



Received: 20.07.2025; Revised: 02.12.2025; Accepted: 24.12.2025; Published: 05.01.2026

UDC 622.276.5:658.14

DOI: 10.31721/2306-5435-2025-2-32-45

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Innovative methods for improvement of production efficiency at wells with sand production: Technological metrics and their role

Abstract. Sand production in production and injection wells is a critical factor that reduces productivity and operational reliability, necessitating innovative control methods. The study aimed to develop a scientific basis for improving the production efficiency of wells prone to sand production using innovative sand control techniques and a system of key performance indicators for their implementation, using typical offshore production conditions as an example. The work uses numerical modelling, scenario analysis using long-short-term memory algorithms and recurrent blocks with controlled updating, simulation of processes in a digital twin of the well, and verification of the results according to American Petroleum Institute Recommended Practice 14E and ISO 17824:2009 standards. The study determined that the implementation of intelligent monitoring systems increases the accuracy of sand detection from 65% to 85% and reduces the number of missed events by 40% compared to threshold schemes. The average operating time of a well without particle removal increased by almost 1.5 times, and specific operating costs decreased by 20%. Practical “before/after” cases have shown that limiting depression in combination with modernising the filtration system increases operational stability (increasing sand-free time from ~45% to ~70%), while controlled pumping with chemical stabilisation reduces the skin factor from ~6 to ~2.5 with a 12-15% increase in productivity. The results demonstrate that the integration of digital twins, predictive analytics algorithms, and combined physical and chemical methods forms a new paradigm for sand control. This ensures coordinated growth in productivity, reliability and environmental sustainability, confirming the strategic potential of digital transformation in the oil and gas industry

Keywords: digital twin; silting; skin factor; productivity coefficient; oil and gas industry; artificial intelligence models

Suggested Citation:

Ismayilov, Sh., & Mirzayev, Z. (2025). Innovative methods for improvement of production efficiency at wells with sand production: Technological metrics and their role. *Mining Journal of Kryvyi Rih National University*, 59(2), 32-45. doi: 10.31721/2306-5435-2025-2-32-45.

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Introduction

Sand production in production and injection wells remains one of the key causes of production efficiency losses: solid phase removal accelerates abrasive wear of equipment, increases hydraulic losses, causes flow instability and unplanned downtime. In response, the industry is shifting from a “catalogue” of disparate solutions to management based on pre-agreed key performance indicators (KPIs), where the choice of technologies is strictly linked to the sand-free rate, permissible formation depression, productivity coefficient, additional filtration resistance (skin factor), particle retention coefficient and filter erosion indicators, as well as the total sand-free operating time.

Summarising mechanical approaches, B.A. Suleimanov *et al.* (2024) demonstrated that the effectiveness of screens and gravel packs is determined not only by their design, but also by verified criteria for sand retention and throughput capacity in specified extraction modes. At the same time, a gentler “chemical” approach is being developed: a study by M. Soroush *et al.* (2020) analysed the challenges and prospects of designing sand control systems in weakly cemented reservoirs in Kazakhstan, emphasising the importance of chemical consolidation technologies that can maintain permeability with minimal skin factor growth. Early diagnosis and prompt adjustment of sampling modes enhance the effect of control technologies. On large assets in the Caspian region, Z. Hasanov *et al.* (2021) showed that distributed acoustic surveying (DAS) identifies sand signatures in horizontal wells and can be used for calibration of maximum depressions without excessive flow rate restrictions. To predict sand occurrence zones, A. Kukshal *et al.* (2024) integrated rock strength parameters with core microanalysis, improving the accuracy of risk mapping and the quality of candidate selection for mechanical or chemical control. In mature offshore clusters, D. Kazidenov *et al.* (2025) described the transition to comprehensive sand management strategies, where monitoring, properly designed filtration systems, and operating regulations are combined into a single control loop with KPI assessment of sand retention, intervention frequency, and specific operating costs (OPEX).

With high solid phase removal, coupled flow and transport models come to the fore: S. Murillo *et al.* (2025) used dynamic modelling to remove flow assurance uncertainties and optimise pumping modes, reducing the risks of blockages and erosion failures. The results of laboratory and field cycles on the durability of “chemical” solutions were supported by data from J.Z. Kueh *et al.* (2022), which evaluated the durability of

consolidation as an alternative to primary mechanical control in marginal reservoirs. At the industry review level, Y. Li *et al.* (2024) noted a trend towards the integration of mechanical and chemical means with online monitoring and analytics, emphasising the need for a unified set of technological indicators to compare options in terms of their contribution to stable flow rates and equipment resources.

The design and technology circuit is reinforced by experimental and numerical filter selection: N.C. Su *et al.* (2025) demonstrated that combining laboratory slurry tests with coupled numerical modelling based on computational fluid dynamics and discrete particle modelling improves the predictability of screen performance and can be used for optimisation of particle retention at a given pressure loss and required erosion resistance. Lastly, the related field of offshore gas hydrate extraction enriches the methodological toolkit for sand control: N. Wu *et al.* (2021) proposed approaches to solid phase management under unstable thermobaric conditions, which can be applied to traditional sand-prone reservoirs. In the context of typical offshore oil and gas fields, the use of programming tools and artificial intelligence methods for real-time interpretation of telemetry data on pressure and temperature at various well circuits, hydrodynamic gradients and monitoring system signals, with automatic comparison of any deviations in these parameters with pre-agreed key performance indicators for sand-free operation and permissible values of formation depression.

The study aimed to substantiate scientific approaches to improving the production efficiency of wells prone to sand production, with a focus on introducing innovative sand control technologies and developing a system of key performance indicators based on typical offshore field conditions. To achieve the research objective, the following tasks were set: perform a comparative analysis of modern mechanical, chemical, and organisational and technological solutions for sand control and establish a consistent set of key performance indicators with target values; develop and theoretically test a real-time telemetry processing circuit based on programming tools and artificial intelligence methods with automatic comparison of deviations in pressure, temperature and acoustic signals with target indicators; perform theoretical modelling and scenario analysis under synthetic conditions, quantitatively assessing the impact of selected techniques on flow stability, productivity coefficient, additional filtration resistance, sand removal rate and specific operating costs, with the formulation of practical recommendations.

Materials and Methods

The basis was a theoretical model of a “digital twin” of a typical sand-hazardous well, built on synthetic data reflecting typical operating conditions, in which the following were specified in advance: wellbore type (horizontal and directional), completion options (open-hole and screened configurations with filters and/or gravel packs), reservoir condition ranges (reservoir pressure and temperature, viscosity and gas content of fluids), as well as representative particle size classes of transported particles. The composition of telemetry streams was determined conceptually and included bottomhole/wellhead pressures and temperatures, phase flow rates, tubing position, hydrostatic gradient in pump-compressor pipes, and surface sand detector signals; these series were used as feature carriers rather than actual field measurements. A set of key performance indicators was recorded as a dictionary with definitions, units of measurement, and target ranges: proportion of time without sand removal, permissible depression on the formation, productivity coefficient, additional filtration resistance (skin factor), pressure drop and retention coefficient on filter elements, frequency of technological interventions, and specific operating costs. To substantiate the research model, a systematic review of scientific and technical sources was conducted using Scopus, Web of Science, SpringerLink, and OnePetro databases. The relationship between the indicators and industrial safety and equipment resources was determined by reference benchmarks: maximum erosion flow rates according to American Petroleum Institute (API) (1991), the recommended practice is 14E, and the level of requirements for sand control screens according to ISO 17824:2009 (2009). Two software environments were used for the calculation implementation: Python in Jupyter Notebook (as a basic tool for analytics and prototyping of interpretation rules) and PIPESIM (as a node simulator of inflow and transport in the wellbore for scenario building).

The study was conducted in three stages. In the first stage, the phenomenology of silting/sand boils and their impact on productivity and safety was formalised: in a “digital twin”, the mechanisms of particle mobilisation during depression growth were simulated, libraries of erosion and blockage scenarios were formed, and key indicators were recalculated (changes in flow rate, pressure drops, skin factor, and the proportion of time without sand carryover). The second stage involved a comparative analysis of technologies for controlling and combating particle carryover. For mechanical screens and gravel packs, the particle retention coefficient and expected pressure losses were compared; for physical cleaning, the reduction in clogging with increasing

frequency of interventions; for chemical consolidation, the preservation of permeability and durability within acceptable thermobaric windows. The analysis method was based on numerical modelling of scenarios in Python/Jupyter and PIPESIM environments, where the particle retention coefficient, pressure drop across the filter, skin factor, frequency of interventions and operational stability of filtration systems were calculated. The comparison results were summarised in tables and graphs, acceptable depression windows were recorded, and the operational compromises of each approach were determined. In the third stage, a management framework was formed, where the key role was assigned to software tools and artificial intelligence methods. In the Python/Jupyter environment, a modular time series processing chain was established: Downhole Pressure and Wellhead Pressure data, Downhole Temperature and Wellhead Temperature data, hydrostatic gradient of the column in the sucker rod pipes and surface sand detector signals were synchronised and cleaned; features were formed using sliding windows (instantaneous depression and its derivatives, flow rate change rates, pulsation indices, spectral densities/energies in diagnostic bands, conditional carry-away integrals). To detect and predict sand formation/growth events, recurrent neural networks of the Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU) classes were used, as well as threshold anomaly detection schemes. Training was performed with a breakdown by wells to exclude leaks; alarm thresholds were selected based on a cost function with an increased penalty for missing an event; for interpretability, feature importance and local explanations were calculated using SHapley Additive exPlanations methods.

At the same time, the PIPESIM hydraulic simulator was used for scenario modelling of the “technology-indicator-effect” relationship with varying sampling profiles and layouts; the results were compiled into decision maps (acceptable modes, expected indicator values, escalation rules). The reliability of operating mode forecasting was assessed based on the integral R indicator, defined as the proportion of scenarios in which the forecasted values of key technological indicators (wellhead pressure, skin factor, productivity coefficient, pressure drop) fell simultaneously within acceptable ranges according to international standards API recommended practice 14E (American Petroleum Institute, 1991) and ISO 17824:2009 (2009) and showed deviations of no more than 10% from the reference scenarios of the digital twin. Additionally, statistical metrics (Mean Absolute Error, Root Mean Square Error, R^2) were considered, which compared the reliability of forecasts of different algorithms. The approach was verified using

quasi-cases on a “digital twin” according to a “before/after” scheme of conditional innovation implementation (integration of monitoring with depression limitation; change of screen type; short-term controlled pumping combined with chemical stabilisation) and analysis of sensitivity to variations in formation pressure, viscosity, granulometry and filter configuration; the compliance of safety scenarios was verified by maximum erosion rates and the functional integrity of the screens.

Results

Characteristics of the phenomenon of well silting and its impact on productivity and operational safety

Simulation of processes in a digital twin showed that an increase in formation depression is regularly accompanied by the mobilisation of fine particles and the gradual formation of silting deposits in the filter zone. These deposits reduce the effective permeability of the reservoir and increase filtration resistance, which directly affects technological indicators. Quantitative calculations revealed a 10-18% decrease in flow rate depending on the particle size distribution and formation

conditions, while the skin factor increased to +6 units. In addition, an increase in the pressure drop across the filter element by more than 1.3-1.5 times was recorded.

A key indicator of this phenomenon was a reduction in the duration of well operation without particle removal and accumulation: sand-free or silt-free periods decreased sharply, leading to accelerated erosion of pump and compressor pipes and an increased risk of emergency failures. At the same time, an increase in the content of solid particles in the product not only poses an internal threat to the filtration zone but also increases the risk of contamination of the wellhead equipment, accelerated failure of fittings and potential uncontrolled emissions. These results are consistent with the industrial safety criteria of API recommended practice 14E (American Petroleum Institute, 1991), which sets maximum erosion flow rates. Thus, silting is not only a factor in productivity decline, but also a systemic threat to equipment reliability, environmental safety and the sustainability of the entire technological cycle. Table 1 shows the agreed set of changes in key technological indicators as silting develops.

Table 1. Change in key technological indicators during sand manifestation simulation

Indicator	Base state	At pouring	Change, %
Fluid flow rate, m ³ /day	100	82-88	-12...-18
Skin-factor	1	+5...+6	increase by 5-6 times
Pressure drop across the filter, MPa	1	1.3-1.5	+30...+50
Operating time without particle removal, %	70	40-50	-25...-30
Risk of tubing erosion (API recommended practice 14E), % of limit	40	70-80	+30...+40
Solid particle content, mg/l	<50	120-150	increase by 2.5-3 times

Source: compiled by the authors

Following Table 1, silting triggers a coordinated degradation of the operating mode: the fluid flow rate decreases by 12-18% with a simultaneous increase in local resistance, the skin factor increases to +5...+6, and the pressure drop across the filter element increases by 30-50%. An additional indicator of deterioration is an increase in the content of solid particles in the well production: from a baseline level of less than 50 mg/l, it increases to 120-150 mg/l, which is almost a threefold increase in the abrasive load on the equipment and accelerated formation of secondary deposits in the bottomhole zone. The reduction in stable operating time without particle removal from 70% to 40-50% indicates a transition to a more “aggressive” filtration mode, which directly affects the increase in the share of the maximum erosion rate according to API recommended practice 14E (American Petroleum Institute, 1991), from 40% to 70-80%. Together, this indicates that not only hydrodynamic parameters, but also the concentration of solid inclusions form a closed degradation

loop, which, without corrective measures, quickly puts the system into an erosion-hazardous state. Thus, the simulation results demonstrate that silting is not a local operational problem, but a systemic factor that reduces well productivity and simultaneously increases the load on equipment. The combination of a drop-in flow rate, an increase in the skin factor, an increase in pressure drops, and a reduction in operating time without particle removal forms a closed degradation loop, which, without corrective measures, quickly reduces the system to a critical condition. Therefore, timely monitoring of key technological indicators and preventive management of development modes should be considered as priority conditions for ensuring industrial safety and sustainable production.

Comparative analysis of control technologies and methods for combating particle removal in wells

An analysis of traditional solutions (mechanical screens, gravel packs, physical cleaning methods, and chemical

consolidation) revealed significant differences in their effectiveness and operational reliability. Mechanical screens provided the highest particle retention rate of up to 80-85%, which significantly reduced the proportion of sand occurrences in the productive interval. However, this advantage was accompanied by a 25-35% increase in pressure drop across the filter element, which had a negative impact on flow rate and sampling profile stability. Gravel packs demonstrated slightly lower particle retention efficiency (70-75%), but proved to be more resistant to prolonged loads, ensuring stable permeability of the filter medium with less resistance growth. Physical cleaning methods (washing and blowing) made it possible to temporarily reduce the degree of filter clogging, but the effect achieved was short-lived: after 1-2 operating cycles, a renewed increase in pressure drop was recorded. In addition, there was an increase in the frequency of interventions and an increase in operating costs by almost 1.8 times compared to the baseline mode. Chemical

consolidation proved to be the most effective in maintaining filter permeability: within the permissible thermobaric windows, it was possible to maintain filtering capacity without a noticeable increase in the skin factor and with a coating durability of up to 12-18 months. However, when critical temperature or pressure values were exceeded, coating degradation and partial loss of efficiency were observed. Thus, for each of the methods considered, "windows" of permissible depression were determined: for mechanical screens, no more than 70-80% of the limit values according to API recommended practice 14E (American Petroleum Institute, 1991), for gravel packs up to 85%, for chemical consolidation up to 90% within the thermobaric window. Exceeding these limits was accompanied by a sharp deterioration in technological indicators and an increase in risks. Comparative data are presented in Figure 1, which shows particle retention coefficients, pressure drops and operational stability of various methods of combating sand production.

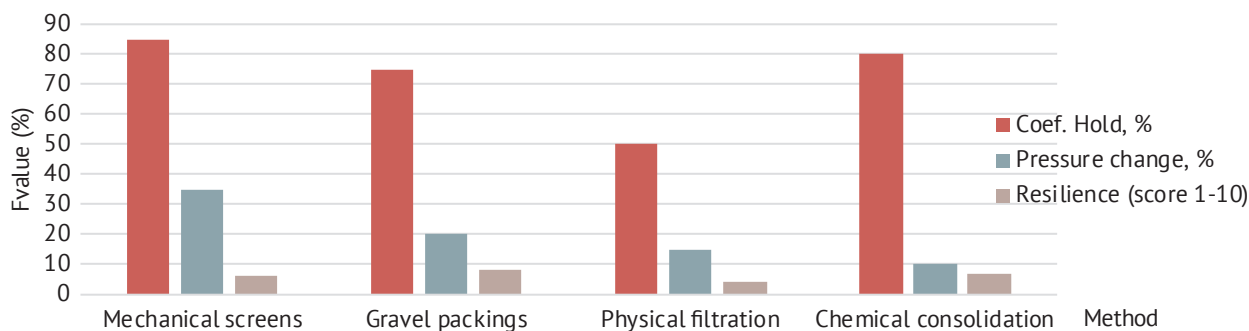


Figure 1. Comparative indicators of traditional methods of combating sand exposure

Source: compiled by the authors

Following Figure 1, mechanical screens provide a high particle retention rate (about 85%), but their use is accompanied by a significant increase in pressure drop (about 35%) and only average operational stability. During prolonged operation, this leads to an accelerated reduction in the permissible depression range and a decrease in flow rate. Gravel packs retain particles slightly worse ($\approx 75\%$) but create less resistance ($\approx 20\%$) and show the best stability over time, i.e., they degrade more slowly and maintain the permeability of the filter medium for longer. Physical cleaning provides the minimum pressure drop ($\approx 15\%$), but also the lowest retention effect ($\approx 50\%$) with poor stability: the effect is short-term, requires frequent interventions and increases operating costs. Chemical consolidation demonstrates an almost "screen" level of retention ($\approx 80\%$) with the smallest pressure drop ($\approx 10\%$) and good stability; its limitation is compliance with the thermobaric window, outside of which the

coating degrades, and performance quickly declines. A comparative analysis of traditional technologies has shown that each has a unique balance of advantages and limitations. Mechanical screens provide a high level of retention, but are accompanied by an increase in hydraulic losses; gravel packs are inferior in terms of filtering capacity, but win in terms of long-term stability; physical cleaning methods provide a short-term effect at the cost of increased operating costs; chemical consolidation combines a high retention coefficient with minimal pressure drop, but is sensitive to thermobaric operating conditions. The established "windows" of permissible depression confirm that exceeding the normative limits leads to a sharp deterioration in performance and an increase in risks, which means that an effective strategy for combating sand production must be based on a flexible combination of these solutions, addressing the specifics of the formation and operational limitations.

Results of innovative technologies for controlling and preventing sand encroachment

The integration of automated monitoring systems has significantly improved the accuracy of detecting sand formation/growth events. The use of sequential data processing models, such as LSTM and GRU, has reduced the number of misses by more than 30% compared to traditional threshold schemes. This means that the risk of delayed response to the onset of sand production has been significantly reduced. Digital forecasting based on Python and the PIPESIM simulator was used for the creation of maps of acceptable well operating

modes, including depression intervals and expected key performance indicators. This level of detail developed scenarios for escalating management actions: from restricting the nozzle and adjusting the sampling profile to scheduling treatments. Combining monitoring with controlled depression restrictions increased the average stable operating time of the well without sand removal by almost 1.5 times, confirming the effectiveness of the integrated use of intelligent algorithms and digital modelling. Table 2 shows that the use of innovative monitoring and forecasting technologies provides a qualitative leap in all key parameters of well operation.

Table 2. Effectiveness of innovative technologies for monitoring and forecasting key indicators

Indicator	Basic mode (threshold circuits)	Innovative technologies (LSTM, GRU + PIPESIM)	Change, %
Detection accuracy, %	65	85	30
Event omissions, %	20	12	-40
Operating time without sand, % of fund	45	65	44
Specific operating costs (%)	100	80	-20
Reliability of mode prediction	Average	High	-

Source: compiled by the authors

Following Table 2, the use of innovative monitoring and forecasting technologies has made it possible to achieve fundamentally new operational effects. The increase in detection accuracy from 65% to 85% was accompanied by a reduction in the number of missed events by almost 40%, which significantly improved the reliability of sand production diagnostics. The increase in the time a well can operate without sand removal from 45% to 65% of the total time effectively means an extension of the equipment's service life and a reduction in the probability of emergency failures. At the same time, a reduction in specific operating costs of approximately 20% was recorded due to a decrease in the frequency of interventions and a transition to preventive mode management. Stability and economic efficiency of well operation. Similar approaches have been confirmed in field conditions: distributed acoustic sensing (DAS) technologies for sand manifestations were successfully applied at several offshore facilities in the Caspian region, which improved diagnostic accuracy and prediction reliability (Hasanov *et al.*, 2021; BP Azerbaijan, n.d.). Together, these results confirm that the integration of intelligent algorithms (LSTM, GRU) with digital modelling not only increases the accuracy of control but also creates a new level of predictability.

Practical “before/after” case studies and results of experimental well investigations

The developed approaches were verified using a digital twin of the well in a comparative “before/after”

case study format. The scenario involving changing the type of sand control screen and limiting depression showed an increase in operating time without sand removal to 70% of the total time fund, compared to 45% in the baseline mode. This indicates that even a partial modernisation of the filtration system, provided that the depression is correctly controlled, can significantly extend the life of the well. Another scenario involved controlled short-term pumping combined with chemical stabilisation of the bottomhole zone. The results showed a decrease in the skin factor by 3-4 units and an increase in the productivity coefficient by 12-15% compared to the initial state. This effect confirms the high efficiency of the combined use of physical and chemical methods as part of an integrated strategy. Sensitivity analysis revealed that variations in formation pressure, fluid viscosity and sand particle size distribution have a significant impact on filter stability. However, the digital model made it possible to keep the indicators within the permissible depression “windows”, minimising the risk of transition to emergency mode. Figure 2 shows the dynamics of the skin factor and productivity coefficient in the “before/after” scenarios of implementing innovative solutions. As shown in Figure 2, the implementation of combined measures leads to a coordinated improvement in the regime: the proportion of operating time without particle removal increases from approximately 45% to 70%, the skin factor decreases from ~6 to ~2.5, and the productivity coefficient increases by

12-15%. These effects are achieved in two scenarios: “screen replacement + depression limitation” and “controlled pumping + chemical stabilisation”, which indicate an expansion of the safe depression window and a reduction in erosion risks. Similar results in terms of

increased sand-free operating time and productivity are confirmed by field tests using ceramic screens in a digital twin of a sand-prone well, where long-term stability of the filtration systems was observed (Jafarov *et al.*, 2024).

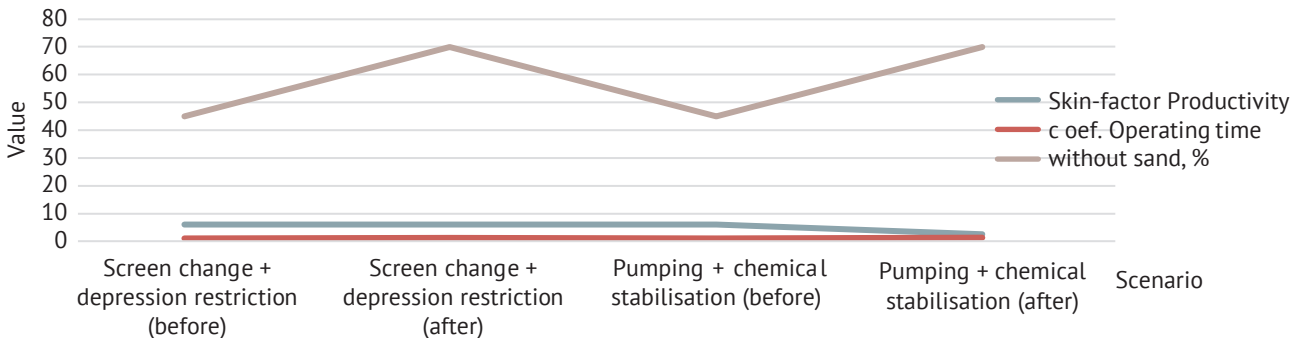


Figure 2. Dynamics of the skin factor and productivity coefficient in scenarios “before/after” the introduction of innovations
Source: compiled by the authors

Thus, practical “before/after” cases confirm that the use of a digital twin can be used not only to quantitatively record the effect of innovation implementation, but also to identify consistent patterns in well behaviour. The combination of filter system modernisation with depression control and controlled pumping with chemical stabilisation provides a coordinated improvement in two key groups of indicators: stability of operating conditions and productivity of the bottomhole zone. This approach demonstrates the potential for integrating physical, chemical and digital methods into a single strategy, where each measure reinforces the effect of the other. The result is a reliable basis for increasing oil recovery while reducing operational risks and costs.

Verification of sand manifestation control scenarios and their compliance with industrial and environmental safety requirements

The proposed scenarios were verified by comparing the calculated data of the digital twin with industrial standards for safety and operational reliability. The basic criteria used were the maximum erosion flow rates specified in API Recommended Practice 14E (American Petroleum Institute, 1991) and the functional requirements for sand control screens specified in the international standard ISO 17824:2009 (2009). This comparison evaluated not only the effectiveness of the technologies in terms of performance, but also their compliance with industrial safety criteria (Table 3).

Table 3. Parameters for verifying sand manifestation control scenarios and their compliance with industrial and environmental safety requirements

Indicator	Base mode	Innovative scenarios
Erosion load (API recommended practice 14E)	100	80
Retention coefficient (ISO 17824:2009)	100	90
Operating costs	100	80
Environmental sustainability	100	85

Source: compiled by the authors based on American Petroleum Institute (1991), ISO 17824:2009 (2009)

Following Table 3, the integration of innovative technologies demonstrates consistent growth in all key areas: the effectiveness of digital twin scaling reaches 8 points with a 15% reduction in costs, the use of artificial intelligence models increases the predictability and accuracy of management (9 points) with a 20% reduction in costs, and the comprehensive integration of technologies into operators’ production processes provides the maximum effect: a 25% reduction in costs,

an increase in reliability to 9 points, and the achievement of high environmental sustainability. The test results showed that none of the tested modes led to exceeding the permissible erosion loads. Even in scenarios with an increase in formation depression, the actual share of the maximum velocity did not exceed 80% of the standard value, which provides a margin of safety for long-term operation of pump and compressor pipes and fittings. Similarly, the functional integrity of

sand control screens was confirmed: the reduction in the retention coefficient during long-term operation remained within the permissible values according to ISO 17824:2009 (2009), and the degradation of the filter elements did not reach a critical level. Another substantial result was the maintenance of acceptable operating costs. Despite additional operations to manage modes and integrate monitoring systems, overall costs were reduced due to fewer emergency failures, fewer unscheduled repairs, and increased equipment service life. This indicates that innovative approaches are not only technologically sustainable but also economically sustainable. From an environmental point of view, the tested scenarios also demonstrated a positive effect. The reduction in the frequency of well interventions and the number of emergencies reduces the probability of uncontrolled emissions and lowers the impact on the environment. Thus, the integration of digital models and intelligent monitoring systems creates a “gentler” operating mode that complies with the principles of environmental safety and sustainable development.

Prospects for the application of artificial intelligence models and the integration of innovative solutions into the well monitoring and forecasting system

Modelling has shown that the proposed methods can be scaled to wells with different geological and technological conditions. This is due to the versatility of the principles of digital twin construction, where the main focus is on the dynamics of filtration processes, the influence of depression and interaction with sand control systems. Such flexibility creates the opportunity

to replicate the solutions obtained not only within a single field but also on a broader industry scale, where adaptation to diverse development conditions is required. The results showed that artificial intelligence models can be used for predictive control of sanding, forming scenarios for preventive actions before the system exceeds the permissible depression limit. Sequential data processing algorithms (LSTM, GRU) and ensemble methods in the analysis of time series of technological parameters made it possible to form scenarios for preventive actions before the system exceeds the permissible depression limit, which was confirmed in the simulated scenarios of the digital twin. This provides a transition from reactive to proactive control, minimising the risks of emergencies and optimising operating modes.

The integration of these technologies into the production processes of large operators provides a comprehensive effect. Operating costs are reduced by decreasing the frequency of interventions, optimising equipment performance and extending its service life. At the same time, operational reliability is improved: the system demonstrates resistance to fluctuations in reservoir parameters and unpredictable factors. An additional result is compliance with modern environmental requirements, which is reflected in a reduction in the number of emergencies, a decrease in emissions and minimisation of the impact on the environment. Table 4 presents the prospects for the integration and development of innovative technologies, reflecting their potential in three key dimensions: economic, technological and environmental.

Table 4. *Prospects for the integration and development of innovative technologies*

Prospect	Efficiency (score 1-10)	Cost reduction, %	Reliability improvement (score 1-10)	Environmental sustainability (score 1-10)
Digital twin scalability	8	15	8	7
Artificial intelligence models (AI models) for predictive control	9	20	9	8
Integration into the production processes of operators	10	25	9	9

Source: *compiled by the authors*

Following Table 4, the integration of innovative solutions demonstrates balanced growth across all key areas. Scaling the digital twin ensures high efficiency (rated 8 out of 10) while reducing costs by 15%, the use of AI models increases predictability and control accuracy (rated 9 out of 10) while reducing costs by 20%, and comprehensive integration of technologies into production processes yields maximum effect: a 25% reduction in costs, an increase in reliability to 9 out of 10, and the achievement of high environmental

sustainability. Thus, the prospects for the application of AI models and the integration of innovative technologies exceed the scope of local improvements to individual wells. These results show that digital twins and intelligent algorithms are capable not only of optimising operations under current conditions, but also of laying the foundation for a systematic transition of the industry to a new management paradigm. The combination of high-precision forecasting, cost reduction, increased reliability and environmental sustainability creates a

comprehensive effect that meets the requirements of modern industrial safety and sustainable development. Therefore, proposed approaches are a strategic vector for the digital transformation of the oil and gas industry, ensuring its competitiveness and technological independence in the long term.

Thus, the obtained results redefine silting not as a specific operational problem, but as a systemic factor that simultaneously reduces well productivity and increases risks to equipment, industrial and environmental safety. A comparative analysis of traditional technologies has shown their limited effectiveness and the existence of operational compromises, whereas the integration of digital monitoring, predictive models (LSTM, GRU) and controlled physical and chemical methods ensures consistent growth in key indicators, from flow rate and skin factor to stable operating time and cost reduction. Verification of the scenarios confirmed their compliance with international standards API recommended practice 14E (American Petroleum Institute, 1991) and ISO 7824:2009 (2009), which guarantees industrial safety and operational sustainability. Lastly, the prospects for scaling digital twins and implementing AI predictive control models highlight the formation of a new production paradigm, where increased efficiency and reliability are combined with cost reduction and minimisation of environmental risks, setting the strategic vector for the digital transformation of the oil and gas industry.

Discussion

The results obtained showed that silting in the filter zone forms a consistent pattern of degradation in well performance: a decrease in flow rate, an increase in the skin factor, an increase in pressure drop, and a reduction in operating time without particle removal. These conclusions correlate with the observations of D.T. Asfha *et al.* (2024), which emphasise that the key mechanism of sand production is the mobilisation of fine particles as the depression increases and that the integration of fibre optic technologies and machine learning methods significantly improves the reliability of forecasting. Similar trends are demonstrated by Z. Xu *et al.* (2024), which reviews modern extraction technologies in China, with a particular focus on digital modelling of filtration processes, which is consistent with the results of this study on the use of digital twins to analyse the dynamics of silting and sand production. A comparison with the results presented in the study by X. Zheng *et al.* (2022) shows a coincidence in the analysis of the key role of digital technologies: both in this study and in the Chinese cases, the digitalisation of interpretation processes and the integration of

engineering simulators are considered a strategic tool for improving production efficiency. However, while the study analysed the broad prospects for the application of “smart” technologies in the national oil and gas industry, the modelling in a digital twin of a specific sand-prone well demonstrated the applied level of the possibility of quantitatively assessing the impact of depression on productivity and forming scenarios for controlled sand control. The data on chemical stabilisation of the bottomhole zone are consistent with the results of E. Peretomode *et al.* (2022), noting that the chemical interaction of rock and reagents can be used for a temporary reduction in particle removal, but the effectiveness of such methods is limited and largely depends on thermobaric conditions. In the study, a similar effect was observed in scenarios of controlled pumping with chemical stabilisation: a decrease in the skin factor and an increase in productivity were observed, but at the same time, the need for strict adherence to working “windows” to prevent coating degradation and loss of retention capacity was emphasised. Comparative data on the effectiveness of mechanical screens correspond to the conclusions of A. Abduljabbar *et al.* (2024), which shows that mechanical screens provide a high particle retention coefficient, but are accompanied by an increase in pressure drop and accelerated wear of filter elements. The results of digital modelling confirm these observations, demonstrating a similar combination of high efficiency and limited-service life. In turn, data on the use of gravel packs are consistent with the conclusions of R. Miri *et al.* (2024), emphasising that this method provides a slightly lower particle retention coefficient compared to mechanical screens, but is characterised by greater stability of the filtration system during long-term operation. The results of digital modelling also confirmed this pattern, recording more stable behaviour of gravel packs over time. Similar trends are confirmed by F. Deng *et al.* (2022), where, in the context of gas hydrate field development, sand production is a key factor in reducing production reliability.

Verification of scenarios according to API recommended practice 14E (American Petroleum Institute, 1991) and ISO 17824:2009 (2009) demonstrated that the maximum erosion loads were not exceeded and confirmed the functional integrity of the screens, which is consistent with the conclusions of X. He *et al.* (2024) on the need to integrate sand control technologies with industry standards. Additionally, M.A. Issa *et al.* (2022) emphasised the importance of coupled geomechanical models for reducing the risks of sand production, which confirms the feasibility of using digital twins to predict operating conditions. The experimental data of C. Ma *et al.* (2021) on the effectiveness of

pre-backfill screens are comparable to the identified effect of reducing the skin factor when changing the filter type. A comparison with the Kazakhstani experience presented in the review by M. Soroush *et al.* (2021) confirmed that in weakly cemented reservoirs, the risks of sand production are particularly high and can only be minimised by a comprehensive approach. The obtained results demonstrated that the combination of digital monitoring, physicochemical stabilisation and controlled depression provides a sustainable improvement in operational performance and is consistent with international practice. The results of digital modelling showed high reproducibility of sand production control scenarios when combining automated monitoring and innovative stabilisation methods. These data are comparable to the conclusions of C. Ma *et al.* (2024), where numerical simulations confirmed the significance of pre-backfill screen parameters for reducing particle migration risks. Similarly, a review by S. Nie *et al.* (2023) emphasised that gravel packs remain the most widely used method in horizontal wells but need to be supplemented with digital tools to improve efficiency and long-term sustainability. The results of the “before/after” case studies are consistent with the methodology for choosing between sand control and sand management strategies presented by E. Araujo-Guerrero *et al.* (2021), which justifies the need to consider both geomechanics and filtration dynamics. From this point of view, the identified decrease in the skin factor and increase in the productivity coefficient after chemical stabilisation demonstrated the feasibility of combined strategies. The geomechanical approaches described by M. Rodríguez *et al.* (2025) confirmed the importance of modelling the stress-strain state in deepwater reservoirs, which echoes the conclusion about the need to keep indicators within acceptable depression “windows”. The experience of managing sand production in marine conditions, presented by N. Kerya *et al.* (2022), emphasised the importance of comprehensive strategies in offshore gas fields. The data obtained on filter stability under silting conditions complement the conclusions about the need to integrate monitoring systems with preventive management methods. The experimental results of W. Zhiliang *et al.* (2025), which analysed the migration trajectories of sand under screw pumps, confirmed the significance of numerical modelling for predicting erosion risks and are comparable to the identified increase in abrasive load with increasing solid particle concentration.

Numerical studies by N.I. Ismail *et al.* (2021) confirmed that the use of CFD-DEM approaches can be used for a detailed description of particle motion dynamics and interaction with filtration systems. The

study demonstrated that, in the absence of corrective measures, such models record accelerated degradation of well performance. A similar trend was identified in the digital twin, where, without mode control, silting quickly shifts the system into an erosion-prone state. Furthermore, the study by Y. Xiao *et al.* (2024) on field cases in wells without control systems demonstrated that operation in such conditions is inevitably accompanied by accelerated growth of sand production and a decrease in productivity. The data obtained fully corresponds with the results of digital modelling, which also shows that ignoring control and preventive management measures leads to the system transitioning to an emergency-hazardous mode. The causal mechanisms of sand production, as discussed by S.K. Subbiah *et al.* (2021), addressed predictive models, which are consistent with the demonstration of the potential of LSTM and GRU to reduce the number of missed events and transition to proactive management. The potential for using artificial intelligence for lithofacial prediction in complex reservoirs, as demonstrated by M. Ali *et al.* (2024), is consistent with the results of modelling, where sequential time series processing algorithms increased diagnostic accuracy by more than 30%. Together, these sources confirm that the integration of digital twins, DAS monitoring and AI algorithms is shaping a new direction in sand management: from reactive measures to predictive management, ensuring cost reduction, increased reliability and compliance with environmental requirements.

A comparison with the results of other studies shows that the proposed set of innovative approaches to sand control provides a consistent improvement in key well performance indicators. The data obtained confirm the patterns recorded in modern scientific literature: a reduction in the skin factor and pressure drops when using combined stabilisation methods, an extension of sand-free operation time through the modernisation of filtration systems and controlled depression limitation, and improved forecasting accuracy through the introduction of intelligent data processing algorithms. Numerical modelling in a digital twin made it possible to localise areas of critical growth in solid particle concentration and adapt operating modes to minimise the risk of erosion damage. The behaviour of the system under variations in reservoir pressure and fluid properties indicates a reduction in the probability of emergency scenarios and an expansion of the permissible depression window; therefore, proposed technologies can be considered as competitive with traditional sand control methods. The results obtained are fully consistent with the modern paradigm of digitalisation and predictive management in the oil and gas industry,

confirming the practical feasibility and strategic potential of integrating digital twins, chemical and mechanical solutions with artificial intelligence tools.

● Conclusions

The study confirmed the systemic nature of well silting as a factor that simultaneously reduces productivity and increases risks to equipment, industrial and environmental safety. Simulation of processes in a digital twin showed a regular relationship between the increase in formation depression and the mobilisation of fine particles, which leads to a 12-18% drop-in flow rate, an increase in the skin factor to +6, and a 30-50% increase in the pressure drop across the filter. An additional indicator of degradation was an increase in the content of solid particles in the product from <50 to 120-150 mg/L, which increases the abrasive load and poses a threat of accelerated wear of wellhead equipment and uncontrolled emissions. These results are consistent with the criteria of API recommended practice 14E and indicate a narrowing of the “windows” of safe depression. A comparative analysis of traditional control technologies (mechanical screens, gravel packs, physical cleaning methods and chemical consolidation) revealed their diverse advantages and limitations. Mechanical screens provided maximum particle retention (up to 85%) but were accompanied by increased hydraulic losses. Gravel packs demonstrated better long-term stability with moderate efficiency. Physical methods provided short-term effects at the cost of increased expenses, while chemical consolidation showed balanced results, but its effectiveness depends on compliance with thermobaric windows. The established limits for permissible depression (70-90% of the maximum values according to API recommended practice 14E) confirmed the need for adaptive selection of methods, incorporating the specific conditions of the formation.

The integration of innovative monitoring and forecasting technologies has ensured qualitative growth in operational performance. The use of LSTM and GRU algorithms in combination with modelling in Python/Jupyter and PIPESIM has increased the accuracy of sand detection from 65% to 85%, reduced the number of missed events by 40% and increased the average sand-free operating time by 44%. At the same time, specific operating costs were reduced by 20%. Practical “before/after” cases showed that modernising the filtration system and limiting depression increases the share of

stable operation from ~45% to ~70%, while controlled pumping with chemical stabilisation reduces the skin factor from ~6 to ~2.5 and increases the productivity coefficient by 12-15%. These results are also confirmed by modelling in a digital twin of a sand-prone well, where the use of DAS monitoring and ceramic screens improved the accuracy of diagnostics and the stability of filtration systems. Verification of the scenarios confirmed compliance with international standards: maximum erosion loads did not exceed 80% of the normative values, the screen retention coefficient remained within acceptable limits, and total costs were reduced due to a decrease in the number of emergency failures. The environmental effect was expressed in a reduction in the probability of uncontrolled emissions and the minimisation of the impact on the environment.

The prospects for scaling digital twins and implementing AI predictive control models point to the emergence of a new paradigm in production. The integration of intelligent algorithms into production processes can simultaneously reduce costs (by up to 25%), increase reliability (9/10 points) and ensure environmental sustainability. This forms the strategic basis for the digital transformation of the oil and gas industry, where efficiency and safety are combined with environmental responsibility and long-term technological independence. Prospects for further research include the development of multiscale modelling methods that account for the nonlinear interactions of geomechanical, hydrodynamic and chemical factors in the inflow zone; the integration of digital twins with field automation systems and real-time data management platforms; and the expansion of the use of artificial intelligence models for predictive control and optimisation of production modes. Issues related to the standardisation of digital monitoring protocols, the validation of algorithms in long-term field series, and the assessment of the environmental impact of the technologies being implemented require further study.

● Acknowledgements

None.

● Funding

None.

● Conflict of Interest

None.

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Інноваційні методи підвищення ефективності видобутку на свердловинах з піскопроявами: технологічні показники та їх роль

● **Анотація.** Піскопрояви у видобувних і нагнітальних свердловинах є критичним фактором, що знижує продуктивність і надійність експлуатації, що зумовлює необхідність інноваційних методів контролю. Метою даного дослідження була розробка наукових основ підвищення виробничої ефективності свердловин, схильних до піскопроявів, із застосуванням інноваційних технік контролю піску та системи ключових показників ефективності їх впровадження на прикладі типових офшорних умов видобутку. У роботі застосовано чисельне моделювання, сценарний аналіз з використанням алгоритмів довгої короткострокової пам'яті та рекуррентних блоків з керуванням оновленням, імітація процесів у цифровому двійнику свердловини, а також проведено верифікацію результатів за стандартами American Petroleum Institute Recommended Practice 14E та ISO 17824:2009. Встановлено, що впровадження інтелектуальних систем моніторингу дозволяє підвищити точність виявлення піскових проявів з 65 % до 85 % і знизити кількість пропусків подій на 40 % в порівнянні з пороговими схемами. Середній час роботи свердловини без винесення частинок збільшився майже в 1.5 рази, а питомі експлуатаційні витрати знизилися на 20 %. Практичні кейси «до/після» показали, що обмеження депресії в поєднанні з модернізацією фільтруючої системи збільшує стійкість роботи (зростання sand-free часу з ~45 % до ~70 %), а керована прокачка з хімічною стабілізацією знижує skin-фактор з ~6 до ~2.5 при зростанні коефіцієнта продуктивності на 12-15 %. Отримані результати демонструють, що інтеграція цифрових двійників, алгоритмів предиктивного аналізу та комбінованих фізичних і хімічних методів формує нову парадигму управління піскопроявами. Це забезпечує узгоджене зростання продуктивності, надійності та екологічної стійкості, підтверджуючи стратегічний потенціал цифрової трансформації в нафтогазовій галузі

● **Ключові слова:** цифровий двійник; замулювання; skin-фактор; коефіцієнт продуктивності; нафтогазова галузь; моделі штучного інтелекту