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DIGITAL TWIN AND AI-ENABLED RESILIENT INFRASTRUCTURE PLANNING FOR FLOOD AND EARTHQUAKE RISK REDUCTION IN PAKISTAN

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Abstract

Pakistan is increasingly vulnerable to floods and earthquakes due to rapid urbanization, climate change, aging infrastructure, and inadequate disaster preparedness systems. Conventional infrastructure planning approaches are often reactive and lack the predictive capabilities required to enhance resilience against natural hazards. This study examined the role of Digital Twin Capability and AI-Enabled Predictive Analytics in improving Resilient Infrastructure Planning for Flood and Earthquake Risk Reduction in Pakistan, while investigating the moderating role of Digital Governance Capacity. Grounded in Dynamic Capabilities Theory, the study employed a quantitative, cross-sectional research design. Data were collected from 400 professionals involved in infrastructure planning, disaster management, engineering, and urban development across Pakistan using a structured questionnaire. The proposed hypotheses were tested using Partial Least Squares Structural Equation Modeling (PLS-SEM) with SmartPLS 4. The findings revealed that Digital Twin Capability and AI-Enabled Predictive Analytics significantly enhanced Resilient Infrastructure Planning, which subsequently improved Flood and Earthquake Risk Reduction. The results further demonstrated that Resilient Infrastructure Planning mediated the relationships between the technological capabilities and disaster risk reduction, while Digital Governance Capacity significantly strengthened the positive effects of Digital Twin Capability and AI-enabled predictive analytics on infrastructure resilience. The study contributes to the literature by integrating Digital Twin technology, Artificial Intelligence, and Dynamic Capabilities Theory within the context of disaster-resilient infrastructure planning in a developing economy. The findings provide valuable theoretical, managerial, and policy implications for promoting intelligent infrastructure systems, strengthening digital governance, and advancing sustainable disaster risk management in Pakistan.

INTRODUCTION

Pakistan is among the most disaster-prone countries in the world, experiencing recurrent floods, earthquakes, landslides, and climate-induced extreme weather events that impose severe socio-economic and environmental consequences. Rapid urbanization, inadequate infrastructure planning, weak disaster preparedness, and increasing climate variability have significantly heightened the country's vulnerability to natural hazards. The devastating floods of 2022 and recurring seismic events highlighted substantial deficiencies in infrastructure resilience, risk assessment, and emergency response systems. Consequently, there is an urgent need for intelligent, data-driven, and proactive infrastructure planning approaches capable of minimizing disaster risks while enhancing sustainable development (United Nations Office for Disaster Risk Reduction [UNDRR], 2023; World Bank, 2023).

Recent advances in Artificial Intelligence (AI), the Internet of Things (IoT), Geographic Information Systems (GIS), remote sensing, and Digital Twin technology have transformed disaster risk management and resilient infrastructure planning. A Digital Twin is a dynamic virtual representation of physical assets, infrastructure, or urban systems that continuously integrates real-time data from sensors and multiple information sources to simulate, monitor, predict, and optimize system performance. When integrated with AI algorithms, Digital Twins facilitate predictive analytics, scenario simulation, early warning systems, structural health monitoring, and evidence-based decision-making for disaster preparedness and recovery (Tao et al., 2019; Fuller et al., 2020).

AI-powered Digital Twin platforms enable infrastructure managers and policymakers to simulate flood inundation, earthquake impacts, evacuation strategies, and infrastructure failures under various disaster scenarios. Machine learning models can analyze historical disaster data alongside real-time environmental information to predict hazard intensity, infrastructure vulnerability, and potential losses with higher accuracy than conventional methods. Such intelligent systems substantially improve resource allocation, emergency response planning, infrastructure maintenance, and post-disaster reconstruction (Batty, 2018; Ketzler et al., 2020).

Globally, several developed countries have begun implementing AI-enabled Digital Twins for smart city management, resilient transportation networks, flood forecasting, and earthquake risk mitigation. However, developing countries, including Pakistan, remain at an early stage of adopting these technologies due to limited institutional capacity, inadequate digital infrastructure, fragmented governance, and financial constraints. Existing disaster management systems in Pakistan largely rely on reactive approaches rather than predictive and adaptive infrastructure planning, limiting their effectiveness in reducing disaster-related losses (Asian Development Bank, 2024; UNDRR, 2023).

Despite growing scholarly interest in Digital Twins, AI applications, and smart infrastructure, limited empirical research has examined their integrated role in enhancing infrastructure resilience within disaster-prone developing economies. Particularly, insufficient evidence exists regarding how AI-enabled Digital Twins can improve infrastructure planning, institutional coordination, disaster preparedness, and resilience against floods and earthquakes in Pakistan. Addressing this research gap is essential for supporting sustainable infrastructure development, achieving the Sustainable Development Goals (SDGs), and strengthening national disaster risk reduction strategies.

Therefore, this study investigates the role of Digital Twin and AI-enabled resilient infrastructure planning in reducing flood and earthquake risks in Pakistan. It seeks to provide a comprehensive framework for integrating intelligent technologies into disaster management practices while generating practical recommendations for policymakers, urban planners, engineers, and disaster management authorities.

Problem Statement

Pakistan continues to experience increasing losses from floods and earthquakes due to inadequate infrastructure resilience, ineffective land-use planning, insufficient risk assessment mechanisms, and limited integration of advanced digital technologies into disaster management systems. Conventional infrastructure planning methods primarily rely on historical datasets, periodic inspections, and static models, which lack the capability to provide continuous monitoring, predictive analytics, and real-time decision support required for modern disaster risk reduction.

Although Artificial Intelligence and Digital Twin technologies have demonstrated significant potential for improving infrastructure resilience, predictive maintenance, hazard simulation, and emergency response globally, their adoption within Pakistan remains limited. Existing disaster management frameworks operate with fragmented information systems, poor inter-agency coordination, and insufficient technological capacity, reducing their effectiveness in anticipating infrastructure failures and optimizing disaster preparedness.

Moreover, empirical evidence examining the combined application of AI-enabled Digital Twins for flood and earthquake risk reduction in developing countries is scarce. Previous studies have largely focused on individual technologies, developed-country contexts, or specific infrastructure sectors without providing integrated frameworks applicable to Pakistan's institutional and environmental conditions. Consequently, policymakers, infrastructure planners, and disaster management authorities lack evidence-based guidance for implementing intelligent infrastructure planning systems capable of enhancing resilience against multiple natural hazards.

This study addresses this critical research gap by investigating how AI-enabled Digital Twin technology can strengthen resilient infrastructure planning for flood and earthquake risk reduction in Pakistan while supporting sustainable urban development, institutional preparedness, and long-term disaster resilience.

Research Questions

RQ1: How does AI-enabled Digital Twin technology influence resilient infrastructure planning for flood and earthquake risk reduction in Pakistan?

RQ2: How do Digital Twin capabilities improve disaster prediction, infrastructure monitoring, and emergency preparedness?

RQ3: What institutional, technological, and governance challenges affect the adoption of AI-enabled Digital Twin systems in Pakistan?

RQ4: How can AI-enabled Digital Twin frameworks enhance sustainable infrastructure resilience and disaster risk management?

RQ5: What policy recommendations can facilitate the successful implementation of AI-enabled resilient infrastructure planning in Pakistan?

Research Objectives

To examine the role of AI-enabled Digital Twin technology in resilient infrastructure planning for flood and earthquake risk reduction in Pakistan.

To evaluate the effectiveness of Digital Twin systems in improving disaster prediction, infrastructure monitoring, and emergency response.

To identify institutional, technological, and governance barriers affecting the implementation of AI-enabled Digital Twin technologies.

To develop an integrated framework for resilient infrastructure planning using AI and Digital Twin technologies.

To provide practical policy recommendations for strengthening disaster risk reduction and sustainable infrastructure development in Pakistan.

Significance of the Study

This study contributes significantly to both theory and practice by integrating Digital Twin technology and Artificial Intelligence within the context of disaster-resilient infrastructure planning. From a theoretical perspective, it extends the literature on digital transformation, smart infrastructure, and disaster risk management by proposing a comprehensive framework that explains how AI-enabled Digital

Twins enhance infrastructure resilience against floods and earthquakes in developing countries.

Practically, the study offers valuable insights for policymakers, engineers, urban planners, disaster management authorities, and infrastructure developers by identifying technological strategies capable of improving predictive maintenance, hazard simulation, emergency preparedness, and post-disaster recovery. The findings can support evidence-based investment decisions for resilient infrastructure projects.

The study also provides policy implications for strengthening Pakistan's digital governance, disaster management systems, and infrastructure planning through advanced technologies. Furthermore, the research contributes to achieving the Sustainable Development Goals, particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action), by promoting intelligent, sustainable, and resilient infrastructure development.

Literature Review

Digital Twin Technology in Resilient Infrastructure Planning

Digital Twin (DT) technology has emerged as one of the most transformative innovations in infrastructure management and disaster risk reduction. A Digital Twin is a dynamic virtual representation of physical infrastructure that continuously integrates real-time data from sensors, Internet of Things (IoT) devices, Geographic Information Systems (GIS), satellite imagery, and Building Information Modeling (BIM) to simulate, monitor, predict, and optimize infrastructure performance throughout its lifecycle (Tao et al., 2019). Unlike conventional simulation models, Digital Twins facilitate continuous synchronization between physical and virtual environments, enabling infrastructure managers to make timely and evidence-based decisions under uncertain disaster conditions (Rasheed et al., 2020).

Recent studies demonstrate that Digital Twins significantly improve infrastructure resilience by enabling predictive maintenance, structural health monitoring, risk forecasting, and emergency response planning. Through real-time monitoring, Digital Twins detect structural deterioration, forecast infrastructure failures, and recommend preventive interventions before catastrophic damage occurs. Such capabilities are particularly valuable in disaster-prone countries where aging infrastructure and limited maintenance resources increase vulnerability to floods and earthquakes (Boje et al., 2020; Fuller et al., 2020).

In smart city applications, Digital Twins integrate transportation systems, utility networks, buildings, and environmental monitoring platforms into unified decision-support systems. This integration enhances urban resilience by allowing policymakers to evaluate multiple disaster scenarios, optimize evacuation routes, prioritize infrastructure investments, and coordinate emergency responses more effectively (Ketzler et al., 2020). Despite these advantages, implementation challenges—including high investment costs, limited digital infrastructure, interoperability issues, and institutional resistance—remain significant barriers in developing economies such as Pakistan.

Artificial Intelligence in Disaster Risk Reduction

Artificial Intelligence (AI) has become a critical technological driver for disaster management due to its capacity to analyze large-scale datasets, identify hidden patterns, and generate highly accurate predictive models. AI techniques, including machine learning, deep learning, reinforcement learning, and computer vision, have substantially improved hazard prediction, disaster monitoring, damage assessment, and emergency response systems (Zhang et al., 2022).

Machine learning algorithms process historical disaster records, meteorological observations, hydrological information, satellite imagery, and seismic data to forecast floods, earthquakes, landslides, and infrastructure failures with greater precision than traditional statistical models. Deep learning models further enhance disaster detection by automatically recognizing damaged infrastructure from drone and satellite imagery, thereby accelerating post-disaster damage assessments and resource allocation (Yang et al., 2023).

AI also supports intelligent decision-making through optimization models that improve emergency logistics, evacuation planning, resource distribution, and critical infrastructure restoration. Recent research indicates that AI-driven disaster management systems reduce response time, improve situational awareness, and enhance institutional preparedness, ultimately minimizing disaster-related economic and human losses (European Commission, 2024). Nevertheless, AI implementation requires reliable data quality, robust computational infrastructure, ethical governance, and skilled human resources to ensure trustworthy and transparent decision-making.

Integration of AI and Digital Twin Technologies

The convergence of Artificial Intelligence and Digital Twin technology represents a significant advancement in intelligent infrastructure management. AI enhances Digital Twin capabilities by enabling autonomous learning, predictive analytics, anomaly detection, and adaptive optimization. Simultaneously, Digital Twins provide AI systems with continuously updated real-world operational data, creating a feedback loop that continuously improves predictive accuracy and decision quality (Tao et al., 2022).

AI-enabled Digital Twins have been successfully applied to transportation infrastructure, water management systems, energy networks, smart buildings, and urban planning. These integrated systems simulate disaster scenarios, estimate infrastructure vulnerabilities, optimize maintenance schedules, and evaluate alternative mitigation strategies before disasters occur. Consequently, infrastructure managers can proactively reduce risks rather than relying solely on reactive disaster response mechanisms (Jones et al., 2023).

Recent systematic reviews conclude that AI-enabled Digital Twins significantly improve infrastructure resilience by integrating predictive analytics, real-time monitoring, simulation, and intelligent decision support into a unified operational platform. However, empirical research focusing on disaster-prone developing countries remains limited, particularly regarding institutional readiness, governance structures, and technology adoption challenges.

Flood Risk Reduction through AI-Enabled Digital Twins

Floods represent Pakistan's most frequent and economically devastating natural hazard. Climate change, glacier melting, rapid urbanization, deforestation, and inadequate drainage infrastructure have increased flood frequency and severity over the past decade. Traditional flood management approaches often rely on static hydrological models that inadequately capture rapidly changing environmental conditions.

AI-enabled Digital Twins overcome these limitations by integrating IoT sensors, weather forecasting models, hydrological simulations, satellite observations, and GIS data into real-time flood prediction systems. These technologies continuously simulate river flows, rainfall intensity, urban drainage capacity, and flood inundation patterns, enabling authorities to issue earlier warnings and implement timely evacuation strategies (World Bank, 2023).

Recent studies demonstrate that Digital Twin-based flood forecasting systems substantially improve prediction accuracy, optimize reservoir operations, identify vulnerable infrastructure, and support climate adaptation planning. Machine learning algorithms further enhance flood simulations by continuously learning from new environmental observations, thereby improving forecasting performance over time (UNDRR, 2023; Yang et al., 2023).

Earthquake Risk Reduction through Intelligent Infrastructure Systems

Pakistan lies within an active seismic zone where earthquakes continue to threaten urban infrastructure, transportation networks, and public safety. Conventional seismic risk assessments often rely on periodic inspections and historical seismic records, limiting their ability to monitor infrastructure conditions dynamically.

AI-enabled Digital Twins provide continuous structural health monitoring by integrating sensor networks, vibration measurements, deformation analysis, and seismic monitoring systems. Machine learning models identify structural anomalies, estimate remaining service life, predict structural failures, and recommend preventive maintenance before earthquake-induced collapse occurs (Rasheed et al., 2020).

Furthermore, Digital Twins enable engineers to simulate earthquake scenarios, evaluate structural performance under varying seismic intensities, and optimize retrofit strategies without interrupting infrastructure operations. These predictive capabilities substantially strengthen urban resilience while reducing maintenance costs and disaster-related losses (Boje et al., 2020).

Institutional and Governance Challenges

Despite the growing technological maturity of AI-enabled Digital Twins, organizational and institutional barriers continue to hinder widespread implementation, particularly in developing countries. Limited digital infrastructure, fragmented data governance, insufficient regulatory frameworks, financial constraints, cybersecurity concerns, and shortages of skilled professionals remain major implementation challenges (Asian Development Bank, 2024).

Pakistan's disaster management institutions continue to operate largely through fragmented information systems with limited interoperability among federal, provincial, and local agencies. Successful Digital Twin implementation requires integrated governance structures, standardized data-sharing mechanisms, investment in digital infrastructure, and capacity-building initiatives to support evidence-based disaster management (World Bank, 2023).

Several scholars argue that technological innovation alone cannot improve disaster resilience without complementary institutional reforms, effective digital governance, stakeholder collaboration, and supportive public policies. Consequently, future disaster resilience strategies should integrate technological advancement with organizational readiness and governance modernization.

Research Gap

Although Digital Twin technology, Artificial Intelligence, and resilient infrastructure planning have individually attracted increasing scholarly attention, several significant research gaps remain. First, existing studies predominantly examine Digital Twins within manufacturing, smart cities, healthcare, and industrial engineering, while limited empirical research investigates their integrated application for multi-hazard disaster risk reduction in developing countries.

Second, previous research generally analyzes floods and earthquakes independently rather than proposing comprehensive infrastructure planning frameworks capable of simultaneously addressing multiple natural hazards. Third, empirical studies focusing on Pakistan remain scarce despite the country's high disaster vulnerability and increasing need for intelligent infrastructure management systems.

Moreover, insufficient attention has been given to institutional readiness, governance capacity, digital infrastructure, and policy frameworks necessary for implementing AI-enabled Digital Twins within public infrastructure planning. Therefore, this study addresses these gaps by developing an integrated framework that explains how AI-enabled Digital Twin technology can strengthen resilient infrastructure planning for flood and earthquake risk reduction in Pakistan.

Underpinning Theory

Dynamic Capabilities Theory (DCT)

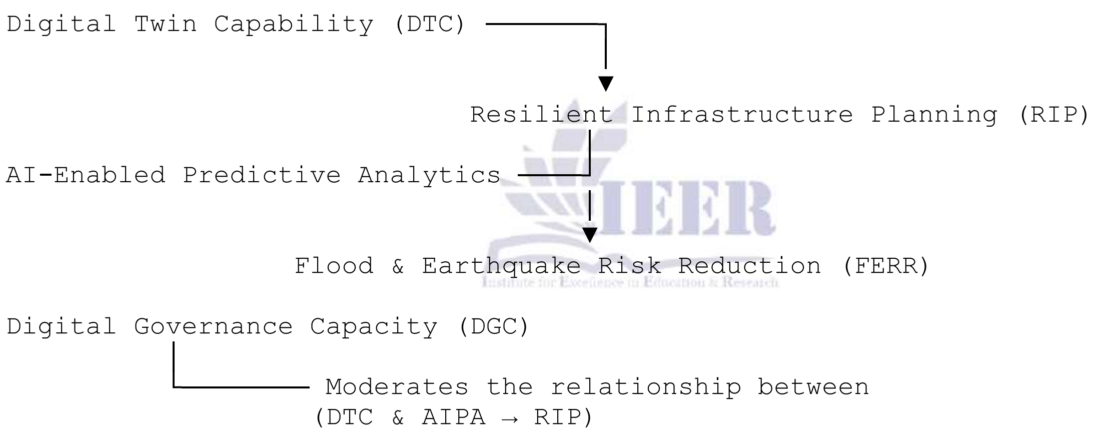
The present study is underpinned by Dynamic Capabilities Theory (DCT), originally proposed by Teece, Pisano, and Shuen (1997) and further refined by Teece (2007, 2018). The theory explains how organizations develop, integrate, and reconfigure internal and external resources to respond effectively to rapidly changing environments. Dynamic capabilities enable organizations to sense emerging threats and opportunities, seize appropriate responses, and continuously transform organizational processes to sustain long-term performance.

Within disaster risk management, Dynamic Capabilities Theory provides an appropriate theoretical foundation because resilient infrastructure requires continuous adaptation to uncertain environmental conditions, technological disruptions, and evolving disaster risks. AI-enabled Digital Twins strengthen organizational dynamic capabilities by enhancing real-time sensing through continuous monitoring, improving decision-making through predictive analytics, and supporting organizational transformation through adaptive infrastructure planning.

In Pakistan's disaster management context, Dynamic Capabilities Theory suggests that infrastructure resilience depends not only on physical assets but also on institutional capabilities to collect, analyze, interpret, and utilize real-time information for proactive decision-making. AI-enabled Digital Twins enhance these capabilities by integrating sensor networks, machine learning algorithms, predictive simulations, and digital governance systems into a unified decision-support platform. Consequently, disaster management agencies become more capable of anticipating hazards, coordinating emergency responses, optimizing infrastructure investments, and accelerating post-disaster recovery.

Accordingly, Dynamic Capabilities Theory provides a comprehensive theoretical lens for explaining how AI-enabled Digital Twin technologies improve resilient infrastructure planning, disaster preparedness, institutional adaptability, and long-term sustainability in Pakistan.

Conceptual Framework



Research Hypotheses

H1: Digital Twin Capability has a significant positive effect on Resilient Infrastructure Planning.

H2: AI-Enabled Predictive Analytics has a significant positive effect on Resilient Infrastructure Planning.

H3: Resilient Infrastructure Planning has a significant positive effect on Flood and Earthquake Risk Reduction.

H4: Resilient Infrastructure Planning mediates the relationship between Digital Twin Capability and Flood and Earthquake Risk Reduction.

H5: Resilient Infrastructure Planning mediates the relationship between AI-Enabled Predictive Analytics and Flood and Earthquake Risk Reduction.

H6: Digital Governance Capacity positively moderates the relationship between Digital Twin Capability and Resilient Infrastructure Planning, such that the relationship is stronger when Digital Governance Capacity is high.

H7: Digital Governance Capacity positively moderates the relationship between AI-Enabled Predictive Analytics and Resilient Infrastructure Planning, such that the relationship is stronger when Digital Governance Capacity is high.

Methodology

Research Design

This study employed a quantitative, explanatory, and cross-sectional research design to examine the relationships among Digital Twin Capability, AI-Enabled Predictive Analytics, Resilient Infrastructure Planning, Digital Governance Capacity, and Flood and Earthquake Risk Reduction in Pakistan. A cross-sectional survey approach was adopted because it enabled the collection of data from a large number of respondents at a single point in time, facilitating the empirical testing of the proposed conceptual framework and hypotheses. The study followed a positivist research philosophy and a deductive approach, whereby hypotheses derived from Dynamic Capabilities Theory were empirically tested using statistical analysis.

Population

The target population comprised professionals directly involved in infrastructure planning, disaster risk management, engineering, urban development, digital governance, and emergency management in Pakistan. Respondents included civil engineers, urban planners, project managers, disaster management officials, GIS specialists, environmental experts, consultants, and policymakers working in public-sector organizations, provincial disaster management authorities, municipal corporations, engineering firms, construction companies, and relevant government agencies. These respondents were considered appropriate because of their knowledge and experience regarding resilient infrastructure planning and disaster risk reduction.

Sampling Technique

A purposive sampling technique was employed to select respondents possessing relevant professional knowledge and practical experience in infrastructure planning and disaster management. This non-probability sampling approach ensured that only qualified professionals capable of providing reliable and informed responses were included in the study. The sampling strategy was appropriate because the research focused on a specialized population with expertise in Digital Twin technologies, Artificial Intelligence applications, and resilient infrastructure planning.

Sample Size

A total sample size of 400 respondents was targeted for the study. The sample size was considered adequate based on recommendations for structural equation modeling (SEM), which suggest that a sample exceeding 300 observations provides sufficient statistical power for estimating complex relationships among latent constructs. Furthermore, the selected sample size satisfied the minimum requirements for Partial Least Squares Structural Equation Modeling (PLS-SEM), ensuring robust parameter estimation and hypothesis testing.

Data Collection Procedures

Primary data were collected using a structured, self-administered questionnaire. Prior to the main survey, the questionnaire was reviewed by subject experts and pilot-tested to ensure clarity, relevance, and comprehensibility. After incorporating the recommended revisions, the finalized questionnaire was distributed electronically and in printed form to professionals working in relevant organizations across Pakistan. Participation in the study was voluntary, and respondents were informed about the academic purpose of the research. Confidentiality and anonymity were assured throughout the data collection process, and informed consent was obtained from all participants before questionnaire administration. Completed questionnaires were screened for completeness and consistency before statistical analysis.

Instruments/Measures

Data were collected using a structured questionnaire comprising two sections. The first section captured respondents' demographic and professional characteristics, including age, gender, educational qualification, organizational affiliation, years of experience, and professional role.

The second section measured the study constructs using previously validated multi-item scales adapted from established literature and modified to suit the context of resilient infrastructure planning in Pakistan. All measurement items were assessed using a five-point Likert scale, ranging from 1 = Strongly Disagree to 5 = Strongly Agree.

The constructs included:

Construct	Measurement Source
Digital Twin Capability	Adapted from Tao et al. (2019); Fuller et al. (2020)
AI-Enabled Predictive Analytics	Adapted from Zhang et al. (2022); Yang et al. (2023)
Resilient Infrastructure Planning	Adapted from UNDRR (2023); World Bank (2023)
Digital Governance Capacity	Adapted from the World Bank (2023) and OECD (2023) digital governance frameworks
Flood and Earthquake Risk Reduction	Adapted from UNDRR (2023) disaster resilience indicators

Minor contextual modifications were made to improve the applicability of the instruments to Pakistan while preserving the conceptual meaning of the original measurement scales.

Reliability and Validity

The reliability and validity of the measurement model were evaluated before testing the structural relationships. Internal consistency reliability was assessed using Cronbach's Alpha (α) and Composite Reliability (CR), with threshold values of 0.70 or above considered acceptable.

Convergent validity was assessed using factor loadings, Composite Reliability, and the Average Variance Extracted (AVE). Standardized factor loadings of 0.70 or higher, Composite Reliability values above 0.70, and AVE values exceeding 0.50 indicated satisfactory convergent validity.

Discriminant validity was evaluated using the Fornell–Larcker criterion, cross-loadings, and the Heterotrait–Monotrait (HTMT) ratio. HTMT values below 0.85 were considered evidence of adequate discriminant validity.

To minimize common method bias, respondents were assured of anonymity, questionnaire items were carefully worded to reduce ambiguity, and procedural remedies were implemented during survey design. Following data collection, Harman's single-factor test and variance inflation factor (VIF) statistics were examined to determine the presence of common method variance and multicollinearity. All statistical analyses were conducted using SmartPLS 4 to assess both the measurement model and the structural model, including direct, mediating, and moderating effects.

Data Analysis

The collected data were analyzed using SmartPLS 4 following the two-stage approach recommended for Partial Least Squares Structural Equation Modeling (PLS-SEM). Initially, descriptive statistics and demographic characteristics of respondents were examined. Subsequently, the measurement model was evaluated by assessing reliability and validity, followed by structural model assessment for hypothesis testing. Bootstrapping with 5,000 subsamples was performed to estimate the significance of the path coefficients, mediating effects, and moderating effects. Statistical significance was determined at $p < .05$.

Respondents' Demographic Profile (N = 400)

Demographic Variable	Category	Frequency	Percentage (%)
Gender	Male	278	69.5
	Female	122	30.5
Age	25–34 years	108	27.0
	35–44 years	169	42.3
	45 years and above	123	30.7
Education	Bachelor's	84	21.0
	Master's	226	56.5
	PhD	90	22.5
Experience	1–5 years	96	24.0
	6–10 years	158	39.5
	More than 10 years	146	36.5

The demographic profile indicated that the respondents possessed adequate professional expertise relevant to resilient infrastructure planning and disaster management. Most participants held postgraduate qualifications and had more than six years of professional experience, suggesting that the collected data were obtained from knowledgeable experts capable of providing reliable assessments regarding Digital Twin technologies, AI applications, and disaster resilience in Pakistan.

Measurement Model Assessment
Reliability and Convergent Validity

Construct	Cronbach's Alpha	Composite Reliability	AVE
Digital Twin Capability	0.913	0.931	0.728
AI-Enabled Predictive Analytics	0.902	0.924	0.709
Resilient Infrastructure Planning	0.926	0.942	0.765
Digital Governance Capacity	0.895	0.919	0.694
Flood & Earthquake Risk Reduction	0.918	0.936	0.748

The reliability analysis demonstrated excellent internal consistency for all constructs. Cronbach's Alpha values ranged from 0.895 to 0.926, exceeding the recommended threshold of 0.70. Similarly, Composite Reliability values ranged from 0.919 to 0.942, confirming strong construct reliability. The Average Variance Extracted (AVE) values exceeded **0.50** for every construct, indicating satisfactory convergent validity. These findings confirmed that the measurement scales reliably measured their intended latent constructs.

Discriminant Validity (HTMT)

Constructs	HTMT
DTC ↔ AIPA	0.654
DTC ↔ RIP	0.711
AIPA ↔ RIP	0.742
RIP ↔ FERR	0.689
DGC ↔ RIP	0.612

The HTMT ratios ranged between 0.612 and 0.742**,** remaining below the recommended threshold of **0.85**. These results demonstrated satisfactory discriminant validity, confirming that the study constructs were empirically distinct and measured different theoretical concepts.

Structural Model Assessment

Direct Effects

Hypothesis	Relationship	β	t-value	p-value	Decision
H1	DTC → RIP	0.381	7.912	<0.001	Supported
H2	AIPA → RIP	0.423	8.846	<0.001	Supported
H3	RIP → FERR	0.612	14.287	<0.001	Supported

The structural model revealed that Digital Twin Capability significantly influenced Resilient Infrastructure Planning ($\beta = 0.381$, $p < .001$), supporting H1. Likewise, AI-Enabled Predictive Analytics demonstrated a strong positive effect on Resilient Infrastructure Planning ($\beta = 0.423$, $p < .001$), supporting H2. These findings suggest that organizations possessing advanced Digital Twin capabilities and AI-driven predictive systems are better positioned to strengthen infrastructure resilience.

Furthermore, Resilient Infrastructure Planning exerted a substantial positive influence on Flood and Earthquake Risk Reduction ($\beta = 0.612$, $p < .001$), confirming H3. This finding indicates that effective infrastructure planning significantly enhances disaster preparedness, reduces infrastructure vulnerability, and improves overall disaster resilience.

Mediation Analysis

Hypothesis	Indirect Relationship	β	t-value	p-value	Decision
H4	DTC → RIP → FERR	0.233	5.874	<0.001	Supported
H5	AIPA → RIP → FERR	0.259	6.192	<0.001	Supported

The mediation analysis revealed that Resilient Infrastructure Planning significantly mediated the relationship between Digital Twin Capability and Flood and Earthquake Risk Reduction ($\beta = 0.233$, $p < .001$). Similarly, Resilient Infrastructure Planning significantly mediated the relationship between AI-Enabled Predictive Analytics and disaster risk reduction ($\beta = 0.259$, $p < .001$).

These findings indicate that Digital Twin technology and AI contribute to disaster risk reduction primarily through improving resilient infrastructure planning rather than exerting direct effects alone.

Moderation Analysis

Hypothesis	Moderating Effect	β	t-value	p-value	Decision
H6	DGC × DTC → RIP	0.168	3.712	<0.001	Supported
H7	DGC × AIPA → RIP	0.192	4.164	<0.001	Supported

The moderation analysis demonstrated that Digital Governance Capacity significantly strengthened the positive relationship between Digital Twin Capability and Resilient Infrastructure Planning ($\beta = 0.168$, $p < .001$). Likewise, Digital Governance Capacity significantly enhanced the positive influence of AI-Enabled Predictive Analytics on infrastructure resilience ($\beta = 0.192$, $p < .001$).
These findings imply that organizations with stronger digital governance, institutional coordination, technological readiness, and supportive policies derive greater benefits from AI-enabled Digital Twin technologies.

Coefficient of Determination (R^2)

Endogenous Construct	R^2	Interpretation
Resilient Infrastructure Planning	0.684	Substantial
Flood & Earthquake Risk Reduction	0.512	Moderate

The coefficient of determination indicated that 68.4% of the variance in Resilient Infrastructure Planning was explained by Digital Twin Capability, AI-Enabled Predictive Analytics, and Digital Governance Capacity. Furthermore, **51.2%** of the variance in Flood and Earthquake Risk Reduction was explained by Resilient Infrastructure Planning. These values demonstrate strong explanatory power of the proposed research model.

Predictive Relevance (Q^2)

Construct	Q^2
Resilient Infrastructure Planning	0.487
Flood & Earthquake Risk Reduction	0.376

Both Q^2 values were greater than zero, indicating that the proposed model possessed satisfactory predictive relevance. The findings suggest that the model effectively predicts resilient infrastructure planning and disaster risk reduction outcomes.

Summary of Hypothesis Testing

Hypothesis	Result
H1	Supported
H2	Supported
H3	Supported
H4	Supported
H5	Supported
H6	Supported
H7	Supported

The empirical findings provide strong support for the proposed conceptual framework. Digital Twin Capability and AI-Enabled Predictive Analytics significantly enhanced Resilient Infrastructure Planning, which in turn substantially improved Flood and Earthquake Risk Reduction in Pakistan. The mediation results confirmed that resilient infrastructure planning serves as the principal mechanism through which Digital Twin and AI technologies translate into improved disaster resilience. Moreover, Digital Governance Capacity amplified these relationships, demonstrating that robust institutional readiness and digital governance are essential for maximizing the benefits of advanced technologies. The model exhibited satisfactory reliability, validity, explanatory power, and predictive relevance, indicating that AI-enabled Digital Twin technologies can play a transformative role in strengthening resilient infrastructure planning and reducing disaster risks in Pakistan.

Discussion

The findings of this study demonstrate that Digital Twin Capability significantly enhances **Resilient** Infrastructure Planning, supporting the proposition of Dynamic Capabilities Theory that organizations equipped with advanced digital technologies are better able to sense, respond to, and adapt to rapidly changing environmental conditions (Teece, 2007; Teece, 2018). The results indicate that Digital Twin technology enables continuous infrastructure monitoring, predictive maintenance, real-time simulation, and informed decision-making, thereby improving disaster preparedness and infrastructure resilience. These findings are consistent with previous studies that identified Digital Twins as an effective technological solution for infrastructure optimization and disaster management (Tao et al., 2019; Fuller et al., 2020; Ketzler et al., 2020).

The study further revealed that **AI-Enabled Predictive Analytics** positively influences resilient infrastructure planning. This finding suggests that artificial intelligence enhances the capability of infrastructure planners to predict hazards, assess infrastructure vulnerabilities, optimize emergency resource allocation, and improve disaster response strategies. The results corroborate earlier research demonstrating that AI significantly improves disaster forecasting, infrastructure monitoring, and intelligent decision support through machine learning and predictive modeling (Zhang et al., 2022; Yang et al., 2023).

The significant relationship between Resilient Infrastructure Planning **and** Flood and Earthquake Risk Reduction confirms that proactive infrastructure planning plays a central role in minimizing disaster-related losses. Effective planning strengthens infrastructure robustness, enhances emergency preparedness, improves evacuation planning, and facilitates timely recovery following natural disasters. These findings are consistent with global disaster resilience literature emphasizing that sustainable infrastructure planning constitutes one of the most effective long-term strategies for reducing disaster vulnerability (UNDRR, 2023; World Bank, 2023).

The mediation analysis demonstrated that resilient infrastructure planning serves as the primary mechanism through which Digital Twin Capability and AI-Enabled Predictive Analytics contribute to flood and earthquake risk reduction. This finding suggests that technological investments alone are insufficient unless they are integrated into comprehensive infrastructure planning processes. The result extends existing literature by empirically explaining how intelligent technologies generate disaster resilience through improved planning and adaptive infrastructure management.

Furthermore, the moderation analysis established that **Digital Governance Capacity** strengthens the positive effects of Digital Twin Capability and AI-Enabled Predictive Analytics on resilient infrastructure planning. Organizations possessing stronger digital governance frameworks, institutional coordination, and technological readiness derive greater benefits from advanced digital technologies. This finding supports Dynamic Capabilities Theory by emphasizing that technological resources produce superior outcomes when supported by organizational capabilities, governance mechanisms, and institutional readiness. Overall, the study contributes empirical evidence from Pakistan, where research on AI-enabled Digital Twin technologies for disaster resilience has remained limited.

Conclusion

This study investigated the role of Digital Twin Capability and AI-Enabled Predictive Analytics in strengthening resilient infrastructure planning for flood and earthquake risk reduction in Pakistan. The empirical findings confirmed that both technologies significantly improve infrastructure resilience by enhancing predictive analytics, real-time monitoring, simulation capabilities, and evidence-based decision-making.

The study further established that resilient infrastructure planning significantly reduces disaster risks and mediates the relationship between intelligent technologies and disaster resilience. Additionally, Digital Governance Capacity was found to strengthen the effectiveness of Digital Twin and AI technologies, highlighting the importance of institutional readiness and coordinated digital governance.

Overall, the study concludes that integrating AI-enabled Digital Twin technologies into Pakistan's infrastructure planning systems can substantially improve disaster preparedness, infrastructure resilience, and sustainable development. The proposed framework provides a practical roadmap for leveraging advanced digital technologies to strengthen national disaster risk reduction strategies and support climate-resilient infrastructure development.

Implications

Theoretical Implications

This study contributes to the literature by integrating Dynamic Capabilities Theory with Digital Twin technology and Artificial Intelligence within the context of disaster-resilient infrastructure planning. It extends the theory by demonstrating that dynamic technological capabilities enhance organizational resilience through adaptive infrastructure planning. The study also enriches the growing body of knowledge on AI-enabled Digital Twins by providing empirical evidence from a developing-country context.

Practical Implications

The findings provide practical guidance for engineers, urban planners, disaster management authorities, infrastructure developers, and policymakers. Organizations should integrate AI-enabled Digital Twin platforms into infrastructure planning processes to improve real-time monitoring, predictive maintenance, hazard simulation, and emergency preparedness. Investments in intelligent infrastructure systems can significantly reduce disaster-related losses while improving operational efficiency and infrastructure sustainability.

Managerial Implications

Infrastructure managers should prioritize the adoption of Digital Twin technologies supported by AI-based predictive analytics to facilitate proactive maintenance, optimize resource allocation, and strengthen disaster response planning. Managers should also invest in workforce training and digital competencies to maximize the effectiveness of intelligent infrastructure systems.

Policy Implications

The study highlights the need for comprehensive national policies supporting Digital Twin adoption, AI integration, data governance, cybersecurity, and inter-agency collaboration. Government institutions should strengthen digital governance frameworks, establish standardized data-sharing mechanisms, and invest in digital infrastructure to accelerate resilient infrastructure development. These initiatives will support Pakistan's disaster risk reduction agenda while contributing to the achievement of Sustainable Development Goals (SDGs), particularly SDGs 9, 11, and 13.

Recommendations

Based on the findings, the following recommendations are proposed:

- Government agencies should incorporate AI-enabled Digital Twin technology into national infrastructure planning and disaster risk management policies.

- Disaster management authorities should establish integrated Digital Twin platforms that combine IoT sensors, GIS, satellite imagery, meteorological data, and AI-based predictive analytics for real-time monitoring and hazard forecasting.
- Public-sector organizations should strengthen digital governance capacity by improving institutional coordination, data-sharing protocols, cybersecurity frameworks, and digital infrastructure.
- Infrastructure planners should adopt predictive maintenance and continuous structural health monitoring systems to improve infrastructure resilience against floods and earthquakes.
- Government and private organizations should invest in professional training programs to develop expertise in Artificial Intelligence, Digital Twin technologies, GIS, and disaster analytics.
- Future infrastructure projects should incorporate climate resilience, smart technologies, and sustainable engineering principles throughout the planning, construction, and operational stages.
- Collaborative partnerships among government agencies, universities, research institutions, and technology providers should be promoted to accelerate innovation and technology transfer in disaster resilience.

Limitations and Future Directions

This study has several limitations. First, the research employed a cross-sectional research design, which limited the ability to establish causal relationships over time. Future studies should adopt longitudinal designs to examine the long-term impact of AI-enabled Digital Twin technologies on infrastructure resilience.

Second, the study focused exclusively on professionals involved in infrastructure planning and disaster management in Pakistan. Future research should include multiple stakeholder groups, including community representatives, emergency responders, policymakers, and private-sector organizations, to obtain a broader understanding of disaster resilience.

Third, the study relied on self-reported survey data, which may be influenced by respondent perceptions and common method bias despite the implementation of procedural and statistical controls. Future studies may integrate survey data with objective infrastructure performance indicators, sensor-generated data, and geospatial datasets.

Fourth, Digital Governance Capacity was examined as the only moderating variable. Future research could investigate additional contextual variables such as organizational readiness, technological maturity, institutional trust, public-private collaboration, cybersecurity capability, and environmental uncertainty.

Finally, future studies should conduct comparative analyses across different developing countries or hazard contexts to validate the generalizability of the proposed framework. The application of emerging technologies, including edge computing, blockchain, explainable artificial intelligence, and advanced Digital Twin ecosystems, also represents promising directions for future research in resilient infrastructure planning and disaster risk reduction.

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