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Leveraging external debt: Stimulate innovation by infrastructure development in Belt and Road countries

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ABSTRACT

Debt caused by the growing infrastructure projects in the Belt and Road Initiative (BRI) countries is a highly debated issue. Grounded in a latecomers' innovation catching-up perspective, this study examines the effect of infrastructure development on innovation outputs within BRI countries. Based on country-level data from 2010 to 2021, we find that infrastructure development significantly enhances innovation performance in BRI countries. Notably, the effect is attributed to countries' external debt. Countries with higher debt management capability, national solvency and debt utilization efficiency, can amplify the beneficial influence of infrastructure development on innovation performance. Furthermore, external debt not only serves as an input of physical capital but also acts as a catalyst for innovation by promoting technology absorption and industrial development. While China's sovereign lending to these countries effectively promotes innovation, debt pressure remains manageable. This paper contrasts with the held notion that infrastructure development constitutes the debt crisis. Our results shed new light on the efficacy of external debt, the external debt results in an expansion of innovation catching-up patterns of BRI countries rather than debt crisis.

1. Introduction

Concerns regarding unsustainable debt levels in developing countries are escalating. As these nations contend with various destabilizing forces, the most economically vulnerable among them face escalating risk of descending into a debt crisis. According to the International Debt Report 2024, in 2023, developing countries incurred a record expenditure of US$ 1.4 trillion to service their debts. The poorest and most vulnerable countries' interest payments on external debt have quadrupled since 2013, hitting an all-time

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high of US$34.6 billion in 2023.[1] Some countries are merely one adverse shock away from the debt crisis.

Since 2013, with the announcement of the BRI, China has invested globally in a portfolio of infrastructure projects such as transport (Lindlacher and Pirich, 2025). This field has gained traction in recent years due to the emergence of China as a global creditor with the announcement of the BRI, numerous questions and misinterpretations about BRI followed (Khanal and Zhang, 2024). Given that developing nations frequently incur substantial debt to fund infrastructure projects, the concern over debt induced by such investments has garnered widespread attention among policymakers. Particularly, concerns about BRI in some developed nations mainly centre around the potential debt-related implications of large projects (Cheng, 2016). Due to insufficient external debt management and repayment capabilities, some countries' economic development cannot keep up with the growth of the external debt scale. The risk associated with such debt becomes apparent when developing countries rely on external borrowing to advance infrastructure development. Certain politicians and media attribute the debt crisis to China's alleged excessive lending (Broz et al., 2020). They frequently magnify the burdens imposed by external debt while ignoring the realities of the BRI countries' use of external debt to achieve development. They accuse China of exacerbating debt pressures among BRI countries and advancing debt diplomacy by investing heavily in infrastructure and providing high-cost loans. For instance, the Sri Lankan Hambantota port project is frequently cited as an example of the alleged debt trap and China's so-called neo-colonialism. Additionally, some academics have expressed skepticism about the genuine benefits of BRI infrastructure projects to local economies and have highlighted instances where such projects have adversely impacted sustainability in BRI countries (Qian et al., 2023).

Infrastructure development serves as a significant strategy for balancing short- and long-term economic growth in any country. It fosters innovation by providing efficient information exchange platforms and streamlined logistics networks, reducing innovation costs and accelerating knowledge dissemination and technology diffusion. High-quality infrastructure also attracts skilled talent and investment, offers essential material and technical support for innovative activities. Consequently, it enhances regional and national innovation capabilities, contributing to sustained economic growth and technological advancement. As posited by the theory of endogenous growth, innovation is a crucial determinant of sustained economic growth (Sampson, 2023). Empirical evidence also demonstrates that the ascension of emerging economies is inextricably linked to advancements in scientific and technological innovation (Akcigit, 2017; Acemoglu et al., 2018). Some BRI countries, such as Kazakhstan, Malaysia, and the United Arab Emirates, have successfully used external debt for infrastructure development, yielding positive results.[2] The projects promoted upgrades of traffic control systems, modern railway technology, and equipment innovation in these BRI countries.

Implementing an innovation catching-up development strategy has become imperative for developing countries seeking to achieve sustainable growth and mitigate debt risks through the systematic enhancement of their scientific, technological, and innovative capabilities. It refers to the process by which BRI countries bridge the gap in innovation capabilities relative to the technological frontier or leading innovators. Rosenstein-Rodan's "The Theory of the Big-push" posits that infrastructure development, particularly in transport, is a prerequisite for economic growth (Rosenstein-Rodan, 1943). Similarly, Rostow's "Theory of Stages of Economic Growth" underscores the critical role of infrastructure in economic growth and advocates its prioritization, especially in developing countries (Rostow, 1960). Most developing countries, characterized by vast territories, large populations, and uneven resource distribution, necessitate extensive infrastructure construction (Egger et al., 2023). Since the reform and opening-up, China's infrastructure has undergone leapfrog development, providing crucial strategic support for rapid economic growth and significant advances in scientific innovation. The era of rapid economic growth in developed countries like the United States and Western Europe coincided with extensive transport infrastructure development (Banerjee et al., 2020). Historical evidence and established theoretical studies unequivocally demonstrate that infrastructure development yields substantial innovation and economic benefits to nations and regions. Given this context, is debt financing for infrastructure in BRI countries a developmental trap or a hopeful opportunity? Does infrastructure development in BRI countries foster unsustainable debt risks or pave the way for sustainable and innovative growth? What are the underlying mechanisms?

In this paper, we aim to challenge prevailing notions of the debt trap and "China's neo-colonialism" by demonstrating that infrastructure construction in BRI economies promotes country-level innovation performance. Our findings indicate that infrastructure construction could promote innovation performance significantly in BRI countries. Notably, national external debt plays a crucial positive role in promoting innovation through infrastructure development. The effectiveness of this impact is influenced by various aspects of a country's external debt structure, including debt management capacity, national solvency, debt utilization efficiency, and default risk. This study offers robust theoretical and empirical evidence for BRI countries to accelerate infrastructure construction while firmly supporting economic globalization. We affirm that establishing a development-first infrastructure cooperation mechanism in the Global South and deepening the global development initiative are the most effective strategies for developing countries to

[1] For the poorest countries, debt has become a nearly paralyzing burden. Specifically, the pandemic and its aftermath have hit these countries hardest. In a time of pinched government budgets, resources were diverted away from other critical areas, including social services and infrastructure development, negatively affected economic growth and exacerbated debt vulnerabilities in many of them. As of the end of September 2024, among 68 IDA-eligible countries, 16% were in external debt distress and 35% were at high risk of distress. Available online: https://www.worldbank.org/en/programs/debt-statistics/idr/products (accessed on 6 March 2025).

[2] For instance, these countries have utilized external debt to finance the development of major infrastructure projects such as Kazakhstan's Atırau–Aktau Railway, the United Arab Emirates' Dostyk-Moyinkum Railway, and Malaysia's East Coast Rail Link. However, they have not experienced a debt crisis. These nations effectively manage debt risks and ensure project completion through strategic debt management and comprehensive economic planning. The innovative and economic benefits generated by these projects are expected to further alleviate the financial pressure associated with their debt obligations.

transform crises into development opportunities.

The organization of this paper is as follows: Section 2 is the literature review. Section 3 introduces the model, data and variables in the empirical study. Section 4 presents empirical analysis. Section 5 concludes.

2. Literature review and research contribution

2.1. Literature review and research hypotheses

2.1.1. Economic development effect of infrastructure

Infrastructure development is fundamental to fostering national economic development and growth. Aschauer's seminal studies on the economic effects of infrastructure investment have demonstrated that significant investments, such as in roads and airports, possess profound explanatory power for economic growth. Generally, infrastructure development played a significant role in propelling US economic development during the 1950s and 1960s (Aschauer, 1989). Subsequent scholarly studies progressively refined understanding of how infrastructure construction enhances economic development by boosting productivity, optimizing resource allocation, expanding employment opportunities, and hastening urbanization (Easterly and Rebelo, 1993; Donaldson, 2018; Sun et al., 2022). Research has substantiated the significant role of infrastructure development in advancing developing countries (Ghani et al., 2016; Baum-Snow et al., 2020).

The level of infrastructure in a country is crucial in facilitating international trade and attracting foreign investments (Baum-Snow, 2010; Egger et al., 2023). Infrastructure development directly enhances transaction efficiency by reducing trade-related costs, including transportation and customs clearance costs (Shirley and Winston, 2004). It allows countries previously hindered by inadequate transport and communication systems to engage in international markets (Portugal-Perez and Wilson, 2012). In terms of attracting foreign investment, infrastructure development influences the location and scale of foreign direct investment (FDI), enhancing the return on FDI, thereby attracting more multinational enterprises to invest on a larger scale. Efficient allocation of infrastructure development resources enables countries to eliminate barriers to investment (Banerjee et al., 2020).

2.1.2. Innovation promotion effect of infrastructure

Relevant literature explores the nexus between infrastructure development and innovation. Scholars have consistently recognized that multiple factors drive innovation (Verhoeven et al., 2016; Acemoglu et al., 2022). The interplay between a country's infrastructure and internal innovation environment significantly enhances its innovation capabilities (Furman et al., 2002; Hall and Lerner, 2009). Infrastructure can boost a country's total factor productivity, realize its informational and modern transformations (Banerjee et al., 2020). Modern industrial sectors benefit from the growth effects of resource reallocation, fostering the development of production technologies and innovation performance (Han et al., 2021; Zhou et al., 2022). Infrastructure development will alter the spatial distribution of intellectuals and improve the efficiency of innovation. High-technology industries and R&D personnel are likely to concentrate in regions with enhanced infrastructure levels to access more opportunities.

Scholars investigate how various types of infrastructure development impact innovation performance. These studies primarily focus on financial, ICT, and transport infrastructures, mainly reporting positive effects (Fernald, 1999; Röller et al., 2001; Egger et al., 2023). There are differences in the extent to which innovation performance is enhanced by different types of infrastructure development (Shahbaz et al., 2021). Given that most BRI countries are developing nations with low economic development and weak industrial capacity, transportation and ICT infrastructure are crucial for their innovation catching-up and economic development. By promoting knowledge exchange, and technology transfer, BRI catalyzes technological innovation and enables sustainable development (Zhu et al., 2024). As "hard" infrastructure types, transport and ICT systems improve organizational efficiency and logistics and transport levels, supporting innovation in countries (Tang et al., 2022). Enhanced transport infrastructure can substantially increase the efficiency of logistics and the movement of personnel, facilitate the exchange of knowledge, technology, and expertise. This enables enterprises to allocate greater resources toward innovation activities, ultimately leading to improved innovation performance. Also, ICT infrastructure serves as the foundational support for informatization, and empowers the promotion of digital and intelligent technological advancements (Sun et al., 2022; Zhang et al., 2024a).

The innovation-enhancing effects of "hard" infrastructures like transport and ICT are more pronounced compared to "soft" infrastructures like finance, which require a certain level of national economic development to be effective. Therefore, while the development of finance infrastructure in BRI countries holds promise for enhancing innovation performance, several structural and systemic challenges hinder its full potential. The underdevelopment of financial systems, limited access to credit, inadequate technological support, and regulatory inefficiencies have all contributed to the limited impact of finance infrastructure improvements on innovation. Based on the above literature review on infrastructure and innovation, we propose the first hypothesis:

H1: Infrastructure development can stimulate innovation in BRI countries, there are variations in how different types of infrastructure development contribute to enhancing innovation performance.

2.1.3. Economic effect of external debt in BRI countries

In modern development economics, external debt can accelerate a country's economic development and recovery. Countries should actively use external resources to overcome savings and foreign exchange constraints (Reinhart and Trebesch, 2016), especially developing countries. According to H.B. Chenery and A.M. Strout's Two-gap Model(Chenery and Strout, 1966) and the Three-gap Model extended by other scholars, developing countries in the process of economic development often fall into savings, foreign exchange and technology shortfalls. For developing countries, they should resort to external resources, such as external debt, to stimulate technological progress and economic growth.

The uneven and lagging infrastructure development in many BRI countries is a significant factor contributing to the slow pace of economic growth. Since the inception of the BRI, it has played a crucial role in fostering prosperity and development in the countries and regions along its corridors (Yasmeen et al., 2022). Several BRI countries have utilized external debt to finance infrastructure development, aiming to foster technological innovation and strengthen international trade cooperation. These nations have successfully constructed key infrastructure projects, such as ports, highways, railways, and airports, including notable initiatives like the China-Europe Railway Express, the China-Pakistan Economic Corridor, and the China-Laos Railway (Huang et al., 2025). These efforts have facilitated advancements in transportation, ICT, and other sectors, promoting technological innovation and the aggregation of innovative resources (Zou et al., 2022; Zhang et al., 2024a).

However, it is worth noting that external debt is a double-edged sword. Due to the prolonged timeline of infrastructure construction, BRI countries may mobilize substantial funds to strengthen infrastructure development, which may lead to an increase in external debt in the short term. Based on the debt threshold theory proposed by Reinhart and Rogoff (2010), once the debt burden exceeds the critical point, the accumulation of debt is highly likely to shift from promoting development to inhibiting development, and even lead to a national economic crisis. Indeed, some BRI countries have resorted to borrowing for infrastructure development, resulting in an increased external debt burden. For instance, Sri Lanka, having borrowed funds to construct the Hambantota Port, faced the challenge of being unable to repay its debt as scheduled. However, a closer examination of this case reveals a different picture. In 2017, Chinese loans accounted for approximately 10 % of Sri Lanka's external debt, with 62 % of these loans being preferential loans offered at interest rates lower than those available in the international market (Fang et al., 2022). This indicates that Chinese loans have not been the primary source of Sri Lanka's external debt burden (Posta and Liu, 2024). Similarly, the external debt challenges faced by the Philippines and Pakistan cannot be solely attributed to Chinese loans, despite the longstanding criticism they have attracted.

The primary factor contributing to the expansion of a country's debt risk is not the mere increase in the size of its external debt, but rather the inability of its economic development to keep pace with this growing debt. Appropriate government debt accelerates capital accumulation, and if the BRI countries' capital accumulation matches the scale of government debt expansion and maintains a certain level of sustainable repayment capacity, the debt risks are controllable (Zhang et al., 2024b). While the repayment pressure is affordable, external debt can help countries achieve their development goals and bring economic benefits. As BRI countries progress in infrastructure development, the accumulation of external debt can stimulate innovation by improving financial accessibility for innovative actors and increasing inputs and outcomes related to innovation. It implies that investments based on external debt can generate financial returns sufficient to cover interest and principal repayment obligations. BRI emphasizes the Facilities Connectivity, fostering capital accumulation and innovative development by providing financial and technical support for infrastructure projects (Zou et al., 2022). This has significant implications for these countries, particularly in enhancing their solvency and mitigating debt risks. Consequently, the external debt is instrumental in helping the BRI countries improve their infrastructure development, foster capital accumulation and innovation catching-up, and ultimately stimulate economic growth. Therefore, we propose the second hypothesis:

H2: Infrastructure development enhances innovation performance in BRI countries, and external debt plays a crucial positive role.

2.1.4. Factors influencing the effect of external debt in BRI countries

Whether BRI countries can achieve the transition process of "indebtedness-development-debt servicing" is the key to avoiding the debt crisis. Countries must be cognizant of the dual effects of external borrowing: the accumulation of debt and its potential for fostering growth (Zhang et al., 2024b). To mitigate default risk, it is essential for countries to strategically restructure their external debt in alignment with their innovation development needs. If a country depends on external debt for infrastructure development but lacks sufficient debt management capacity, efficient debt utilization, and national solvency to support the debt level, it faces a high default risk, which can hinder innovation and slow economic development (Posta and Liu, 2024). This, in turn, weakens the country's resilience to external shocks and may lead to a debt crisis. Therefore, in the "indebtedness-development-debt servicing" process, BRI countries must carefully consider debt management, utilization, solvency, and the associated default risk, as these factors significantly impact their innovation capacity and economic progress.

In terms of debt management capacity, it refers to a country's ability to effectively plan, organize, and implement policies to manage its external debt. When developing infrastructure, the debt management capacity of BRI countries should be structured to minimize fiscal risks and ensure long-term debt sustainability. It is essential to ensure that borrowing does not lead to unsustainable debt levels or a debt crisis, as proper debt management plays a crucial role in fostering long-term innovation development (Wang et al., 2023). The proportion of short-term external debt (with maturity of less than one year) serves as a key indicator of a country's external debt management capacity. A lower proportion of short-term external debt suggests stronger debt management capabilities and a more resilient debt repayment strategy. Effective external debt management necessitates a well-structured debt composition, wherein the country aims to minimize short-term debt while ensuring sufficient repayment capacity, thereby striking a balance between debt servicing pressure and long-term financial sustainability.

In terms of debt utilization efficiency, it refers to how effectively a country deploys external debt to achieve its objectives, particularly with respect to fostering economic growth and enhancing international competitiveness. In the context of infrastructure development, this efficiency is reflected in the allocation of external debt toward productive investments that generate returns and stimulate economic expansion, rather than being squandered or misallocated. For example, when a country's export and GNI growth rates surpass the growth rate of external debt, it indicates high debt utilization efficiency. This occurs when BRI countries effectively utilize external debt to fund projects that stimulate production, expand exports, and increase GNI, thereby fostering long-term economic growth and technological progress. Conversely, low debt utilization efficiency would lead to increasing repayment pressures that outpace national solvency, heightening the default risk. In scenarios where regular debt servicing becomes unmanageable, whether the resolution takes the form of default, restructuring, or debt relief, the impact on the country's economic stability and innovation capacity can be severe (Reinhart and Trebesch, 2016).

In terms of national solvency, it refers to a country's ability to meet its long-term financial obligations, specifically its debt commitments, without resorting to excessive borrowing or defaulting. A country is considered solvent if it has the resources and capacity to repay its debt sustainably without jeopardizing its fiscal health or overall economic growth. When developing infrastructure, BRI countries achieve innovation development utilizing external debt which can generate sufficient revenue to cover its liabilities, the external debt repayment capacity will be enhanced despite the debt burden increase. National solvency is the key to avoiding falling into the debt trap, international reserves and exports are important supports for BRI countries' external debt solvency. Robust export performance indicates a stable source of international reserves for the country, which serve as a critical fund source for servicing external debt in international markets. International reserves and export revenues ensure that the BRI countries retain solid capacities to meet their debt obligations, even amid fluctuations in the global economic environment.

In terms of default risk, it specifically refers to the likelihood that a country will fail to meet its external debt obligations on time, or may not be able to repay them at all. During periods of global economic downturns, debtor countries often face significant challenges in maintaining debt sustainability, particularly when external debt is used to finance infrastructure projects, thereby exacerbating the risk of a debt crisis. For BRI countries, external debt serves as a crucial source of financing for domestic infrastructure development and innovation promotion. Provided that debt risks remain manageable and economic development is sustainable, creditors are generally willing to extend loans to BRI countries without undue concern about default risk. When the ratio of external debt and debt service payments to GNI becomes excessively high, the ensuing liquidity crisis can easily degenerate into a solvency crisis, the country's default risk increases (De Grauwe and Ji, 2013). In such cases, the government may prioritize debt repayment, leading to funding shortfalls for critical areas such as research, education, and infrastructure, which can, in turn, impede long-term technological advancement. Based on the above literature review, we propose the third hypothesis:

H3: In promoting innovation through infrastructure development, the debt management capacity, debt utilization efficiency, national solvency, and default risk are critical influencing factors in effectively leveraging external debt of BRI countries.

2.2. Research gap and our contribution

Throughout the previous literature, there are several research gaps to narrow. First, in terms of infrastructure, existing quantitative studies often focus on the economic impacts of single infrastructure types (Ahlfeldt and Feddersen, 2017; Hornbeck and Rotemberg, 2019; Kpognon, 2022; Egger et al., 2023), and infrastructure investment (Shirley and Winston, 2004; Zou et al., 2022; Bo et al., 2024). The lack of analyses encompassing various infrastructures and their heterogeneity presents a significant limitation. The absence of a comprehensive quantitative assessment of infrastructure may introduce bias into the conclusions drawn from the study. Second, the samples in existing studies typically include only 64 BRI countries along the route (Herroro and Xu, 2017; Du and Zhang, 2018), which limits the universality of the research conclusions. However, as of 2023, >150 countries have already signed the cooperation documents for BRI construction. Current literature temporarily fails to comprehensively and systematically analyze the development status of the BRI countries and even classifies them simplistically as BRI and non-BRI countries. More research is required in the context of all BRI economies. Third, despite many examples of research on BRI, such as evaluating the impact on the economy, trade and investment (Wang et al., 2021; Xie et al., 2023). However, studies evaluating innovation catching-up capacity from the perspective of infrastructure development across all BRI countries remain relatively scarce. Last, despite the proliferation of debt conspiracy theories surrounding the BRI (Cheng, 2016; Broz et al., 2020), quantitative research on this topic remains relatively limited. This scarcity poses significant challenges in accurately assessing the impact of the BRI, particularly in addressing concerns related to the debt trap. This hinders a comprehensive understanding of the logical linkages between a country's infrastructure development, external debt decisions, and innovation performance.

Therefore, this paper contributes to the literature by comprehensively quantifying the innovation-promoting effects of infrastructure and exploring transmission mechanisms through external debt in BRI. The contributions of this study are evidenced in several key aspects. First, following the empirical approach of Donaubauer et al. (2016), we estimated infrastructure development levels in 144 BRI countries using the UCM model. This approach addresses the limitations of previous research, which is prone to being influenced by single-type infrastructure and infrastructure investment. Additionally, this methodology provides a more detailed macro-level enhancement to previous quantitative research on the impact of infrastructure on innovation performance. Our newly developed infrastructure index systematically evaluates the relationship between infrastructure and economic development in BRI countries. It contributes to deepening the understanding of infrastructure development in BRI countries. Second, by including 144 BRI countries as research subjects, this study effectively addresses the existing shortfall in attention toward other BRI countries in related studies. The data significantly enhanced the precision and robustness of BRI countries' identification, offering more comprehensive insights. This approach overcomes the limitations of prior research that lacked universality and comparability. Third, from the perspective of latecomers' innovation catching-up capacity, this paper conducts a comprehensive analysis of how and to what extent infrastructure development impacts a country's innovation performance. We accurately evaluate the innovation catching-up capacity of the BRI driven by infrastructure. Finally, we examine the study within the framework of external debt, and systematically study the role of external debt in promoting innovation through infrastructure. This approach allows for a more in-depth understanding of how external debt acts as a positive bridge between infrastructure and innovation. It provides a robust data basis and scientifically verified academic support for the refutation of the debt trap viewpoints of the BRI. Our findings contribute positively to current research on the relationship between countries and governments regarding debt governance issues.

3. Methodology

3.1. Empirical framework

To examine the impact of infrastructure construction on innovation performance in BRI countries, we develop the following baseline model:

$$inno_{it} = \beta_0 + \beta_1 \cdot infra_{it} + \beta_2 X + \mu_i + \theta_t + \varepsilon_{it} \tag{3.1}$$

In our model, i represents country, and t represents year. The dependent variable *inno* corresponds to the innovation performance. The independent variable *infra* corresponds to the infrastructure index. X includes control variables. The terms μ and θ signify the fixed effects for country and year, respectively. Lastly, ε represents the residual error term.

3.2. Data and variables

Based on the previous research, this paper is based on a broad annual dataset of 144 countries, covering the 2010–2021 period and arrives at a total of 1728 observations.[3]

3.2.1. Independent variable

The Unobserved Components Model(UCM) was introduced in the literature by Goldberger (1972). It is a special case of a wider class of latent variable models which is closely related to the empirical Bayes estimator discussed in Efron & Morris (1972). UCM is employed to cover the largest possible number of developing and developed countries. To combine data from different sources into infrastructure indices, we follow the research and employ UCM (Kaufmann et al., 2011; Donaubauer et al., 2016; Kaufmann and Kraay, 2024). In UCM, observed data in each area are a linear function of unobserved infrastructure and an error term, rescaling the respective aggregate index from year to year.

Unlike traditional index construction methods that often rely on simple averages or principal component analysis, UCM explicitly recognizes that observed indicators are imperfect measurements of the underlying phenomenon. This approach is theoretically grounded in state-space modeling traditions, where the true state (infrastructure quality) is not directly observable but can be inferred from multiple related indicators with varying degrees of measurement error (Chalmovianský and Němec, 2022; Júlio and Maria, 2024).

UCM is the alternative method of the Autoregressive Integrated Moving Average model (ARIMA). The unobserved indicators of infrastructure are regarded as random indicators in UCM. In cases where the indicators are imprecise and incomplete, time-series forecasts are made based on the observed indicators to circumvent the problem of missing data. In principle, the indicators constructed by UCM provide a more accurate and comprehensive response to the level of infrastructure development, improving the reference value and applicability of this paper. For BRI countries where data availability and quality can be inconsistent across time and space, UCM's ability to handle missing data and integrate heterogeneous indicators is particularly valuable. The theoretical advantages of UCM over ARIMA lie in its structural approach to handling latent variables. While ARIMA focus primarily on the temporal dynamics of observed series, UCM explicitly models the relationship between observed indicators and the unobserved infrastructure quality. This structural approach provides a more theoretically sound basis for index construction, particularly when the goal is to measure an underlying concept rather than merely predict future values of a time series(Telg et al., 2023; Farmer et al., 2024).

UCM represents a significant advancement in index construction methodology, particularly for capturing complex multidimensional concepts like infrastructure development. The theoretical foundation of UCM lies in its recognition that infrastructure is a latent construct that cannot be directly measured but must be inferred from observable outcomes. This aligns with infrastructure theory which conceptualizes infrastructure as a multidimensional system of interconnected physical and organizational structures that facilitate societal and economic functions. UCM is particularly suited for capturing this complexity because it allows for the integration of heterogeneous indicators while accounting for their varying reliability and relevance.

Our overall index is based on three sub-categories of infrastructure: transport, ICT and finance infrastructure. In addition to an overall index, we build subindices for specific components. With this approach, we can provide a consistent picture of the availability and quality of infrastructure in a large panel dataset of developing and developed countries. This comprehensive approach is particularly important for BRI countries, which represent a diverse range of economies at different development stages. By constructing a multidimensional infrastructure index, we can capture the nuanced infrastructure landscapes across these varied economies

[3] The selection of 2010-2021 as our sample period is grounded in method considerations. First, this period provides optimal balance between temporal coverage and data quality for UCM methodology, which requires sufficient time series observations to decompose observed indicators into signal and noise components. Second, post-2010 data exhibits substantially reduced missing values across our infrastructure indicators for the 144 countries, minimizing potential selection bias in our OLS estimation. Third, the period encompasses sufficient pre-BRI implementation variation, essential for identification in our fixed-effects specification. Fourth, beginning in 2010 avoids the non-stationarity issues and structural breaks associated with the 2008-2009 global financial crisis, improving the consistency of our parameter estimates. In the robustness test (*Appendix A*), we employ data from 2013 and 2014 to represent the post-BRI period, and the results remain significantly positive.

more accurately than would be possible with single-indicator approaches. The theoretical justification for our three-category approach stems from infrastructure development literature that identifies these dimensions as critical pillars supporting economic development. Transport infrastructure facilitates the movement of goods, services, and labor. ICT infrastructure enables information flows and technological adoption. Financial infrastructure provides the capital allocation mechanisms necessary for economic growth. This multidimensional approach is theoretically superior to single-dimension measures as it captures the complementary nature of different infrastructure types in supporting economic activity. Moreover, these three dimensions correspond to the primary infrastructure development goals articulated in BRI policy documents, making them particularly relevant to our research context.

In this paper, UCM is constructed based on Kaufmann et al. (2011), and the core idea and main steps are as follows. The infrastructure index reflects a country's infrastructure endowment, but in theory, this cannot be perfectly measured. All observable infrastructure indicators include a portion of the unobserved infrastructure. To fully measure each country's infrastructure index, it is necessary to obtain an expectation of the distribution of the unobserved portion of infrastructure based on the country's data for the observed indicators. This approach draws on measurement theory in statistics, which recognizes that any observed indicator consists of both a signal (the true underlying concept) and noise (measurement error). UCM formalizes this relationship by expressing each indicator as a function of the unobserved infrastructure quality plus an error term. This decomposition allows us to extract the common signal across multiple indicators while filtering out indicator-specific noise. The signal extraction capability is crucial when analyzing BRI countries, where noise in individual indicators may arise from various factors including reporting differences, economic shocks, or policy changes specific to particular countries or periods.

Given the different observed infrastructure indicators j, the mean of the conditional distribution of the unobserved infrastructure represents the estimate of infrastructure in country c. The unobserved infrastructure is estimated as a sum over all J observed available infrastructure indicators weighted by the individual sources according to their precision:

$$E\left[I_i\middle|y_{i1},\ldots,y_{ij}\right]=\sum_{j=1}^{J}w_{ij}\frac{y_{ij}-\alpha_j}{\beta_j} \tag{3.2}$$

In this model, the subscripts i and j represent the country and the indicators, respectively. y corresponds to the infrastructure index. w represents the relative weight of each indicator. α and β are the estimated parameters, and the calculation formula will be given in the following. The infrastructure index of this paper is calculated in several steps as observed infrastructure index y of country c and indicator j by a linear function of an unobserved and imperfect measure of infrastructure I and an error term ε:

$$y_{ij}=\alpha_j+\beta_j\left(I_i+\varepsilon_{ij}\right) \tag{3.3}$$

The linear specification in Eq. (3.3) is theoretically grounded in classical test theory, which posits that observed scores are linear functions of true scores plus random error. The parameters α and β serve important theoretical functions: α represents the indicator-specific intercept that accounts for systematic differences in measurement scales across indicators. β captures the indicator's sensitivity to changes in the underlying infrastructure quality. This parameterization allows for the proper integration of indicators measured on different scales and with different relationships to the underlying concept. The estimated parameters α_j and β_j map the unobserved indicators into the observed data space, and different underlying data sources and units of measurement are processed simultaneously. The error term is assumed to be independent and identically distributed with mean $E[\varepsilon_{ij}]=0$ and variance $var[\varepsilon_{ij}]=\sigma_j^2$. The variance differs across indicators but is consistent across countries. Further assuming the errors to be independent across sources allows us to identify the particular information from each data source. The correlation between two different data sources can be attributed to the common underlying unobserved infrastructure I.

Each data source is weighted according to its precision, i.e., the weight assigned to each data source is inversely proportional to the variance of measurement error in the source. This approach makes sense given the logic of UCM, data sources that are more precise should be assigned more weight to reduce the variance of the estimate of infrastructure development. The weight w_{ij} is a decreasing function of the variance of the indicator j and an increasing function of the variance of all indicators. Due to variations in the availability of data sources, these weights differ across countries and vary by year. The smaller the variance of indicator j, the higher its precision and the weight assigned to the respective indicator:

$$w_{ij}=\frac{\sigma_j^{-2}}{1+\sum_{j=1}^{J}\sigma_j^{-2}} \tag{3.4}$$

Furthermore, the data availability for indicators may vary from year to year, we need to rescale our indices of infrastructure to ensure comparability across years and countries. The adjusted index is:

$$I_{i,t,adjusted}=I_{i,t}-I_{i,t+1,add}\frac{N_{t+1}-N_t}{N_t}-I_{i,t+1,miss}\frac{N_t-N_{t+1}}{N_t} \tag{3.5}$$

Where $I_{c,t+1,\ add}$ corresponds to the mean indicator of the countries entering the sample in the following year, and $I_{c,t+1,\ miss}$ corresponds to the mean indicator of the countries missing in the following year. N_t is the number of countries in the sample in the respective year. The more countries enter the sample in recent years, the lower the mean from the previous years. The factor is:

$$\sqrt{\frac{N_{t+1}}{N_t} - \frac{N_{t+1} - N_t}{N_t}\left(var\left(I_{c,t+1,add}\right) + I^2_{c,t+1,add}\right) - \frac{N_t - N_{t+1}}{N_t}\left(var\left(I_{c,t,miss}\right) + I^2_{c,t,miss}\right)} \tag{3.6}$$

Where $var(I_{c,t+1,\ add})$ is the variance of the additional countries entering the sample in the following year while missing in the current year, $var(I_{c,t+1,\ miss})$ is the variance of the countries missing in the following year but present in the current year.

As mentioned earlier, the individual indicators from the 29 data sources are assigned to the three dimensions of infrastructure development and are combined into three aggregate indicators using UCM. Our overall index is based on three sub-categories of infrastructure: transport, ICT and finance infrastructure and 29 indicators to comprehensively measure the infrastructure development level of BRI countries. The statistical methodology converts the data sources into common units and constructs a weighted average that combines the information in each of the data sources. The methodology also produces margins of error that capture the unavoidable imprecision involved with measuring infrastructure development across countries. In each sub-index, we consider not only the quantity aspects of infrastructure but also quality measures. Table 1 provides the infrastructure indices. Fig. 1 shows some representative BRI countries' infrastructure index. As can be seen, the level of infrastructure in most countries has been rising year after year. In particular, Russia, India and Indonesia have higher levels of infrastructure development.

3.2.2. Dependent variable

The current measurement of a country's existing level of innovation consists of two main aspects: innovation outputs and innovation inputs. This paper focuses on the impact of infrastructure on innovation performance, we use innovation outputs as the dependent variable. According to existing relevant studies, although some scholars believe that the number of patents is flawed in measuring innovation capacity, it is controversial to use it to measure the country's innovation performance. However, since the number of patents granted can quantify the whole process of innovation output and has a significant positive correlation with innovation, the patent data is still quite scientific, and it is a reliable variable to measure innovation performance (Acs et al., 2002; Jalles, 2010). Drawing on the studies by Pradhan et al. (2018), we utilize patents granted by countries (*Inno*) to measure the country's innovation performance. Data is sourced from the World Intellectual Property Organization. Fig. 2 shows the innovation performance of the same sample of representative BRI countries in Fig. 1. Initially, the level of infrastructure development has an impact on innovation performance. We can see Russia, India and Indonesia also have higher levels of innovation performance, which is broadly consistent with the upward and downward trends in the level of infrastructure development.

Table 1
Indicators of infrastructure index.

Type	Code	Indicators	Source
Finance- Infrastructure	*F1*	Bank accounts per 1000 adults	World Bank
	F2	Stock price volatility	
	F3	Stock market turnover ratio (%)	
	F4	Stock market total value traded to GDP (%)	
	F5	Bank Z-score	
	F6	Private credit by deposit money banks to GDP (%)	
	F7	Private credit bureau coverage (% of adults)	
	F8	Listed domestic companies	World Federation of Exchanges
	F9	Commercial bank branches (per 100,000 adults)	International Monetary Fund
	F10	Claims on private sector (annual growth as % of broad money)	
	F11	Automated teller machines (ATMs) (per 100,000 adults)	
	F12	S&P Global Equity Indices (annual % change)	S&P Global
ICT- Infrastructure	*I1*	Individuals using the Internet (% of population)	World Bank
	I2	Secure Internet servers (per 1 million people)	
	I3	Mobile cellular subscriptions (per 100 people)	
	I4	Fixed telephone subscriptions (per 100 people)	
	I5	Fixed broadband subscriptions (per 100 people)	
	I6	International bandwidth usage	International Telecommunication Union
	I7	Lit/equipped international bandwidth capacity	
	I8	M2M mobile-network subscriptions	
	I9	Number of Internet service providers (ISPs)	
Transport- Infrastructure	*T1*	Air transport, freight (million ton-km)	World Bank
	T2	Air transport, passengers carried	
	T3	Air transport, registered carrier departures worldwide	
	T4	Rail lines (total route-km)	
	T5	Railways, goods transported (million ton-km)	
	T6	Railways, passengers carried (million passenger-km)	
	T7	Container port traffic (TEU: 20-foot equivalent units)	
	T8	Liner shipping connectivity index (maximum value in 2004 = 100)	United Nations Conference on Trade and Development (UNCTAD)

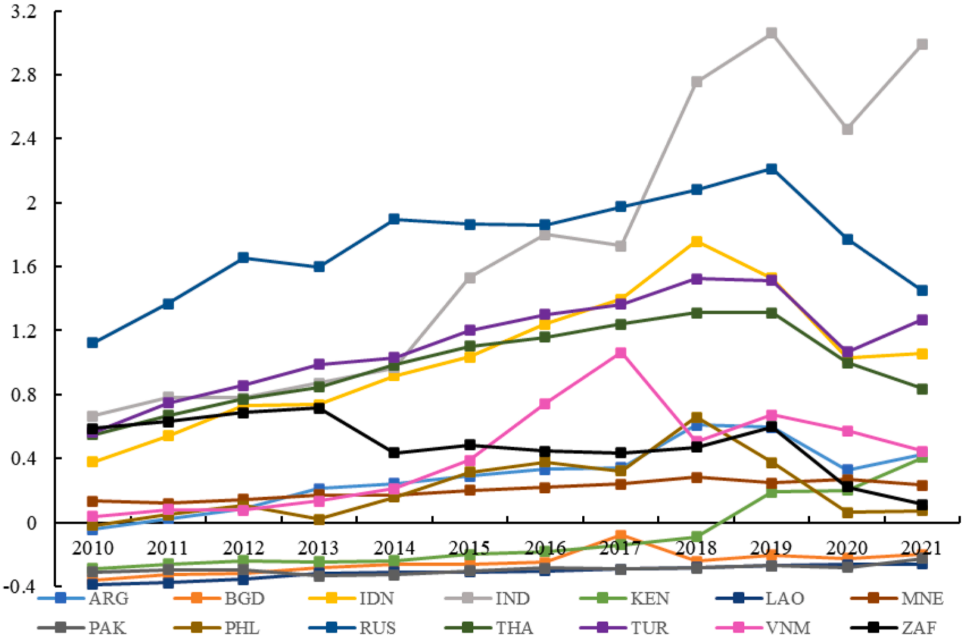

Fig. 1. 2010–2021 Infrastructure index.

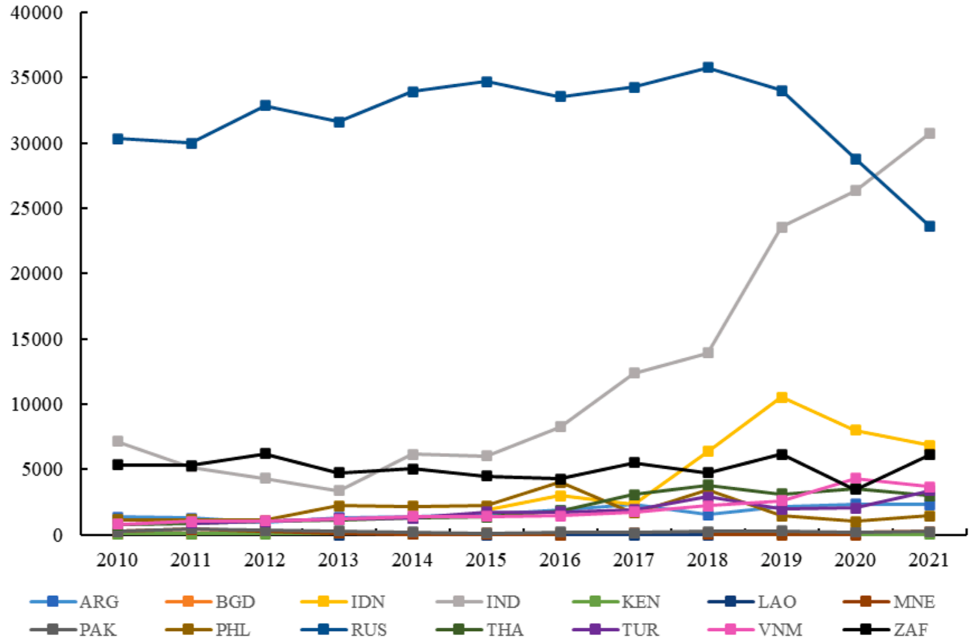

Fig. 2. 2010–2021 Innovation performance.

3.2.3. *Control variables*

Our regression model incorporates a series of control variables which are as follows: (1) Considering the impact of national power on innovation (Arkolakis et al., 2018), the faster the national economic growth, the greater the support for innovation. We use the gross national product per capita (*lngdp_per*) as a proxy variable for national strength. (2) The more connected a country is to the outside world, the stronger its drive for innovation (Liu et al., 2000), FDI can affect innovation outputs through technology diffusion and knowledge absorption (Neto and Veiga, 2013). We use the FDI (*lnfdi*) as a proxy variable for country outreach. (3) Whereas other social factors, such as social dependency pressure in the country, have an impact on innovation, we use the age dependency ratio (*dependency*) to control for the impact of social development on innovation performance. (4) Population (*lnpopu*) is an important influence on innovation performance (Coccia, 2014; Galindo and Méndez, 2014). To eliminate the numerical differences of the variables and to alleviate the problem of heteroskedasticity, we take the natural logarithm and perform inverse hyperbolic sine transformations for some numerical variables. Table 2 provides our descriptive statistics.

Table 3 shows that infrastructure construction in the BRI countries is positively correlated with innovation performance, which provides preliminary evidence for the conclusions of this paper. The strength and direction of the relationship between the variables, as well as the internal logic of the impact of the infrastructure development on innovation performance, need to be further empirically tested. Since some of the correlation coefficients in Table 3 are greater than 0.6, to test the multicollinearity in the model, this paper carries out the Variance Inflation Factor (VIF) test, and the test results are reported in Table 4. In the results, the VIF values of all variables are lower than the empirical value of 10, with the lowest value of 1.73, and the highest value of 3.47. Therefore, it can be concluded that the regression model does not have serious multivariate covariance problems and is constructed reasonably.

4. Empirical analysis

4.1. Baseline results

To quantify the innovation-promoting effect of infrastructure, we employ the baseline model (3.1) and estimate it using Ordinary Least Squares (OLS) regression. Across all regressions, we ensure the inclusion of the country and year fixed effects. Table 5 displays the findings from the baseline regression. In Column (1), the regressions are conducted without the inclusion of any control variables, and only country and year fixed effects are controlled for. The coefficient associated with infrastructure (*infra*) is found to be significantly positive at the 1 % significance level in these columns. When control variables are incorporated, as seen in Columns (2) - (5), the coefficient on infrastructure (*infra*) continues to be significantly positive at the 1 % significance level. Analyzing the findings from Table 5, it becomes evident that infrastructure development has a significant positive impact on innovation performance in BRI countries. These results provide strong empirical support for our first hypothesis (H1) that infrastructure development can stimulate innovation in BRI countries. The consistently positive and statistically significant coefficients across all model specifications demonstrate the robust relationship between infrastructure and innovation performance, suggesting that infrastructure serves as a crucial foundation for technological advancement in BRI countries.

For robustness, we provide several checks, including alternating variables, changing the data range, adding more control variables, changing models, dividing sample periods, a sensitivity analysis, a placebo test, and a double machine learning analysis, bolstering our confidence that our results can be interpreted as causal. The results can be seen in the Appendix A.

4.2. Endogeneity test

There are potential risks of endogeneity within the results. Infrastructure might not be directly causing countries to enhance their innovation performance. Instead, it could be that the country with high innovation capacity is largely concentrated on promoting infrastructure development, and has a leading role in supporting the efficient construction and stable operation of its infrastructure projects. This endogeneity concern suggests that further analysis is warranted to disentangle the causal relationship between infrastructure improvements and countries' innovation performance.

In tackling the potential endogeneity issue, following the studies (Nunn and Qian, 2014), we employ an instrumental variable approach using two-stage least squares (IV-2SLS) regression. Previous research has indeed indicated that land elevation is a major factor in infrastructure activities (Mohammadi and Taylor, 2017). We utilize the data of countries' urban land area where elevation is below 5 m provided by the World Bank as the instrumental variable. This choice assumes that urban land area below 5 m is generally considered to be significantly and positively associated with infrastructure development. Theoretically, the lower the elevation of urban land, the more human activities and the higher the demand for infrastructure development. Infrastructure projects are easier and cheaper to carry out at lower altitudes, which in turn increases the benefits of the projects, thus promoting infrastructure development and ultimately improving the quantity and quality of infrastructure. At the same time, there is no close correlation between urban land area where elevation is below 5 m and innovation. Therefore, this paper uses urban land area where elevation is below 5 m as

Table 2
Descriptive statistics.

Label	Variable	Obs	Average	SD	Min	Max
infra	Infrastructure index	1728	0.08	0.76	−0.51	9.16
infra-finance	Finance Infrastructure index	1728	0.14	0.93	−1.00	5.20
infra-transport	Transport Infrastructure index	1728	0.10	1.40	−0.56	20.77
infra-ICT	ICT Infrastructure index	1728	0.01	0.71	−0.31	14.41
Inno	Patent granted	1008	5.21	2.53	0.00	13.45
lnpopu	Population	1728	15.78	1.94	11.14	21.07
lngdp_per	Per capita GDP	1709	8.42	1.27	5.74	11.80
lnfdi	FDI	1581	20.65	2.10	12.15	26.53
dependency	Age dependency ratio	1728	59.84	18.02	16.17	106.60

Table 3
Correlation coefficient.

	Inno	*infra*	*lnpopu*	*lngdp_per*	*lnfdi*	*dependency*
Inno	1					
infra	0.630	1				
lnpopu	0.551	0.289	1			
lngdp_per	0.334	0.438	−0.244	1		
lnfdi	0.660	0.515	0.604	0.417	1	
dependency	−0.375	−0.428	0.131	−0.752	−0.385	1

Table 4
Variance inflation factor.

	infra	*lngdp_per*	*lnpopu*	*lnfdi*	*dependency*	Mean
VIF	1.73	3.47	3.10	2.99	1.81	2.62
1/VIF	0.58	0.29	0.32	0.33	0.55	0.42

Table 5
Baseline regression.

	(1)	(2)	(3)	(4)	(5)
Infra	0.359***	0.344***	0.302***	0.334***	0.334***
	(0.082)	(0.079)	(0.080)	(0.080)	(0.081)
Lnpopu		4.470***	4.783***	4.985***	5.004***
		(0.571)	(0.583)	(0.588)	(0.745)
lngdp_per			0.424***	0.279*	0.281
			(0.155)	(0.166)	(0.173)
Lnfdi				0.064*	0.063*
				(0.038)	(0.038)
Dependency					0.001
					(0.012)
Constant	5.303***	−67.440***	−76.174***	−79.619***	−79.979***
	(0.087)	(9.294)	(9.857)	(9.989)	(13.094)
N	1008	1008	1005	941	941
R2	0.034	0.096	0.103	0.116	0.116
Year FE	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes
F	2.558	7.235	7.236	7.163	6.707

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

Table 6
Endogeneity test.

	(1)	(2)
	infra	*inno*
Iv	0.010***	
	(0.001)	
Infra		1.686***
		(0.274)
Lnpopu	1.18***	3.776***
	(0.302)	(0.894)
lngdp_per	0.466***	−0.390
	(0.068)	(0.238)
Lnfdi	−0.053***	0.123***
	(0.015)	(0.046)
dependency	0.022***	−0.017
	(0.005)	(0.015)
N	1030	728
Cragg-Donald Wald F statistic	107.80	
Kleibergen-Paap LM test statistic	109.46	
P-value of underidentification LM statistic	0.00	

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

instrumental variable selection.

Table 6 presents the outcomes of the analysis. Column (1) discloses the results from the first stage of the regression, illustrating that urban land area where elevation is below 5 m (*Iv*) exhibits a positive correlation with infrastructure. The second-stage outcomes of the instrumental variable regression are delineated in Column (2). The coefficients of infrastructure (*infra*) are uniformly and significantly positive at least at the 1 % significance level. These results affirm that the primary conclusions remain valid after addressing the issue of endogeneity.

4.3. The role of external debt

The preceding section provides evidence that infrastructure exhibits a favorable innovation promotion effect. A noteworthy next step involves figuring out the role of external debt. The debt trap theory of infrastructure projects is essentially countries questioning the economic attributes of the BRI, arguing that the BRI is mixed with political factors. They accuse China of forcing countries to cede control of infrastructure projects, making the countries unable to repay their debts and leading to the suspension of investment projects. Then the debt crisis is triggered, and the countries fall into the debt trap (Hurley et al., 2019). However, when developing countries incur debt risk with the help of external debt to promote infrastructure development, the root cause is not the debt itself (Jobst and Gray, 2013). Factors accounting for this crisis include the failure of some overseas projects to come to fruition or realize anticipated financial dividends, and an increase in debt vulnerabilities in borrowing countries.

From Fig. 3, the external debt shocks of BRI countries from 2010 to 2021 show a steady increase. The BRI countries with higher external debt, such as Russia, India and Indonesia are also in the leading position in terms of infrastructure development and innovation performance (Fig. 1& Fig. 2). From the basic data, it can be initially inferred that external debt is an important resource for BRI countries to promote innovation through infrastructure development. Specifically, the country's capacity to manage external finance is an important influence on the promotion of innovation in infrastructure development. Further analyses in this section examine whether the BRI countries are in the debt trap or the debt transition in the process of innovation in infrastructure promotion. Our examination centres on the role of external debt, especially national capability, debt utilization efficiency, default risk and source of funds in the process through which infrastructure impacts countries' innovation performance.

This section adopts the stepwise test method to analyze the mechanism effect of the national total external debt level *(lndebt_t)*. To establish a mechanism effect, we employ a three-step approach following the methodology (Baron and Kenny, 1986). In Eqs. (4.1) to (4.4), first, we estimate the direct effect of infrastructure development on innovation performance. Second, we examine whether infrastructure affects the potential mediator, external debt. Third, we test whether external debt affects innovation performance. Finally, we include both infrastructure development and external debt in the same model to determine whether the effect of infrastructure development on innovation is reduced when controlling for external debt. The regression models are specified as follows:

$$Inno_{it} = \beta_0 + \beta_1 \cdot infra_{it} + \beta_2 X_{it} + \mu_i + \theta_t + \varepsilon_{it} \tag{4.1}$$

$$lndebt\_t_{it} = \gamma_0 + \gamma_1 \cdot infra_{it} + \beta_k X_{it} + \mu_i + \theta_t + \varepsilon_{it} \tag{4.2}$$

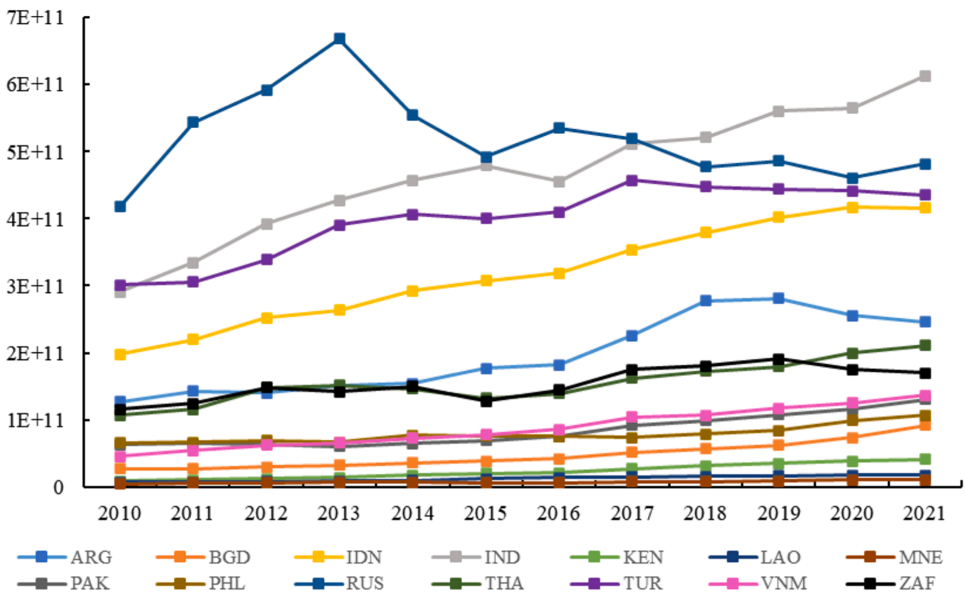

Fig. 3. 2010–2021 External debt stocks, total (DOD, current US$).

$$Inno_{it} = \delta_0 + \delta_1 \cdot \text{ln}debt\_t_{it} + \beta_k X_{it} + \mu_i + \theta_t + \varepsilon_{it} \quad (4.3)$$

$$Inno_{it} = \lambda_0 + \lambda_1 \cdot infra_{it} + \lambda_2 \text{ln}debt\_t_{it} + \beta_k X_{it} + \mu_i + \theta_t + \varepsilon_{it} \quad (4.4)$$

Where *Inno* represents innovation performance, *infra* represents infrastructure development, *lndebt_t* represents the natural logarithm of total external debt stocks, *X* is a vector of control variables, μ_i and θ_t are country and year fixed effects, and ε_{it} is the error term.

Table 7 reports the results of the mechanism effect, which show that the country's external debt plays a partial mediating role between infrastructure construction and innovation performance in BRI countries. Column (1) in Table 7 confirms the direct positive effect of infrastructure on innovation performance. Column (2) demonstrates that infrastructure development positively influences external debt levels, while Column (3) shows that external debt positively affects innovation performance. Most importantly, Column (4) reveals that when both infrastructure and external debt are included in the model, both coefficients remain positive and significant, confirming that external debt serves as a pathway through which infrastructure affects innovation. These findings strongly support hypothesis H2 that infrastructure development enhances innovation performance in BRI countries, with external debt playing a crucial positive role in this relationship. Contrary to the debt trap narrative, our results indicate that external debt serves as a productive mechanism through which infrastructure development is translated into innovation.

During the development process of BRI countries, external debt may primarily serve to bridge the financial gap required for infrastructure development, thereby stimulating innovation. To better understand how external debt contributes to innovation in BRI countries, we examine both innovation inputs and innovation vectors. As BRI countries advance their infrastructure, an increase in external debt can foster innovation by enhancing financial access for innovative agents and augmenting innovation-related inputs. The empirical results presented in Appendix B, demonstrate that external debt positively influences capital access, innovation inputs, and the development of main innovators. Consequently, external debt serves as a stable and reliable catalyst for fostering innovation, not just about filling the funding gap for infrastructure.

4.4. Influencing factors of the external debt's role

Building on the established mechanism role of external debt, this section investigates factors influencing the role of external debt in promoting innovation through infrastructure development by using moderation effects and group experiments. Consistent with the third hypothesis (H3), we analyze how four critical dimensions: debt management capacity, debt utilization efficiency, national solvency and default risk, affect the effectiveness of external debt in translating infrastructure development into innovation outcomes. By systematically examining these conditional factors, we aim to identify the enabling environments under which external debt effectively promotes innovation in BRI economies.

4.4.1. Debt management capability

Based on the baseline results, we find that the country's external debt plays an important role in infrastructure construction and innovation performance in BRI countries. To examine how a country's debt management capability moderates the relationship between infrastructure and innovation, we utilize the CPIA debt policy rating (*cpia*), the ratio of short-term external debt to total external debt (%) (*debt_se*) and the ratio of short-term external debt to total international reserves (%) (*debt_sr*) to measure the countries' debt management capability, respectively. We employ the following regression model to evaluate these moderating effects:

$$Inno_{it} = \beta_0 + \beta_1 \cdot infra_{it} + \beta_2 DMC_{it} + \beta_3 (infra_{it} \cdot DMC_{it}) + \beta_k X_{it} + \mu_i + \theta_t + \varepsilon_{it} \quad (4.5)$$

Where *Inno* represents innovation performance, *infra* represents centered infrastructure index, *DMC* represents one of the three centered debt management capability measures (*cpia, debt_se*, or *debt_sr*), and the interaction term captures the moderating effect. *X* is a

Table 7
The role of external debt.

	(1)	(2)	(3)		(4)
	Inno	*lndebt_t*	*Inno*		*Inno*
Infra	0.334***	0.038*			0.409***
	(0.081)	(0.022)			(0.085)
lndebt_t			0.325**		0.298*
			(0.157)		(0.154)
Constant	−79.979***	−11.307***	−95.597***		−90.646***
	(13.094)	(2.951)	(14.957)		(14.691)
N	941	1126	623		623
R2	0.116	0.661	0.135		0.171
Controls	Yes	Yes	Yes	Yes	
Year FE	Yes	Yes	Yes		Yes
Country FE	Yes	Yes	Yes		Yes
F	6.707	123.0	5.220		6.489

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

Table 8
Debt management capability.

	(1)	(2)	(3)
Infra	−0.574	0.634***	0.384***
	(0.693)	(0.156)	(0.093)
Cpia	0.915***		
	(0.324)		
infra×cpia	1.788**		
	(0.776)		
debt_se		−0.797	
		(0.595)	
infra×debt_se		−0.877*	
		(0.485)	
debt_sr			−0.001**
			(0.000)
infra×debt_sr			−0.001*
			(0.001)
Constant	−45.542	−93.434***	−73.775***
	(36.733)	(14.714)	(16.515)
N	248	623	616
R2	0.071	0.173	0.144
Controls	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
F	0.801	6.192	4.889

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

vector of control variables, μ_i and θ_t are country and year fixed effects, and ε_{it} is the error term.

After centrally processing the data, we then construct their interaction terms with infrastructure, namely *infra×cpia, infra×debt_se* and *infra×debt_sr* to be incorporated into the model for testing. The regression results presented in Table 8 show that the coefficients for the interaction terms are at least at a 10 % significance level.

The results are shown in Table 8. The CPIA debt policy rating is the key indicator in national debt sustainability assessments (1=low to 6=high). It assesses whether the countries' debt management strategy is conducive to minimizing budgetary risks and ensuring long-term debt sustainability. The coefficient for *infra×cpia* is significantly positive, suggesting that with the increase in the debt policy rating, the positive effects of infrastructure on countries' innovation performance are increasing. The sustainability of debt policies is an important factor in reflecting the level of a country's debt management capability. It means that countries' improved debt policy can lower the burden brought about by external debt, and the enhancement of the countries' debt sustainability can effectively increase the promotion effect of infrastructures on innovation performance.

In contrast, the coefficients for *infra×debt_se* and *infra×debt_sr* are significantly negative, indicating that they significantly downsize the positive impact of infrastructure on innovation. In terms of the ratio of short-term external debt to total external debt (*debt_se*), the maturity structure of a country's external debt is a key factor in its ability to control the debt servicing risk. Short-term debt is affected by fluctuations in the international economy and financial markets. The higher the proportion of a country's short-term debt, the lower its debt management capacity. When a country's debt repayment is relatively concentrated in a certain period, it will lead to a low level

Table 9
Debt utilization efficiency.

	(1)	(2)	(3)	(4)
	Exports		GNI	
	High (>1)	Low (<1)	High (>1)	Low (<1)
infra	0.266***	0.558***	0.215*	0.588***
	(0.095)	(0.163)	(0.117)	(0.169)
Constant	−84.930***	−88.224***	−91.783***	−71.688***
	(18.104)	(22.025)	(23.654)	(16.421)
N	546	395	481	460
R2	0.138	0.176	0.099	0.197
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
F	4.298	4.079	2.554	5.778

Notes: We use 1 as the boundary, "High" and "Low" in the table mean the size of the coefficients. When the coefficient > 1, that means this country's debt utilization efficiency is low. *Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.*

of funds stability. It is difficult for the country to adjust its debt-servicing funds in accordance with national conditions, and the funds needed for innovative development will be relatively reduced.

In terms of the ratio of short-term external debt to total international reserves (*debt_sr*), also reflects the countries' debt management capability. When a country's payment means for external debt servicing are insufficient, it may use its international reserve assets temporarily to service its external debt. When a country's short-term external debt to international reserves ratio is great, the country may use its international reserves to service its external debt that year, reflecting the country's weaker debt management capacity and lower resistance to emergency risk. It will lead to a reduction in the opportunity for innovation development caused by insufficient funds, and the speed of technological development and economic development will slow down.

The above results demonstrate that the debt management capacity of BRI countries moderates the relationship between infrastructure development and innovation. Specifically, countries with stronger debt management capacity exhibit a more pronounced innovation-promoting effect from infrastructure development. In contrast, when a country's debt management capacity is relatively weak, its infrastructure development may lead to an increase in external debt levels without fostering innovation and may even trigger a debt crisis. Based on debt management capacity, as shown in *Appendix C.2.4.*, the results indicate that even in countries with relatively low debt management capacity, infrastructure development does not necessarily weaken innovation capacity.

4.4.2. Debt utilization efficiency

Detailed tests based on indicators related to debt management are provided in the previous section. This section examines the efficiency of external debt utilization in BRI countries and its impact on innovation promotion. We use exports and GNI to refer to the country's debt utilization efficiency, we divide the countries into coefficients high and low using 1 as the boundary. When the coefficient < 1, it indicates that the country's export and GNI growth rate is faster than the growth rate of external debt, and the country's external debt utilization capacity is relatively high. Its ability to convert external borrowing into investment that contributes to the expansion of exports and GNI development is strong. The results in Table 9 show the innovation-promoting effect of infrastructure is significant in BRI countries with high or low efficiency of external debt utilization, which indicates that BRI countries are objectively efficient in their debt utilization.

In terms of exports expending, it is the ratio of external debt growth (%) to export growth (%). This indicator can reflect the extent to which the country's external debt promotes exports. The smaller the indicator, the more effective the country's external debt is used in the export sector. The median coefficient of export growth of BRI countries is 0.17, which indicates that their external debt is used for domestic productive investments or export industries is higher. The rate of export growth is higher, and the external debt promotes the development of the country's foreign trade. From the results in Columns (1) and (2) of Table 9, both high and low levels of export expansion capacity. National infrastructure can effectively promote innovation, and the countries with a lower level of this index have a more pronounced effect. It is possible that when a country's export expansion capacity is stronger, it can carry out independent innovation based on the feedback information from the host market. It can formulate corresponding infrastructure construction and innovation development plans, and improve its own technological level and R&D capacity. For countries with larger coefficients, their external debt may be used more for domestic consumption or non-production construction infrastructure projects, or the import of high-technology products, resulting in a relatively low innovation promotion effect.

In terms of GNI promotion, it is the ratio of external debt growth (%) to GNI growth (%). This indicator reflects the contribution of external debt borrowing to national economic development. Overall, BRI countries' GNI growth is faster than external debt growth, and the median of the overall external debt utilization coefficient is 0.52. The results are shown in Columns (3) and (4) of Table 9 which are similar to the exports expending. Counties with high or low levels of GNI promotion capacity, their infrastructure can promote innovation, and the countries with a higher level have a more pronounced effect. If a country with a lower level, it indicates that the country's external debt is used to improve domestic infrastructure or develop domestic innovative projects, thus promoting the national economy. When the coefficient is greater than 1, the increase in the country's national income and standard of living has not exceeded the growth in external debt. This is possible because the country's foreign factor expenditures are likely to be higher and it is still relying on imports, which also provides support for infrastructure in promoting innovation.

4.4.3. National solvency

National solvency comprehensively reflects a country's economic strength and capacity for stable development. In this section, based on the total external debt shock data, we utilize the ratio of international reserves to total external debt stocks and the ratio of total external debt stocks to exports to measure the national solvency.

In terms of the ratio of international reserves to total external debt stocks, reflects the ability of a country to use its international reserve assets to service its external debt. The higher the ratio, the higher the country's debt solvency. The more international reserves of the country, its import payment capacity and external debt repayment capacity are stronger. It can meet the needs of international payments at the same time, anti-risk and the ability to cope with the crisis is also stronger. The results are shown in Columns (1) and (2) of Table 10, the positive impact of infrastructure construction on innovation performance is mainly concentrated in countries with high levels of international reserves as a ratio of external debt. Countries holding more foreign exchange reserves can guarantee the convertibility of foreign capital outflows.

Table 10
National solvency.

	(1) International Reserves to Debt	(2)	(3) Debt to Exports	(4)
	High	Low	High	Low
infra	0.321***	0.289	0.054	0.311***
	(0.083)	(0.417)	(0.181)	(0.073)
Constant	−72.663***	−56.663**	−83.897***	−24.777
	(16.552)	(25.351)	(16.642)	(29.547)
N	621	320	641	300
R2	0.135	0.127	0.106	0.235
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
F	5.114	2.317	3.984	4.554

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

Meanwhile, the ratio of total external debt stocks to exports reflects the ability of a country's export earnings to service the external debt. The smaller the proportion, the higher the country's ability to repay its external debt, and the lower the liquidity risk. When the country's export revenue makes it difficult to meet the needs of external debt servicing, its external debt management capacity and solvency capacity are weak, which will undermine the funds needed for innovative development. The results are shown in Columns (3) and (4) of Table 10, the positive impact is mainly concentrated in countries with low levels of external debt as a ratio of exports.

4.4.4. *Default risk*

Compared to countries with more fragile fundamentals, countries with lower default risk can undertake larger infrastructure investment projects that lead to more technological innovation effects. The government with higher default risk, and its lower liquidity may affect the level of government subsidies and R&D expenditures, which in turn may inhibit the quantity and quality of innovation output. In this section, we test the effect of default risk in the process where infrastructure drives countries to enhance their innovation performance. Using the median as the delineation point, this paper conducts empirical regressions by grouping countries according to the ratio of external debt to GNI and the ratio of interest payments on external debt to GNI, respectively.

As shown in Columns (1) and (2) of Table 11, the ratio of external debt to GNI reflects the overall national default risk. The positive impact of infrastructure development on innovation performance is mainly concentrated in countries with low default risk. This is possible because the higher the ratio of external debt to GNI, the countries have a higher default risk and less fiscal space, which makes them have difficulty in undertaking large-scale infrastructure projects and obtaining policy financing support. Even if infrastructure projects are completed, there are difficulties in subsequent operation and maintenance. It is difficult for firms to leverage financial support, and ultimately it is difficult for infrastructure to contribute to innovation.

Similarly, countries with a lower interest rate on their external debt, have lower default risk. Because they have lower debt-servicing pressure and costs, and are better able to use external debt funds to advance infrastructure projects and promote innovative development. The empirical results, as shown in Columns (3) and (4) of Table 11, show that the positive impact of infrastructure development on innovation performance is mainly concentrated in countries with a lower level of interest payments on external debt to GNI. Countries with low default risk can use external debt on the knife edge and improve innovation performance.

Table 11
Default risk.

	(1) External debt to GNI	(2)	(3) Interest payments on external debt to GNI	(4)
	High	Low	High	Low
Infra	0.070	0.249***	0.179	0.254**
	(0.192)	(0.073)	(0.163)	(0.103)
Constant	−91.524***	55.917**	−77.854***	−17.047
	(15.748)	(28.349)	(14.739)	(40.774)
N	642	299	696	245
R2	0.135	0.199	0.119	0.182
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
F	5.248	3.768	5.021	2.586

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

Furthermore, we examine the heterogeneous impacts of infrastructure across various dimensions, including different types of infrastructure and country classifications. The results can be seen in Appendix C. Specifically, countries' repayment pressure on infrastructure projects funded by Chinese loans remains manageable, their innovation performance improves. From the above empirical results, it can be concluded that in the process of infrastructure development in the BRI countries, they use external debt to fill the gaps in financial and technological development and promote their technological progress and economic growth. It can be considered that the process of promoting the development of infrastructure, is still in the stage of debt-driven development, and the country's development is still in the stage of financial and technological gaps(Chenery and Strout, 1966). Without external debt, they do not have sufficient funds to support infrastructure development, not to mention the inability to promote innovation. This confirms that the BRI countries need to use external debt to achieve innovative development when building infrastructure, as we mentioned above.

The debt trap theory ignores not only the positive contribution of debt in the process of national economic development but also the innovation promotion function and debt risk mitigation role of infrastructure construction as a public asset. The BRI countries need to raise a large amount of funds in the process of infrastructure construction(Hurley et al., 2019), which may increase the scale of national debt to a certain extent in the short term, but this does not necessarily mean that external debt will bring crises and risks. External debt is an important means for a country to regulate its economic operation and make up for its fiscal deficit. Reasonable national debt is conducive to promoting scientific and technological innovation and economic growth. The development of developing countries based on external debt is a high-risk and high-return strategy. Whether or not external debt can play a role depends on several factors, such as the debt management capacities, national solvency, utilization efficiency of debt and default risk, any failure in any one of these areas may lead to policy practices that deviate from the expected development goals. These empirical findings provide strong support for the third hypothesis (H3) that debt management capacity, debt utilization efficiency, national solvency, and default risk are indeed critical factors in determining how effectively BRI countries can leverage external debt to promote innovation through infrastructure development.

5. Conclusion and discussion

China has financed and constructed substantial amounts of infrastructure projects in BRI countries, the BRI countries always take on substantial amounts of external debt for these projects' development. Western policymakers conceive of BRI's construction of infrastructure as expensive and superficial projects, which ultimately lead to unsustainable levels of debt. The debt crisis questions whether infrastructure development is capable of lifting economic prospects. Based on the innovation latecomers' catching-up strategies, this paper argues that BRI countries are not ensnared in a debt crisis due to infrastructure development. Instead, it actively responds by enhancing innovation performance. We conduct an empirical analysis to investigate the impact of infrastructure on the innovation performance of BRI countries. Our empirical findings reveal that: (1) There is a significant positive impact of infrastructure levels on countries' innovation performance. (2) A deeper analysis reveals that external debt plays a significant role in infrastructure and innovation performance. When a country's debt structure includes higher debt management capability, higher national solvency, higher debt utilization efficiency and lower default risk, the effect is more pronounced. This enhanced effect indicates that specific debt structures can heighten a country's responsiveness to innovation, aligning with its commitments to innovation catching-up development. (3) The positive impact of infrastructure on national innovation performance is predominantly observed in transport and ICT infrastructure, but not in financial infrastructure. The promotion effect is not uniformly distributed across all types of countries. (4) In conclusion, this study provides robust evidence that infrastructure significantly improves the innovation performance of BRI countries, with the effect modulated by various debt factors. In promoting infrastructure construction, these countries have effectively converted debt into innovative development resources without falling into an unsustainable debt trap. This means that the indebted countries, both in absolute and relative terms, are not in distress.

This study elucidates the governance dynamics and decision-making logic of BRI countries concerning infrastructure projects and debt sustainability. Additionally, it provides a scientific basis for policymakers to establish effective policy intervention mechanisms to address the debt trap. For countries aspiring to innovation catching-up development, it is crucial to base their strategies on the national development process and prioritize key infrastructure development. These countries should promote an economic development strategy that fully utilizes the resources available through their national currency. Governments must adopt a balanced view on debt sustainability in BRI countries, recognizing the beneficial role of external debt financing in national economic development. Debtor countries should actively engage in differentiated competition and complementary cooperation with various creditor countries, making use of the comparative advantages of Chinese funds in productive areas such as transport and communications, as well as the US funds in institutional areas such as education, healthcare and commercial finance.

Several research gaps remain for future investigations. Due to the complexity of countries' debt structures, the ways in which external debt and its lending conditions influence the mindsets of national leaders and domestic economic development have not been thoroughly examined in this study. Additionally, the impact of infrastructure on a country's sustainable development requires further exploration, particularly from the perspective of national behavioral economics, to deepen our understanding of the trends and implications of debt for sustainable development. It is crucial to investigate the cognitive and decision-making processes of national and governmental leadership to assess how infrastructure projects and debt crises shape economic sustainability and governance practices.

CRediT authorship contribution statement

Yonghui Han: Supervision, Software, Methodology, Conceptualization. **Jinghua Mai:** Writing – review & editing, Writing – original draft, Visualization. **Fan Zhang:** Writing – original draft, Software, Data curation. **Ruilin Luo:** Visualization, Investigation.

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Appendix A. Robustness test

A.1. Alternate variables

We endeavour to establish the robustness of our findings by varying the dependent and independent variables. To accommodate the discrepancies in innovation performance measurement techniques. We generate annual patent applications by country as (*Inno2*) and *Global Innovation Output Sub-index* in the *Global Innovation Index* as (*Inno3*), yielding *inno2* and *inno3* as the new dependent variable. Additionally, we apply the *Global Innovation Infrastructure Sub-Index* in the *Global Innovation Index* as the new independent variable (*infra2)* for testing. Most of the BRI countries are developing countries, characterized by underdeveloped economies and financial systems, with a limited presence of banks, private credit institutions and other financial infrastructures. To reduce the impact of finance infrastructure, we rebuild and apply a new index as the new independent variable (*infra3*), based on transport and ICT sub-categories of infrastructure by using UCM. Table A1 delineates the outcomes of these robustness assessments, both yielding similar results. Columns (1) through (4) disclose the results of alternating the variables. The coefficients remain significantly positive at the 1 % and 5 % significance levels across all alternative specifications of the variables. These empirical results align with our baseline conclusions, underscoring their validity despite the application of various measures for variables.

A.2. Change data range

The year of sample selection may affect the results. Since the BRI was launched in 2013, to mitigate the influence of the data range, we utilize data from 2013 to 2021, as well as from 2014 to 2021, to represent the post-BRI period and test the robustness of the results. Columns (5) and (6) of Table A1 show the results. Furthermore, Considering the persistent nature of the changes in global economic data caused by COVID-19, and to reduce the impact of extreme values, we exclude 2020 and 2021 from our sample to reassess our results. The global outbreak of a pandemic can lead to shortages of supplies, restrictions on the movement of people, traffic closures and financial pressures, which can have a severe influence on the countries' economic development(Wen et al., 2022). Column (7) of Table A1 reports the results of the test. The results remain consistent with our benchmark regression findings which underscores the reliability of our results.

A.3. More control variables

Column (8) of Table A1 reports the testing results of control variables addition. The level of urbanization (*Urban*) is closely related to the development of innovation, urbanization provides a broad market demand and development platform for innovation. Foreign trade (*lntrade*) reflects the degree of cooperation between countries, the higher a country's foreign trade dependence, the easier it is to introduce advanced technology and products to achieve technological accumulation. The country's total external debt (*lndebt_t*) reflects the level of its external debt, the pressure of a country's external debt is an important influence on the advanced technology development and innovation competitiveness enhancement. The proportion of the population aged 15–64 years to the total population (*popu_1564_*) reflects the ratio of a country's labour force. The more the labour force is, the more labour resources it has, and the stronger the country's scientific and technological innovation capability is. The empirical results show that after adding more control variables, the coefficients remain significantly positive at the 1 % significance levels, and the effect is robust.

Table A1
Robustness Test I.

	(1) *Inno2*	(2) *Inno3*	(3) *Inno*	(4) *Inno*	(5) *Inno*	(6) *Inno*	(7) *Inno*	(8) *Inno*
infra	0.190***	1.507***			0.270***	0.187*	0.384***	0.361***
	(0.051)	(0.359)			(0.092)	(0.104)	(0.095)	(0.090)
infra2			0.014**					
			(0.007)					
Infra3				0.246***				
				(0.058)				
lnpopu	2.211***	−10.163***	5.508***	5.061***	3.347***	2.642**	5.077***	5.198***
	(0.449)	(2.977)	(0.743)	(0.743)	(1.028)	(1.282)	(0.869)	(0.857)
lngdp_per	0.181*	1.252	0.333*	0.277	0.214	0.227	0.296	0.168
	(0.106)	(0.846)	(0.185)	(0.173)	(0.189)	(0.204)	(0.199)	(0.226)
lnfdi	0.031	−0.116	0.066*	0.058	0.056	0.066	0.026	0.064
	(0.023)	(0.160)	(0.038)	(0.038)	(0.041)	(0.044)	(0.042)	(0.054)
dependency	−0.016**	0.291***	0.003	−0.000	−0.013	−0.023	0.002	0.114
	(0.007)	(0.052)	(0.012)	(0.012)	(0.015)	(0.018)	(0.015)	(0.074)
urban								0.058*
								(0.030)
lntrade								0.352
								(0.256)
lndebt_t								0.277*
								(0.157)
*popu_1564_*								0.221
								(0.176)
Constant	−31.169***	142.551***	−89.297***	−80.686***	−51.744***	−40.081*	−80.644***	−123.017***
	(7.835)	(52.972)	(13.146)	(13.068)	(17.944)	(22.239)	(15.248)	(23.571)
N	1046	1180	874	941	713	631	792	612
R2	0.089	0.822	0.111	0.117	0.067	0.047	0.109	0.183
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
F	5.584	302.2	5.917	6.755	3.279	2.122	5.879	5.821

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

A.4. Sensitivity analysis

Based on the sensitivity analysis method proposed by Cinelli et al. (2020), we employ the variance relationship among potential omitted variables (*Z*), independent variable, and dependent variable to estimate the strength of omitted variables. This study designates the gross national product per capita (*lngdp_per*) from the control variables as the proxy for the potential omitted variable, with estimation results presented in Fig. A1. The horizontal axis represents the partial *R2* of the omitted variable *Z* on the independent variable (*infra*), controlling for all other variables, while the vertical axis represents the partial *R2* of the omitted variable *Z* on the dependent variable (*inno*), controlling for *infra* and other control variables. The upper graph is an isopleth of the estimated coefficients for the core explanatory variable, and the lower graph shows the corresponding t-statistics isopleth for the estimated coefficients.

The results indicate that even when the strength of the potential omitted variable is three times that of Size, the estimated coefficient for *infra* remains negative. This confirms that the omitted variable does not alter the direction of the estimated coefficients in the baseline regression. Regarding statistical significance, when the strength of the omitted variable is three times that of *lngdp_per*, the t-value of the estimated coefficient remains less than −1.96, significant at the 5 % confidence level. This suggests that the baseline regression results are unlikely to be strongly affected by omitted variable bias.

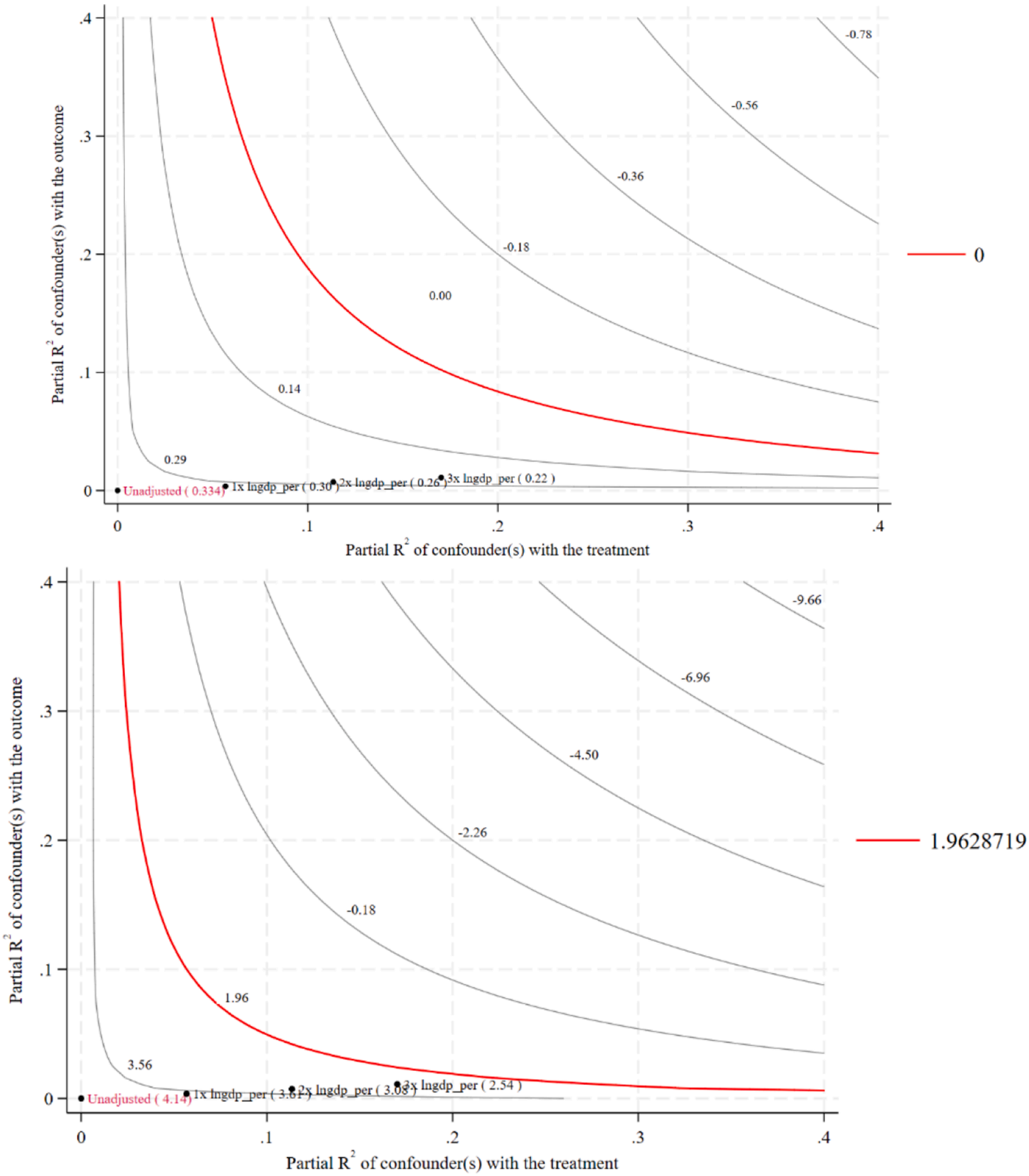

Fig. A1. Robustness Test II: sensitivity analysis.

A.5. Placebo test

Despite the above robustness tests of the results using a variety of approaches, there may still be other unobservable, time-varying effects of omitted variables. To address the concern that there are still other factors that might influence the results, this section utilizes a placebo test as a methodological strategy. The premise of the placebo test is that if the observed improvements in innovation performance are genuinely attributable to infrastructure, then such improvements should not be observed before the occurrence of infrastructure construction level improvement. In our test, the actual innovation performance of countries is kept intact, ensuring that the only variable being manipulated is the timing of the infrastructure construction level improvement. Then, the temporal link between countries' innovation performance and infrastructure is deliberately disrupted by constructing a pseudo-infrastructure index. This process involves randomizing the timing of infrastructure construction level improvement relative to countries' innovation performance data. The countries' innovation performance is then regressed on the pseudo-infrastructure index to test the strength and significance of the association. To reinforce the validity of the placebo test, we perform a permutation test consisting of 2000 random matchings.

The outcomes of the placebo tests are depicted in Fig. A2, which illustrates the distribution of the regression coefficients obtained from the placebo tests. We find that the regression coefficients from the placebo tests are centred around zero and follow a normal distribution, indicating that the associations between countries' innovation performance and the pseudo-infrastructure index are generally non-significant. The coefficient estimates from the actual benchmark regression are situated in the upper tail of the placebo test coefficient distribution. This placement suggests that the observed associations in the benchmark regression are unlikely to be due to chance and are not consistent with the distribution of coefficients from the placebo tests. As a result of these placebo tests, we can infer with greater confidence that the improvement in countries' innovation performance observed in the benchmark regression is not an artifact of unobserved factors but is likely a consequence of infrastructure. Thus, the placebo test provides additional support for the causal interpretation that infrastructure has a positive effect on countries' innovation performance.

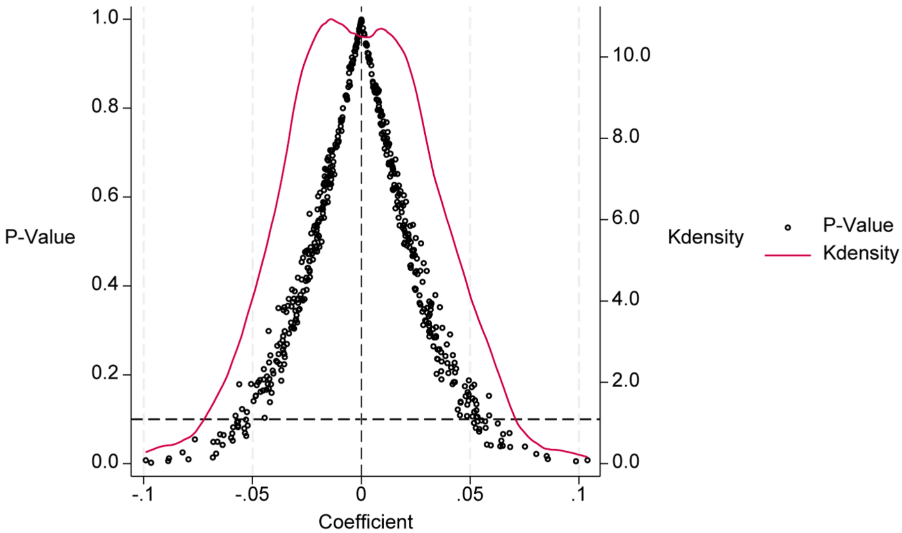

Fig. A2. Robustness Test III: Placebo test.

A.6. Changing model

Considering the influence of model setting, we further employ GMM, Poisson, Negative Binomial and Tobit regression models for robustness testing.

First, the country's innovation activities are persistently characterized. In this paper, based on the benchmark regression model, the lagged one period of the host country's innovation performance is introduced to construct a dynamic panel model and estimate it using the system GMM and difference GMM methods respectively. Columns (1) and (2) of Table A2 show the results of system GMM and difference GMM, respectively. Both *AR(1)p* are <0.1, indicating that there is first-order autocorrelation in the perturbation term, while both *AR(2)p* are greater than 0.1, indicating that there is no second-order autocorrelation in the perturbation term, which satisfies the conditions for the use of moments estimation. It can be seen that the level of infrastructure development is significantly positive at least at the 5 % level, and the first-order lagged term of innovation performance also passes the 5 % significance test. This indicates that the main conclusions of this paper still hold even after considering the dynamic panel bias. It shows that innovation performance has a significant cumulative effect in the long run.

Second, considering that the number of patents granted is a count variable, the use of logarithmical patents granted may bias the estimates. We use Poisson regression and Negative Binomial regression applicable to count variables for estimation. No legitimization is done on the dependent variable in Poisson and Negative Binomial regression. The results, as shown in Columns (3) and (4) of Table A2, show that the coefficients on the independent variable *infra* are significantly positive at the 1 % significance level for both

Poisson and Negative Binomial regressions. The core conclusions of the paper still hold.

Further, given the restricted range of values taken for the dependent variable innovation (*inno*), with truncated, disconnected and censored features, the fact that regression model treatments may affect the validity of the results. We use the Tobit model regression, and the results are reported in Column (5) of Table A2, with significantly positive coefficients.

Table A2 delineates the outcomes of these robust assessments. The coefficients pertaining to infrastructure remain significantly positive at the 1 % and 5 % significance levels across all alternative regression models. These empirical results are in consonance with our baseline conclusions, underscoring their validity despite the application of various regression models. The baseline regression results remain robust after considering model-setting issues.

Table A2
Robustness Test IV: changing models.

	(1) *SYS-GMM* *Inno*	(2) *DIF-GMM* *Inno*	(3) *Poisson* *patent*	(4) *Negative Binomial* *patent*	(5) *Tobit* *Inno*
L.Inno	0.362***	0.176**			
	(0.133)	(0.073)			
Infra	0.326***	0.328**	0.195***	0.201***	0.334***
	(0.122)	(0.152)	(0.001)	(0.022)	(0.077)
Lnpopu	0.636***	3.103**	−0.365***	0.320***	5.066***
	(0.160)	(1.333)	(0.040)	(0.035)	(0.712)
lngdp_per	0.516***	0.079	0.308***	0.205***	0.272*
	(0.171)	(0.175)	(0.006)	(0.061)	(0.165)
Lnfdi	0.009	0.053**	0.026***	−0.006	0.064*
	(0.053)	(0.021)	(0.001)	(0.023)	(0.037)
dependency	−0.022*	−0.007	−0.064***	0.011***	0.000
	(0.012)	(0.024)	(0.000)	(0.004)	(0.012)
Constant	−10.585***			−6.248***	−76.155***
	(2.853)			(0.936)	(11.416)
N	794	650	940	940	941
AR(1)p	0.0018	0.0000			
AR(2)p	0.96	0.94			

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

A.7. Double machine learning

The curse of dimensionality and multicollinearity problems of traditional regression models have the potential to affect the accuracy of the estimators. In this section, we refer to dual machine learning (Chernozhukov et al., 2018), avoid the curse of dimensionality caused by redundancy of control variables and mitigate the problem of biased estimation due to limited control variables. Variables are affected by many economic and social factors, conventional regression may bring about a biased model setting. Dual machine learning avoids the problem of model misspecification by virtue of the advantages of machine learning algorithms in handling nonlinear data (Yang et al., 2020a). The dual machine learning model is used to estimate the effect of BRI countries' infrastructure on innovation performance, the sample split ratio is 1:3, and the regression results are shown in Table A3. Column (1) of Table A3 shows the results after controlling for city fixed effects, time fixed effects, and both linear and quadratic terms of the control variables over the full sample period. It can be found that the regression coefficients of the effect of BRI countries' infrastructure development on innovation performance are positive at the significant at the 1 % level, indicating that the baseline results are robust.

To eliminate dual machine learning model setting bias from influencing conclusions, we continue the regression based on Column (1) of Table A3. We change the ratio of sample division from 1:3 to 1:5, Column (2) shows the result. Then, we change the machine learning algorithms, replacing the previous prediction algorithms with LASSO, gradient descent and neural networks. It explores the possible effects of the algorithms on the conclusions of this paper. Column (3) to Column (5) of Table A3 show the results. Overall, the proportion of samples split in the dual machine learning model, the machine learning algorithm used for prediction and the form of model estimation will not affect our conclusions. They only change the size of the innovation promotion effect to some extent, suggesting that the conclusion is robust.

Table A3
Robustness Test V: double machine learning.

	(1) 1:3	(2) 1:5	(3) *Lasso*	(4) *Gradient Descent*	(5) *Neural Network*
infra	0.539***	0.326***	0.380***	0.819***	0.756***
	(0.129)	(0.048)	(0.055)	(0.137)	(0.111)
Constant	0.019	−0.004	0.014	0.010	−0.027
	(0.061)	(0.025)	(0.026)	(0.033)	(0.054)
N	941	941	941	941	941
Linear term	Yes	Yes	Yes	Yes	Yes
Quadratic term	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

A.8. *Sample period division*

The impact of infrastructure development on national innovation development is a slow process. The innovation performance is not instantaneously adjusted after national infrastructure development, there may be a time lag. In order to reduce the impact of this bias on the regression results, we draw on the sample period division method (Trefler, 1993, 2004; Baier and Bergstrand, 2007; Anderson and Yotov, 2016). We re-regress the sample using three different sample interval division methods (3-, 4- and 5-year). The corresponding regression results are shown in Table A4. The regression coefficients of all division methods are significantly positive, and the trend of the relative size of the regression coefficients is consistent with the results of the baseline regression. This shows that the impact of BRI countries' infrastructure development on innovation performance is basically independent of the sample interval. The regression results are still robust even after considering the lag of infrastructure development.

Table A4
Robustness Test VI: sample period division.

	(1) 3-year	(2) 4-year	(3) 5-year
Infra	0.376***	0.463***	0.384**
	(0.121)	(0.157)	(0.174)
Lnpopu	5.021***	5.964***	6.121***
	(1.043)	(1.440)	(1.629)
lngdp_per	0.167	0.311	0.578
	(0.234)	(0.337)	(0.408)
Lnfdi	0.101*	0.014	0.073
	(0.051)	(0.098)	(0.098)
dependency	0.001	0.016	0.016
	(0.018)	(0.025)	(0.028)
Constant	−80.041***	−95.784***	−101.856***
	(18.309)	(25.401)	(29.132)
N	468	317	229
R2_Adjusted	0.9257	0.9076	0.9159

Appendix B. Channels of external debt for innovation

In this section, we examine how external debt contributes to innovation in BRI countries, focusing on capital access, innovation inputs and main innovators. The corresponding regression results are shown in Table B1. From the perspective of capital access, the inflow of external debt can facilitate the establishment and enhancement of credit information systems, guarantee mechanisms, and financing platforms in BRI countries. To quantify this effect, we use the *Getting Credit Total Score* in *Doing Business* as the indicator (*Getting Credit*). By optimizing the credit access environment, external debt can create more convenient financing channels, provide long-term and low-cost financial support, thereby alleviating the challenges associated with enterprise financing. This improved access to financial resources particularly benefits innovative enterprises, especially start-ups and high-tech firms. This will enable them to secure the necessary funding to advance technological research and development, and product and business model innovation.

In terms of innovation inputs, as external debt increases, the BRI countries' financial situation improves, enabling both enterprises and governments to allocate more resources toward technical cooperation and licensing agreements with multinational companies. External debt funds can be utilized to cover licensing fees for technical cooperation, patent royalties, and other related costs. We use payments of Charges for the use of intellectual property as the indicator (*IP_payments*). By investing in the use of intellectual property rights, countries can acquire foreign innovations and advanced technologies, thereby promoting the technological innovation and product development of local enterprises. The sharing or licensing of intellectual property rights facilitates technological progress within domestic firms, helping them achieve innovation catch-up. Furthermore, a robust intellectual property protection environment incentivizes enterprises to engage more actively in research, development, and innovation activities, fostering a sustainable cycle of technological advancement.

From the perspective of main innovators, external debt financing in developing countries is often directed toward manufacturing development that incorporates innovation (Yang et al., 2020b). Manufacturing enterprises are the main innovators in technological advancement. We use Manufacturing value added (% of GDP) as the indicator (*Manu_*). The inflow of external debt financing enables manufacturing enterprises in BRI countries to acquire the latest global technologies, thereby increasing product value addition and improving profitability. With enhanced financial resources, enterprises are better positioned to invest in research and development, thereby advancing the innovation and development of the manufacturing sector, facilitating a country's progress toward innovation catching-up development. Moreover, external debt can also be strategically utilized to attract high value-added industries, such as precision manufacturing, intelligent equipment production, and high-end materials. This further boosts the value-added component of the manufacturing sector and fosters the country's overall innovative development.

Table B1
Channels of external debt for innovation.

	(1) *Getting Credit*	(2) *IP_payments*	(3) *Manu_*
lndebt_t	1.426***	0.780***	0.900***
	(0.321)	(0.202)	(0.252)
Constant	−70.535**	8.929	1.259
	(31.465)	(19.261)	(23.453)
N	1002	856	1047
R2	0.387	0.080	0.028
Controls	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
F	37.28	4.070	1.691

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

Appendix C. Heterogeneity analysis

In this section, we proceed to examine the heterogeneous impacts of infrastructure across various dimensions, including different infrastructure types and country types.

C.1. Heterogeneous effects by infrastructure types

Differences in the extent to which innovation performance is enhanced by different types of infrastructure development (Shahbaz et al., 2021), with transport, financial, and ICT infrastructures demonstrating distinct characteristics. The regression results for the respective sub-samples of infrastructure are reported in Table C1. The impact of specific types of infrastructure on innovation performance varies significantly. Our analysis indicates that transport infrastructure development has the most significant facilitating effect, followed by ICT infrastructure, while finance infrastructure has not temporarily.

This may be because most of the BRI countries are developing countries. Due to their development stages, conditions, environment and goals, they rely more on transport and ICT infrastructure to promote innovation, which are more fundamental. An efficient transport system is crucial for facilitating the free flow of resources between districts and optimizing economic spatial patterns. This can significantly reduce transport costs for enterprises and improve efficiency (Egger et al., 2023). It drives the agglomeration of innovative resources and the diffusion of knowledge and technology, ultimately enhancing regional innovation and generating spillover effects. This creates a crucial foundation for developing and applying basic science and technology, thereby promoting national innovation. In terms of ICT infrastructure development, including the Internet, communication networks, and the Internet of Things, it accelerates information transmission (Wernsdorf et al., 2022). Widespread adoption of ICT infrastructure helps countries reduce information search costs, and subsequently enhances innovation efficiency (Acharya et al., 2022). Particularly, high-tech industries are sensitive to advancements in ICT infrastructure and information technology. The development level of a country's ICT infrastructure significantly impacts the innovation capacity of high-tech industries (Forman and Zeebroeck, 2019).

Lots of developing countries have low levels of financial market development, they can not take full advantage of the dividends of improved finance infrastructure, which is not the main way to promote their innovation. Compared to developed countries, developing countries lag in financial market development at this stage. Evident financial discrimination exists (Broz et al., 2020). In promoting scientific and technological innovation, most BRI countries face issues such as uncertainty of returns, adverse selection, and moral hazard. These challenges may undermine the role of financial infrastructure in promoting scientific and technological innovation. These results provide empirical support for the first hypothesis (H1).

Table C1
Heterogeneity Test I: infrastructure type.

	(1)	(2)	(3)	(4)
Infra	0.334***			
	(0.081)			
infra-finance		0.090		
		(0.100)		
infra-transport			0.186***	
			(0.055)	
infra-ICT				0.142***
				(0.041)
Constant	−79.979***	−85.213***	−83.126***	−82.186***
	(13.094)	(13.183)	(13.086)	(13.101)
N	941	941	941	941
R2	0.116	0.098	0.110	0.110
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
F	6.707	5.578	6.302	6.340

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

C.2. Heterogeneous effects across countries

C.2.1. Income groups

For middle-income countries, infrastructure construction projects are in line with their needs to promote industrialization and economic transformation. Most of these countries are at a critical stage of upgrading their industrial structure (Xie et al., 2023). For this analysis, we categorize the sample into four income groups according to the World Bank's classification criteria. The results of the grouped regressions are presented in Table C2. It reveals that the positive influence of infrastructure on innovation performance is predominantly observed within upper-middle and lower-middle-income countries. This may be ascribed to the fact that high-income countries already have a high level of infrastructure development and industrialization, the infrastructure development is not significant for them. The low-income countries are still in the initial stage of establishing infrastructure, with insufficient accumulation of basic innovation and learning capacity. It is difficult to transform the optimization of resource allocation brought about by infrastructure development into innovation capacity. Therefore, the contribution of infrastructure to their innovations is also limited.

Table C2
Heterogeneity Test III: income groups.

	(1) High	(2) Upper-Middle	(3) Lower-Middle	(4) Low
Infra	0.105	0.429***	0.643***	−0.594
	(0.207)	(0.102)	(0.186)	(3.185)
Constant	−113.733***	−108.939***	−5.596	42.796
	(29.813)	(20.969)	(26.761)	(145.046)
N	280	328	258	70
R2	0.192	0.274	0.109	0.246
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
F	3.404	6.310	1.555	0.815

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

C.2.2. Economic freedom and government effectiveness

The development of infrastructure projects exhibits notable disparities across countries with different economic freedom levels. We partition the complete sample into high economic freedom and low economic freedom in accordance with The Heritage Foundation's *Index of Economic Freedom*, using the sample median as the delineation point. This indicator measures the degree of marketisation of the country, i.e. the higher the degree of government non-interference or protection of free competition and markets within the constitutional boundaries, the higher the index. The regression results for the samples are reported in Columns (1) and (2) of Table C3. It shows that the positive impact of infrastructure on innovation performance is mainly concentrated among countries with lower economic freedom, while it is not significant in countries with higher levels. The possible reason is that countries with high economic freedom have more paths to achieve innovation. They can achieve innovation through market cooperation, capital utilization, cultural cultivation, and institutional innovation, relying less on the innovation-promoting effect of infrastructure. It is also possible that the market mechanism of the backward countries is not mature. In the early stage of national development, affected by the special attributes of infrastructure construction, the governments of backward countries have to intervene in infrastructure construction for economic development considerations (Acharya et al., 2022). The stronger the state intervention, the more it can control the direction of infrastructure development, and the easier it is to promote a country's innovation directionally and purposefully.

In addition, the quality of government public services and the capacity for policy formulation and implementation differ among countries with different levels of government efficiency (Kaufmann et al., 2011). The government can provide a strong institutional guarantee for the implementation of infrastructure projects, reduce various uncertainties in projects to promote innovation performance. Considering this, the present study segments the sample based on government effectiveness levels, utilizing the *Government Effectiveness* sub-index of *the Worldwide Governance Indicator*. The sample is bifurcated into a "High level of Government Effectiveness" group and a "Low level of Government Effectiveness" group, using the sample median as the delineation point. The regression outcomes are displayed in Columns (3) and (4) of Table C3, reveal that in regions with a higher degree of government effectiveness, the impact of infrastructure on countries' innovation performance is more pronounced. In countries characterized by high government effectiveness, governments, officials, enterprises and consumer awareness regarding innovation are more potent forces, thus driving countries to bolster their innovation performance. Countries with high government efficiency have higher levels of synergy and collaboration between central and local institutions in cross-sectoral development. They can support the translation of the benefits of infrastructure development into innovation. In addition, countries with less efficient governments have more institutional barriers and fewer dynamic innovation agents, makes it difficult to develop a virtuous innovation ecosystem.

Table C3
Heterogeneity Test IV: economic freedom and government effectiveness groups.

	(1) Economic Freedom	(2)	(3) Government Effectiveness	(4)
	High	Low	High	Low
infra	0.161	0.348***	0.295***	0.766
	(0.181)	(0.085)	(0.088)	(0.468)
Constant	−94.487***	−24.198	−92.057***	−80.729***
	(16.310)	(29.188)	(17.399)	(22.513)
N	625	316	633	308
R2	0.142	0.152	0.136	0.126
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
F	5.267	2.780	5.295	2.189

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

C.2.3. Creditor countries

Over the past two decades, China has become one of the largest creditors among the low- and middle-income countries. Compared with traditional creditors such as the United States, China is mainly invested in infrastructure projects, such as communications and transport. The United States invests more in education and health care, social expenditures and commercial finance. This section compares the external lending of the two creditors, China and the United States. Columns (1) to (6) of Table C4 show the results of the ratio of the BRI countries' external debt from China and the United States to their total external debt.

As shown in Table C4, empirical results find that the innovation promotion of infrastructure is more significant when the countries borrow more from China than from the US, and this effect holds for total, long- and short-term external debt. China's external debt has proven to be particularly effective in fostering the innovation development of the BRI countries, primarily due to its rational allocation of funds, adaptable cooperation models, cost-effective financing, a strong emphasis on technical collaboration and flexible debt management strategies.[4] It can be inferred that Chinese loans have the advantages of large capital size, capital patience, and stable capital flows, cooperation with the debtor countries adheres to the principle of non-interference in internal affairs, with fewer conditions attached (Hernandez, 2017). The short-term debt structure of BRI countries can be analyzed using short-term external debt data from China and the United States. Columns (5) and (6) of Table C4 show the results. Compared to China, the proportion of short-term debt relative to the United States is relatively high. In these countries, the innovation-enhancing effect of infrastructure development appears to be insignificant. Moreover, In the corporation between China and other BRI countries, the status gap between the supply

[4] There are some cases in Pakistan, Kenya, Bangladesh and other BRI countries in recent years. These cases demonstrate that China's external debt holds distinct advantages in advancing infrastructure development and fostering innovative growth in BRI countries, particularly through its emphasis on long-term infrastructure investments, technology transfer, and mutually beneficial partnerships. In contrast, U.S. foreign debt tends to prioritize short-term financial aid and policy-driven reforms. While such assistance addresses certain social challenges, its impact on infrastructure development and technological innovation remains comparatively limited.

and demand of funds and the interest conflict is smaller. Most of China's loans are invested in BRI countries' infrastructure projects, contributing to their abilities to create fixed assets and improve repayment capacities. The repayment pressure caused by Chinese loans is affordable for debtor countries and can bring innovation performance of infrastructure, which will help the BRI countries enhance their international competitiveness and realize catching-up development.

Table C4
Creditor countries.

	(1) Total	(2)	(3) Long-term	(4)	(5) Short-term	(6)
	CHN>USA	USA>CHN	CHN>USA	USA>CHN	CHN>USA	USA>CHN
Infra	1.018***	0.670	1.018***	0.670	0.897***	0.216
	(0.205)	(0.696)	(0.205)	(0.696)	(0.312)	(1.021)
Constant	−200.081***	−62.393***	−200.081***	−62.393***	−256.618***	−187.310***
	(24.054)	(23.932)	(24.054)	(23.932)	(59.064)	(37.305)
N	352	224	352	224	91	166
R2	0.338	0.115	0.338	0.115	0.636	0.274
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
F	9.228	1.356	9.228	1.356	6.123	2.785

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

The previous section analyzes the distinct effects of China and the United States as creditors by examining the impact of their funds on the innovation effects of infrastructure development in BRI countries. In the following section, we further investigate the innovation effects of infrastructure development resulting from funds lent by the General Government Sector and the Public Sector in both countries. Columns (1) to (4) of Table C5 show the results of the ratio of the countries' external debt from China and the United States's general government sector to their total external debt from the general government sector.[5] Columns (5) to (8) of Table C5 show the results of the ratio of the countries' external debt from China and the United States's public sector to their total external debt from the public sector. The results indicate that, compared to from the United States, a greater number of BRI countries are relatively more dependent on external debt from China's public and general government sectors, with more pronounced innovation-promoting effects of their infrastructure development.

Table C5
Creditor countries' sectors.

	(1) General Government NFL	(2)	(3) General Government DOD	(4)	(5) Public Sector NFL	(6)	(7) Public Sector DOD	(8
	CHN>USA	USA>CHN	CHN>USA	USA>CHN	CHN>USA	USA>CHN	CHN>USA	USA>CHN
infra	0.882***	1.503*	1.102***	0.063	0.912***	0.969	1.010***	0.881
	(0.172)	(0.851)	(0.193)	(0.734)	(0.179)	(0.715)	(0.206)	(0.664)
Constant	−119.872***	−120.763***	−204.114***	−55.426**	−117.305***	−141.311***	−200.033***	−60.951**
	(19.948)	(38.584)	(27.350)	(25.249)	(19.602)	(33.206)	(24.106)	(23.902)
N	328	204	318	229	328	229	348	225
R2	0.298	0.133	0.344	0.084	0.311	0.176	0.338	0.114
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
F	7.084	1.335	8.528	0.978	7.485	2.128	9.168	1.353

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

[5] Due to the more severe data gaps in other creditor components, this section conducts heterogeneity tests exclusively for these two sectors. General government sector comprises long-term external obligations of public debtors, including the national government of all levels, and political subdivisions (or an agency of either). Public sector conveys information about the distribution of long-term debt for DRS countries by type of debtor (central government, state and local government, central bank, public and mixed enterprises, and official development banks). DOD means external debt stock, and NFL means external debt net flows.

C.2.4. Debt management capacity

Debt management capacity has been shown to moderate the relationship between infrastructure development and innovation, enhancing the innovation-promoting effect when adequately managed. In this section, we continue to test for heterogeneous effects of debt management ability.[6] International definitions of national debt management capacity indicators vary according to country-specific conditions. Therefore, we adopt international practice as a benchmark for the group test. In general, it is considered reasonable to maintain the ratio of short-term external debt to total external debt below 25 % and the ratio of short-term external debt to international reserves below 50 %, as this reflects a higher level of national debt management capacity. Accordingly, we conduct a heterogeneity test based on the *debt_se* and *debt_sr* variables, with the results presented in Table C6. The findings indicate that when the ratio of short-term external debt to total external debt is high, the innovation effect of infrastructure construction is more pronounced. Similarly, the innovation impact of infrastructure development is primarily concentrated in countries with a lower ratio of short-term external debt to foreign exchange reserves. As shown in Table C6, even when national debt management capacity is relatively low, infrastructure development does not result in diminished innovation capacity.

Table C6
Debt management capacity.

	(1) *debt_se*>25 %	(2) *debt_se*<25 %	(3) *debt_sr*>50 %	(4) *debt_sr*<50 %
Infra	0.236**	0.864***	0.120	0.404***
	(0.092)	(0.181)	(0.167)	(0.093)
Constant	−43.148**	−108.631***	−56.653***	−99.390***
	(20.198)	(17.634)	(17.141)	(21.346)
N	426	515	532	409
R2	0.137	0.193	0.125	0.180
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
F	3.527	6.424	3.956	4.557

Note: Robust standard errors in parentheses. *** denotes significance at 1 %, ** at 5 %, and * at 10 %.

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[6] Regarding the *cpia* variable, which employs a scoring system ranging from 1 (low) to 6 (high), we use 2 and 3 points as baselines for analysis. Testing the *cpia* sample data reveals that only 181 samples have scores below 3, and 74 samples have scores of 2 or lower, with a sample mean of 3.37. This indicates that most BRI countries exhibit a high level of debt policy sustainability in our sample. Given that a single variable may not comprehensively capture the strength or weakness of debt management capacity, this study utilizes three variables to represent debt management capacity. Considering the limitations of sample size and variable testing, we conduct a heterogeneity test solely on the *debt_se* and *debt_sr* variables to assess the situation of countries with relatively weaker debt management capacity. Furthermore, due to inconsistencies in the current measurement of countries experiencing debt crises, this study does not specifically examine whether countries with weaker debt management capacity are prone to falling into debt crises as a result of utilizing external debt for infrastructure development.

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