam monitoring and operations. The technologies most likely to be deployed on tailings dams are those associated with visualisation and integration of data and systems. These include augmented- and virtual-reality, IoT, machine learning, drone- and satellite-photography, and other concepts such as Light Detection and Ranging (LiDAR), and digital twins.

Survey design

For this research, a survey was developed and distributed to various experts in the field of tailings dam design, operation, and management in Sub-Saharan Africa. The main goal of the survey was to obtain opinions from experts and practitioners on the potential for 4IR technologies to better manage tailings dams, and which 4IR technologies have the highest potential to prevent failure and, thus, reduce risk.

It included experts employed at consulting firms, mining houses, tailings dam operators, and research professionals at universities. The distribution targeted an audience with a range of years of experience, ranging from less than five years to more than twenty years. The age and employment distribution ensured a spectrum of views.

There were 26 responses to the survey with relatively diverse profiles. The split between consultants and mining houses was 62% to 38%, respectively, with a homogeneous distribution of years of experience within the tailings dam industry.

Results

Tailings dam failure databases (Bowker, Chambers, 2015; WISE, 2022; Piciullo et al., 2022) were analysed to determine the ratio of documented failures that occurred from in-service versus decommissioned tailings dams. Overall, 82% of failures were reported on in-service tailings dams. This finding emphasises the importance of managing the risk associated with operations, monitoring, and management of in-service operational tailings dams.

Inherent risk rating

Experts were asked to rate the likelihood and consequence of the inherent risk associated with tailings dam failures. Although tailings dam failures are site specific, this approach combines the site-specific risks to achieve a cumulative generalised perceived risk of failures. The likelihood ratings ranged from 0 (never) to 5 (almost certain), and the consequence ratings ranged from 0 (insignificant) to 5 (severe). The likelihood and consequence ratings, as perceived by experts, were used to determine an inherent risk rating for each of the failure mechanisms. The risk rating per survey for each failure mechanism was calculated using Equation 1 (Unguras et al., 2020).

$$\text{Risk rating} = \text{likelihood x consequence} \qquad [1]$$

The relative inherent risks by failure type as rated by the experts in the survey are shown in Figure 1. It becomes evident that the perceived risks associated with tailings dams range from ‘medium’ to ‘very high’.

According to Shah et al., risks rated this high require mitigation strategies, continuous monitoring, and management attention (Shah et al., 2020).

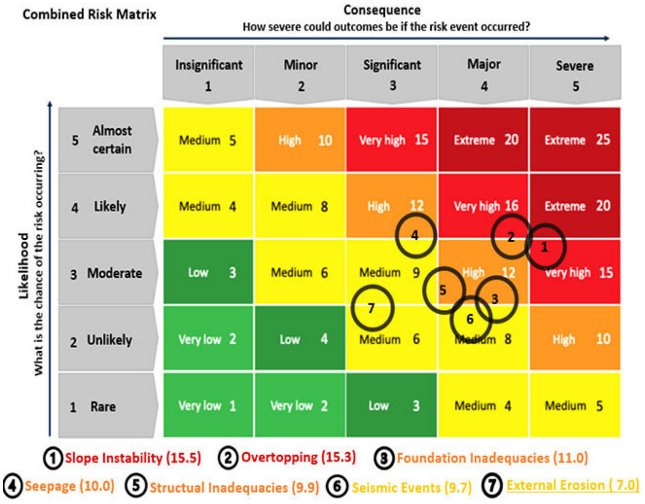
Current monitoring techniques used on tailings dams

Experts were asked to report on how tailings dams are currently being monitored, manually or automatic, and to what extent. For manual monitoring techniques, they were asked to assign a rating (0 = never manually monitored, to 5 = always manually monitored). Similar feedback was requested for automated monitoring techniques.

Table 1

Root causes of tailings dam failure

Climate change	Mismanagement	Insufficient early detection
As stated by Azam and Li (2010), failures due to extreme weather events increased by 15% from the pre-2000s to the post 2000s. It is attributed to climate change with heavier storm events of shorter duration where the design of the facility is unable to contain and decant the storm event (Azam, Li, 2010).	Mismanagement of tailings facilities resulted in 20% increased dam failures from pre-to post 2000’s. This is attributed to operational guidelines not being followed, or rapid increases in mine production to benefit from a fluctuation in commodity prices. As a result, the rate of rise cannot be accommodated (Piciullo et al., 2022).	Failures with causes such as seepage, overtopping, foundation failure, mismanagement, slope instability and erosion, typically show signs of deterioration prior to failure. The facility first reduces in stability, showing signs of irregularities before the failure occurs (Piciullo et al., 2022).



	Insignificant 1	Minor 2	Significant 3	Major 4	Severe 5
5 Almost certain	Medium 5	High 10	Very high 15	Extreme 20	Extreme 25
4 Likely	Medium 4	Medium 8	High 12	Very high 16	Extreme 20
3 Moderate	Low 3	Medium 6	Medium 9	High 12	Very high 15
2 Unlikely	Very low 2	Low 4	Medium 6	Medium 8	High 10
1 Rare	Very low 1	Very low 2	Low 3	Medium 4	Medium 5

Figure 1—Perceived inherent risk matrix

A weighted average was calculated by multiplying the assigned rating, 0 to 5, by the number of responses per rating. The average weighted rating was calculated for each manual and automated monitoring technique. Figure 2 illustrates the weighted averages, comparing the percentage difference between manual and automated monitoring adoptions per typical monitoring technique. It becomes evident that for all aspects monitored, manual monitoring currently outweighs the automated techniques.

Comparing all typical monitoring concepts associated with tailings dams, a weighting average of 3.4 was calculated for manual monitoring, and 2.1 for automated monitoring. It seems that manual monitoring techniques are 37% more likely to be adopted in industry than automated monitoring techniques.

A sigmoidal function (commonly referred to as an S-curve) is often used to describe the adoption of technology by industry. During the first phase, referred to as the initial or 'emerging/birth' phase, adoption is slow. This is followed by an exponential growth phase where adoption occurs rapidly. The rate of adoption increases as benefits becomes clear. Finally, adoption decelerates during a phase referred to as the 'mature and decline' phase. This phase represents market and technology saturation (Denning, 2020; Cristóbal, 2017; Kucharavy, 2011).

The weighted average ratings that were used in Figure 2, were subsequently used in conjunction with the S-curve adoption rate theory. A zero-rating referring to no -, or minimum adoption in the market, and a five-rating refers to full adoption in the market and market saturation.

In Figure 3(a) and 3(b), the adoption level of both manual and automatic monitoring techniques was superimposed on adoption S-curves. It is evident that the majority of manual monitoring techniques are currently within the 'mature' phase. This is in contrast with the adoption level of autonomous monitoring techniques currently in the 'growth' phase. It is highly likely that the adoption of these techniques will grow and move to the exponential growth phase as benefits become clear and awareness spreads.

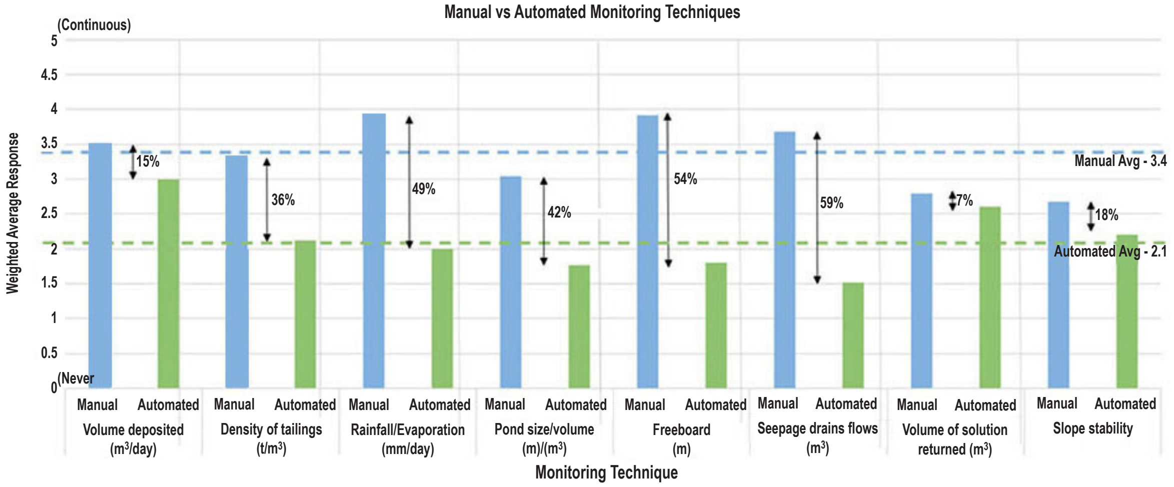


Figure 2—Frequency of manual and automated techniques in industry

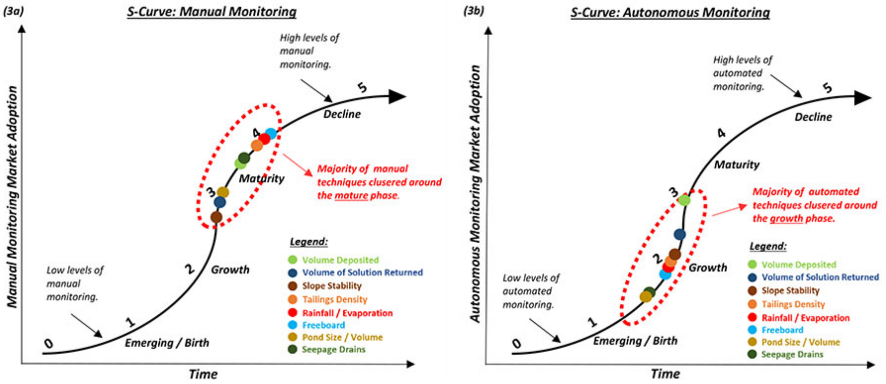


Figure 3—Manual and automated ratings overlayed on S-curves

The potential of 4IR technologies to improve tailings dam operations

The top technologies that experts believe will improve tailings dam operations are: (1) IoT, (2) drone technology, and (3) machine learning. The potential of VR and AR are perceived to be significantly less.

A constraint of the survey is that the different technologies were rated in isolation. The integration of various technologies offers potential. This may be the reason IoT and machine learning, which are typically dependant on other information sources, were rated so high.

It is also evident from the rankings in Figure 4, that experts believe technologies associated with the integration of data and information (such as IoT and machine learning), can have a higher potential impact on understanding and anticipating tailings dams performance than other technologies used in isolation.

The potential application of the two highest rated technologies, IoT, and drone technology, as shown in Figure 4, is discussed in more detail in Table 2.

The potential of 4IR technologies to mitigate risks associated with tailings dams

The 4IR technologies shortlisted in this study offer varying potential to mitigate the different dam failure mechanisms. The survey respondents were asked to rate the potential of each 4IR technology to mitigate the risk of a specific failure mode. The judgement was captured on a 3-point scale (0 – no risk mitigation potential, 1 – some risk mitigation potential, 2 – high risk mitigation potential). The ratings (0, 1, or 2) of all the respondents were added together to get a holistic view of 4IR technologies risk mitigation potential. The number of respondents who believe that a specific technology has potential to improve tailings dam monitoring and operational management and can be used as a risk mitigation tool have been converted into a percentage and is shown in Figure 5.

The data depicted in Figure 5 imply that all failure mechanisms can potentially be anticipated by 4IR technologies. The experts indicated that machine learning and IoT are perceived to have the highest potential to mitigate risks associated with the failure mechanisms.

From the results it is also evident that different technologies seem to be better suited for different types of failure mechanisms. For example, drone technology seems to offer a high potential to mitigate risks associated with overtopping, and a low potential to mitigate risks associated with seismic events.

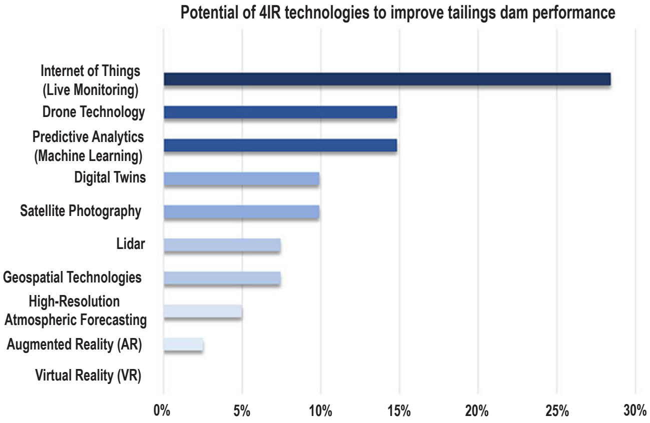
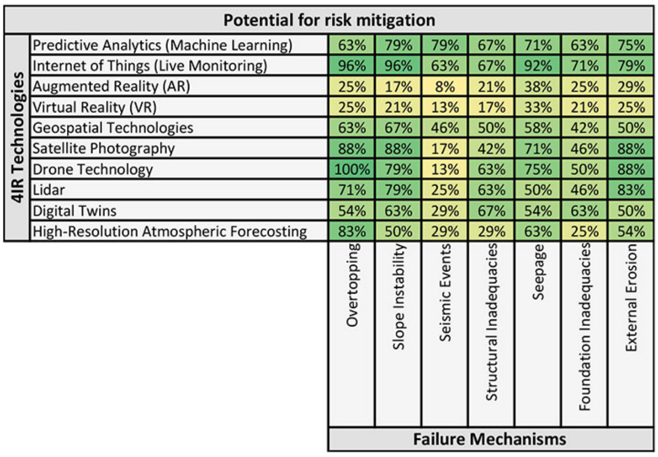


Figure 4—The relative potential of 4IR technologies to improve tailings dam performance



Potential for risk mitigation

4IR Technologies	Overtopping	Slope Instability	Seismic Events	Structural Inadequacies	Seepage	Foundation Inadequacies	External Erosion
Predictive Analytics (Machine Learning)	63%	79%	79%	67%	71%	63%	75%
Internet of Things (Live Monitoring)	96%	96%	63%	67%	92%	71%	79%
Augmented Reality (AR)	25%	17%	8%	21%	38%	25%	29%
Virtual Reality (VR)	25%	21%	13%	17%	33%	21%	25%
Geospatial Technologies	63%	67%	46%	50%	58%	42%	50%
Satellite Photography	88%	88%	17%	42%	71%	46%	88%
Drone Technology	100%	79%	13%	63%	75%	50%	88%
Lidar	71%	79%	25%	63%	50%	46%	83%
Digital Twins	54%	63%	29%	67%	54%	63%	50%
High-Resolution Atmospheric Forecasting	83%	50%	29%	29%	63%	25%	54%

Failure Mechanisms

Figure 5—Potential for risk mitigation with 4IR technologies

The four failure mechanisms that are best anticipated by 4IR technologies are: (1) overtopping, (2) slope instability, (3) seepage, and (4) external erosion. These occurrences are measurable or visible and therefore benefit from automated measuring techniques supported by the IoT or through drone surveys. The lowest mitigation potential of a failure mechanism by a 4IR technology are (1) structural inadequacies and (2) foundation inadequacies. These failure mechanisms could be more difficult to detect due to construction deficiencies and that their actual behaviour is hidden from physical observation. For example, a foundation failure due to weak spots in the foundation of the embankment, or a structural irregularity where the concrete in the penstock tower may crush due to poor concrete design or poor quality, is difficult to detect.

Table 2

The potential conceptualised application of the two highest rated mitigation technologies

Internet of Things (IoT)	Drone Technology
In tailings dam management IoT can be utilised to connect and in real-time monitor the performance of a facility. The attributes measured and displayed in a central control room include all measurable aspects of the facility, such as seepage, pond sizes and volumes, and deposition- or solution volumes. These measurable items could also possibly come from other 4IR technologies such as drones, satellites, and sensors, linked to geospatial technologies.	Micro air unmanned vehicles have positively transformed the tailings dam industry in recent years. Experts believe that drones will have a significant impact on improving tailings dam operations in the future. Drones can be used on tailings dams to monitor operations on a continuous basis. These could include monitoring seepage, deformation, freeboard, pond area and volume measurements, beach slopes, and defects in areas previously inaccessible on foot.

Discussion and limitations

The survey results did not generate any surprising feedback and were mostly aligned with the literature review. Experts were overwhelmingly of the opinion that 4IR technologies could be used for risk mitigation of tailings dam operations. It might be questioned how reliably experts can judge the future potential of technology partially developed and currently in early stages of deployment. However, the survey results are consistent, and a degree of theoretical saturation was observed in the study. Saturation associated with quantitative research is reached when an increase in respondents does not seem to change the outcome of the survey.

Shortcomings were observed. Firstly, treating the failure mechanisms as independent occurrences is not necessarily correct, since some of the failure mechanisms are interlinked and difficult to analyse in isolation. The root causes and indirect triggers might be underappreciated and skewed as the survey only focused on the ultimate failure mechanisms. A second shortcoming of the survey is the fact that 4IR technologies were observed in isolation. 4IR technologies are often deployed in a system benefiting from the interconnection of several technologies.

An element that was not considered in this study was the cost and benefit of various technical options. The costs associated with 4IR technologies differ significantly (Chikwanda, 2023). An improvement and potential future extension to the study could be to quantify costs vs risk mitigation benefits per 4IR technology, and thus, consider their implementation.

Cybersecurity risks, a negative development associated with new technologies, have not been considered in the study. Information and data associated with tailings dams tend to be confidential and data leaks could possibly have an impact on the risks generated with the deployment of 4IR technologies. This might even result in sabotage or cyber ransom attacks.

The authors are of the opinion that the 4IR could have a substantial positive impact on operational monitoring and management of tailings dams. The interconnectivity, advanced analytics, and automated nature of these technologies should be very beneficial to mitigate risks associated with tailings dam failures.

Conclusions and recommendations

Research findings

Based on the experts' ratings, the inherent risk of dam failure plotted in the medium to high-risk zone on a risk matrix, indicates that a significant number of risks are present in tailings dam operations.

Experts indicated that manual monitoring techniques are currently extensively used in monitoring dams. The manual monitoring techniques seem to be in the 'mature' phase of technology adoption. The newer automated techniques more recently deployed, are in the 'birth and growth' phases of adoption. It seems that a transition in the use of monitoring techniques might be underway from manual to automated techniques.

Although the survey was only completed by 26 respondents, all expressed a strong opinion that 4IR technologies can mitigate tailings dam risks. The development and propagation of all failure mechanisms can be mitigated by 4IR technologies, some offering higher potential than others. Overtopping and slope instability are the top two failure mechanisms that contribute to 48% of recorded failures. These two failure mechanisms have also been identified as benefiting most from the introduction of 4IR technologies. A 100% of respondents believe that drone technology could reduce the risk of slope stability, whilst 96% of respondents believe that the IoT can reduce the risk of overtopping.

Table 3 summarises most of the findings of this research and the view of the surveyed experts. The type of dam failures is listed in the order of their perceived inherent risk. For each failure mechanism the performance criteria to monitor are listed and the most relevant 4IR technology and its likelihood of having the potential to mitigate risk is listed.

It is evident that 4IR technologies already contribute to the operation and management processes of tailings dams. The authors are of the opinion, and the survey also indicates, that 4IR technologies will significantly increase in use, efficiency, and accuracy in the years to come. The initial cost of 4IR technologies is limiting mining houses in implementing these technologies for tailings dams. It is however very likely that the costs of these technologies will reduce in the future. No single 4IR technology will solely be able to mitigate all risks associated with tailings dam failures, and a suite of integrated technologies should be considered per tailings dam to increase the efficiency of early, accurate, and efficient risk detection measures.

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Table 3

Risk mitigation model and proposed 4IR technologies

Failure mechanism	Inherent risk	Aspect to be monitored/mitigated	Possible solution	Mitigation potential		Proposed technology
Slope instability	Very high	Slope stability, seepage, general defects	Continuos slope stability, early detection	Very high	96%	1st: loT (Live monitoring)
				Very high	88%	2nd: Satellite photography
Overtopping	Very high	Pond size, freeboard, weather forecasting	Water management, early detection, predictive analytics	Very high	100%	1st: Drone technology
				Very high	96%	2nd: loT (Live monitoring)
Foundation inadequacies	High	General foundation defects	Continuous monitoring of foundation defects	High	71%	1st: loT (Liver monitoring)
				Moderate	63%	2nd: Predictive analytics (Machine learning)/Digital twins
Seepage	High	Moisture on embankment perimeter	Moisture detection, continuous monitoring	Very high	92%	1st: loT (Live monitoring)
				High	75%	2nd: Drone technology
Structural inadequacies	High	General structural defects	Continuous monitoring of structural defects	Moderate	67%	1st: Predictive analytics (Machine learning)
				Moderate	67%	2nd: loT (Live monitoring/ Digital twins)
Seismic events	Medium	Ground movement acceleration	Ground movement detection, warning signs, predictive analytics	High	79%	1st: Predictive analytics (Machine learning)
				Moderate	63%	2nd: loT (Live monitoring)
External erosion	Medium	Crack identification, crack dimensions	Early detection, continuous monitoring	Very high	88%	1st: Satellite photography,
				High	79%	2nd: loT (Live monitoring)

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