2 Global good practices for infrastructure resilience to natural disasters

Ensuring infrastructure resilience to natural disasters is highly context-specific, but some universal principles apply. Based on global good practices, this chapter presents seven guiding principles for enhancing infrastructure resilience to natural disasters. It discusses why and how to: i) Adopt a life cycle approach, factoring in resilience throughout the entire lifespan of projects from planning and design to operation and maintenance; ii) Align interests through effective collaboration among stakeholders to ensure collective action towards resilience goals; iii) Conduct comprehensive risk assessments to identify vulnerabilities and develop robust mitigation strategies; iv) Measure impacts to understand the consequences of natural disasters and guide informed decision making; v) Invest in capacity building and knowledge management to empower individuals and organisations with the skills and information needed to plan, implement and operate resilient infrastructure; vi) Carry out strategic preventive maintenance; and vii) Deploy cutting-edge technology and fostering innovation in design to enhance infrastructure resilience and adaptability to changing environmental conditions.

Introduction

Infrastructure development in emerging and developing economies should ensure higher levels of economic efficiency and local socio-economic empowerment to achieve national development visions. It should aim to reduce poverty, income and gender inequality, and social exclusion, while improving labour productivity and competitiveness as well as ensuring environmental and social safeguards (OECD/CAF/ECLAC, 2013[1]; Ministry of Foreign Affairs Japan, 2016[2]). To this end, G20 members formulated the Roadmap to Infrastructure as an Asset Class under Argentina's 2018 presidency, and endorsed the G20 Principles for Quality Infrastructure Investment under Japan's 2019 presidency (G20, 2019[3]; OECD, 2020[4]; OECD, 2021[5]) (Box 2.1).

Box 2.1. The G20 Principles on Quality Infrastructure

Quality infrastructure has been widely recognised as key to achieving sustainable, resilient and inclusive growth. In the 2030 Agenda for Sustainable Development, SDG no. 9 on Industry, Innovation and Infrastructure calls for the development of "quality, reliable, sustainable and resilient infrastructure, including regional and cross-border infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all". Quality infrastructure contributes to the achievement of other goals envisaged in the 2030 Agenda for Sustainable Development. Improved infrastructure services can result in lower inequalities and greater inclusion (SDGs no. 5 and 10), improved well-being (SDG no. 3), increased access to clean water and sanitation (SDG no. 6) as well as to jobs and education (SDGs no. 4 and 8), and more resilient and sustainable cities (SDG no. 11). Moreover, quality infrastructure can contribute to poverty reduction (SDG no. 1) while also meeting environmental goals (SDGs no. 13, 14 and 15).

Various global fora in addition to the G20 have recently recognised the importance of, and contributed to the definition of, quality infrastructure. In 2016, the G7 summit in Ise-Shima, Japan endorsed the *Principles for Promoting Quality Infrastructure Investment.* The significance of investing in quality infrastructure with open, fair access and responsible financing was also confirmed at the G7 Charlevoix Summit in Canada in June 2018. The G7 under the Japanese Presidency also reinforced the importance of quality infrastructure in the G7 Hiroshima Leaders' Communiqué in 2023 (G7, 2023[6]).

The G20 Principles for Quality Infrastructure Investment are to:

1. Maximise the positive impact of infrastructure to achieve sustainable growth and development
2. Raise economic efficiency in view of life-cycle cost
3. Integrate environmental considerations in infrastructure investments
4. Build resilience against natural disasters and other risks
5. Integrate social considerations in infrastructure investments
6. Strengthen infrastructure governance

Source: (UNDP, 2018[7]), (G7, 2018[8]) and (G7, 2016[9]).

Ensuring infrastructure resilience to natural disasters is highly context-specific. However, some general principles apply and when implemented they can increase the effectiveness and the efficiency of prevention, reaction and re-building efforts.

This chapter presents seven guiding principles for making infrastructure resilient to natural disasters. These principles are based on the case studies discussed in detail in Chapter 3 of this report, and on the expert and peer-review process implemented in the framework of the preparatory works of the 2024 edition of the *Compendium of Good Practices on Quality Infrastructure*. The seven principles are not intended to be exhaustive, and they are all of equal importance and interrelated.

Each guiding principle is presented following a similar structure:

- the rationale and the associated benefits and/or costs of non-aligned action
- the enabling conditions for implementation, associated with a clarification of the specific challenges and needs in the specific case of developing countries
- good practices for implementation.

Each section concludes with a short box referring to how the principle has been implemented in a specific case. Although each box associates one case study with one of the guiding principles, all the case studies can be associated with most of the identified principles. The association of a case study with a guiding principle has been made based on the most prominent feature of each case study.

The seven guiding principles are:

- adopting a life cycle approach
- ensuring interests' alignment through effective collaboration
- conducting risk assessment
- measuring impacts
- investing in capacity building and knowledge management
- carrying out strategic preventive maintenance
- deploying cutting-edge technology and fostering new design and innovation.

Adopting a life cycle approach

The life cycle approach in infrastructure refers to a comprehensive perspective that considers from the outset that each infrastructure project encompasses multiple phases, from planning and design to construction, operation, maintenance, and eventual decommissioning or renovation.

This approach recognises that infrastructure assets have long life spans and undergo various phases throughout their life cycle, each of which presents unique challenges and opportunities. The life cycle approach matters because it enables stakeholders to make informed decisions that optimise the performance, resilience and sustainability of infrastructure assets over their entire lifespan.

This approach is essential for effective infrastructure planning – which includes project preparation and design – and it is a precondition to ensure infrastructure's resilience to natural disasters. It allows identifying from the outset the interdependencies between the different phases and to effectively plan and invest by minimising costs and maximising efficiency. A decision taken during the construction phase can lead to changes in the operation and maintenance phases. For example, roads constructed with durable materials to withstand stress changes, might require less frequent but more comprehensive maintenance. Roads in flood-prone areas can incorporate adapted design features such as single-lane raised roads (another decision and action implemented during the construction phase) that will impact reaction capacities and change operations during emergency responses. To ensure that infrastructure is planned, designed, constructed, operated, maintained and renovated or repurposed in a way that makes it resilient to natural disasters, the life cycle approach matters because it enables:

- **Integrated risk management.** By considering the entire life cycle of infrastructure, planners can integrate risk management strategies at each stage, from design to maintenance. This includes identifying potential hazards, assessing vulnerabilities and implementing appropriate mitigation measures to prevent or minimise the impact of natural disasters.

- **Resilience enhancement.** Infrastructure designed with a life cycle approach can incorporate resilience features at the outset and in all phases to enhance its ability to withstand natural disasters. For example, incorporating robust materials, appropriate construction techniques, and disaster-resistant designs during the planning phase can significantly reduce the vulnerability of infrastructure to various hazards.
- **Adaptive capacity.** Planning with a life cycle approach allows for the integration of adaptive measures that enable infrastructure to respond effectively to changing environmental conditions and evolving disaster risks over time. This flexibility ensures that infrastructure remains resilient and adaptable in the face of emerging challenges.
- **Cost savings and sustainable investment.** Taking a life cycle approach in planning infrastructure projects allows for more efficient allocation of resources. It enables the identification of cost-effective solutions that provide optimal performance and functionality throughout the asset's lifespan. Investments made upfront in resilience measures, such as hazard-resistant construction and proactive maintenance, result in long-term cost savings by reducing the need for expensive repairs and reconstruction in the aftermath of natural disasters and by ensuring operations or minimising disruptions in the aftermath of a natural hazard.

It is of utmost importance to carry out a life-cycle cost analysis in the planning phase. Implementing a life cycle approach necessitates conducting comprehensive life-cycle cost analysis during the project planning phase. This analysis should encompass not only initial construction expenses but also ongoing maintenance, operation and end-of-life costs to determine the most cost-effective solutions. To ensure that the life-cycle cost analysis in the planning phase is carried out, targeted policies and, in certain cases, regulations, are needed. In particular, these policies and regulations might include:

- Incentives, in the form of direct and indirect financial support to projects that embrace a life cycle approach. These incentives should direct developers to prioritise sustainability and long-term benefits over short-term gains.
- Environmental impact assessments to evaluate the potential environmental consequences of infrastructure projects throughout their life cycle. This includes assessing resource usage, emissions, and potential habitat disruptions.
- Development and implementation of systems to collect, manage and share life-cycle data. Access to comprehensive data facilitates informed decision making and future improvements.

Developing countries encounter more pronounced challenges than advanced economies in implementing a life cycle approach in infrastructure planning, due to several factors, including:

- **Limited resources.** Developing countries often have constrained financial, technical and human resources, making it difficult to conduct comprehensive life-cycle cost analyses or invest in long-term infrastructure solutions.
- **Capacity constraints.** Developing countries may lack the technical expertise and institutional capacity required to perform robust life-cycle assessments, collect relevant data, and make informed decisions throughout the infrastructure life cycle.
- **Short-term focus.** Developing countries may be under pressure to prioritise short-term economic considerations over long-term sustainability and resilience, leading to infrastructure projects that prioritise initial competitive construction costs rather than considering long-term life-cycle costs.
- **Regulatory and institutional constraints.** In several cases, developing countries lack the necessary regulatory and institutional framework for implementing a life cycle approach and integrating resilience at the outset in the infrastructure planning phase.

In addition to a mindset shift in infrastructure planning in developing countries towards infrastructure as a strategic asset rather than a cash-cow, international partnerships emerge as pivotal to overcome these challenges and support developing countries' uptake of a life cycle approach in infrastructure to ensure resilience to natural disasters. In particular, international partnerships can contribute to:

- Increase public awareness and stakeholder engagement. Raising awareness among policy makers, stakeholders and the public about the importance of a life cycle approach in infrastructure planning is essential to ensure buy-in and support for long-term infrastructure investments.
- Update the regulatory frameworks, and national and local policies to mandate the adoption of a life cycle approach in infrastructure planning and development, taking into account each country's specificities, and historical and geographical context.
- Invest in capacity building initiatives to enhance technical skills and institutional capacity in life-cycle analysis, data collection and decision-making processes related to infrastructure planning.
- Foster knowledge sharing and peer dialogue. Partnerships and collaborations with international organisations, development agencies and advanced countries to share best practices, knowledge, and experiences in implementing life cycle approaches in infrastructure planning contribute to foster advancements in developing countries and enable the co-development of new practices in the current fast evolving global landscape.
- Explore innovative financing mechanisms, such as public-private partnerships, green bonds or impact investment funds, to mobilise resources for sustainable infrastructure projects with a focus on life-cycle considerations (ITF, 2018[10]).

By addressing these challenges and implementing appropriate strategies thanks to supportive international partnerships, developing countries can enhance their capacity to adopt a life cycle approach in infrastructure planning and contribute to building more sustainable and resilient infrastructure systems.

Box 2.2. India has adopted a life cycle approach to infrastructure which resulted in increased resilience to natural disasters in its highway projects

India has implemented measures to ensure its highway projects are resilient to natural disasters at all stages of the process, from planning and design through construction, operation, maintenance, to end-of-life. In the planning phase, a risk assessment has been conducted for all the lifespan of assets. During the planning stage, India has conducted detailed studies of an area's topology, geography and hydrology to avoid higher-risk areas or ensure that mitigation systems can effectively match the risks. Additionally, disaster exposure mapping (e.g. earthquakes) has been utilised to determine which areas require specific levels of investment in different disaster mitigation features.

During the construction phase, India has opted for tailored structural features such as flexible pavements, reinforced embankments, retaining walls and proper drainage systems. The country has also incentivised the use of high-quality and tested materials, such as high-strength concrete, to ensure the durability and resilience of its highway projects.

India mandates regular preventive maintenance and inspections to uphold the integrity of the infrastructure assets. Disaster management plans are established, outlining response measures and evacuation routes in advance to expedite emergency response efforts. Additionally, India has implemented an automatic traffic management system to assist emergency responders in acting more quickly during natural disasters.

Source: Case study "Increasing connectivity and preserving the environment through sustainable highways in India" in Chapter 3 – Making infrastructure resilient to natural disasters: Learning from concrete projects in Africa, Asia, Latin America and the OECD.

Ensuring interests' alignment through effective collaboration

Effective collaboration among multiple stakeholders is essential to prevent, react and rebuild infrastructure. Effective collaboration refers to domestic and international efforts. Effective collaboration results in faster, more equitable and improved actions deriving from interests' alignment (OECD, 2024[11]). It ultimately helps to foster financial risk-sharing among various public and private entities across sectors and countries affected by the impacts of natural disasters and it enhances project efficiency by facilitating knowledge exchange among these entities. It also contributes to project equity by allowing to consider everybody's perspective. By engaging with a diverse range of stakeholders, collaboration brings together varying perspectives, expertise and resources, leading to a more comprehensive understanding of challenges and a more effective response. Collaboration contributes to:

- **Increasing government, civil society, and private sector awareness and know-how.** Effective collaboration builds the knowledge base for government actions and public-private partnerships and increases the collective response capacity to prevent and mitigate the impacts of natural disasters. Infrastructure systems are interconnected, and disruptions in one sector can have cascading effects on others. Collaborative efforts ensure a holistic approach that considers the interdependencies and interactions between different systems, thereby reducing vulnerability and enhancing overall resilience.
- **Cost and implementation sharing.** Effective collaboration allows for efficient division of labour in implementation as well as cost-sharing and funding pooling across multiple actors, ultimately resulting in increased cost effectiveness. Collaboration also facilitates a better distribution of risks, thereby reducing capital costs.
- **Leveraging diverse expertise.** By pooling together diverse skill sets, knowledge and preferences, collaboration enhances the effectiveness of disaster response and resilience-building efforts. Various stakeholders, including governments, private sector entities, community groups and non-governmental organisations, offer unique insights into local needs and priorities. Collaborating with these stakeholders ensures that resilience strategies are inclusive and address social equity issues, as well as the needs of the concerned communities. Collaboration also facilitates more comprehensive scenario planning and risk management strategies, aiding in the identification of potential vulnerabilities and areas requiring greater attention to enhance infrastructure resilience.

Collaboration yields numerous benefits in terms of cost reduction, increased financing and social acceptance, thereby averting delays and cost overruns. Resilient infrastructure often necessitates substantial financial investments, technical expertise and operational capabilities. Collaboration enables the pooling of resources, sharing of best practices, and tapping into the expertise of multiple parties, leading to more efficient and cost-effective solutions.

To align interests and achieve effective collaboration for infrastructure resilient to natural disasters, the following actions are of pivotal importance. In particular, it is important to act in the prevention phase, as these practices need to be already in place and operational before the reaction and rebuilding phase, as they will be crucial for effective response to natural disasters:

- **Developing a common vision focused on long-term sustainability.** Work together to develop a shared vision for resilient infrastructure that aligns with the goals and priorities of all stakeholders. This common vision can serve as a guiding framework for collaborative efforts and decision making. Emphasise the importance of long-term thinking and investment in resilience over short-term gains. Prioritise strategies and initiatives that promote the sustainability and effectiveness of resilient infrastructure in the face of evolving challenges.
- **Establishing clear communication channels.** Ensure open and transparent communication among stakeholders to foster trust and understanding. Regular updates, meetings and feedback mechanisms can help maintain clear communication channels.

- **Building trust among stakeholders.** Foster trust through transparent decision-making processes, equitable representation and mutual respect for diverse perspectives. Building relationships based on trust can help overcome competing interests and conflicts.
- **Establishing clear governance mechanisms.** Define clear decision-making structures and governance mechanisms that ensure equitable participation and representation of all stakeholders. It is important to establish fair rules for funding allocation and knowledge-sharing can promote collaboration and mitigate governance challenges. It is also necessary to define clear institutional responsibilities and inter-institutional collaboration mechanisms, as well as establishing mechanisms for co-ordination between the national and local government levels (OECD, 2024[12]; SNG-WOFI, 2022[13]).
- **Establishing multi-stakeholder partnerships.** Developing countries can create multi-stakeholder partnerships involving government agencies, local communities, private sector entities, non-governmental organisations (NGOs) and international organisations. These partnerships enable diverse stakeholders to contribute their expertise, resources and perspectives to resilience-building efforts.
- **Incentivising collaboration through policy measures.** Governments can incentivise collaboration for resilience building through policy measures such as tax incentives, grants and subsidies for collaborative projects and initiatives. Policy frameworks that encourage public-private partnerships (PPPs) and cross-sectoral collaboration can facilitate the pooling of resources and expertise for infrastructure resilience.
- **Engaging local communities.** Engaging local communities in resilience-building efforts is crucial for ensuring that infrastructure projects meet the needs and priorities of the people they serve. Community participation in decision-making processes, project planning and implementation can enhance the relevance, effectiveness and sustainability of resilience initiatives.

Four issues challenge collaboration in resilient infrastructure projects, and are of particular relevance in the case of developing countries:

- **Competing interests.** Different stakeholders may have divergent interests, priorities and objectives regarding infrastructure development, leading to conflicts and difficulties in finding common ground for collaboration.
- **Resource constraints.** Building resilient infrastructure often requires substantial financial resources, technical expertise and data. Limited resources among collaborating parties can hinder the implementation of collaborative initiatives.
- **Governance and institutional challenges.** In multi-stakeholder collaborations, decision-making structures and governance mechanisms may not be well-defined or agreed upon. This ambiguity can slow down the decision-making process and create uncertainties.
- **Short-term thinking.** Resilient infrastructure requires a long-term perspective, but some stakeholders might prioritise short-term gains over investing in resilience, potentially overlooking the importance of long-term sustainability and effectiveness.

To address these gaps, international partnerships are essential in particular for:

- **Promoting information sharing and knowledge exchange.** Governments and organisations in developing countries can facilitate information sharing and knowledge exchange platforms focused on resilience building. These platforms can include workshops, conferences, webinars and online portals where stakeholders can share best practices, lessons learned, and innovative solutions for infrastructure resilience.
- **Enhancing capacity building.** Capacity building programmes can be implemented to enhance the technical skills and knowledge of stakeholders involved in infrastructure development and disaster risk management. This includes training programmes, workshops and educational

initiatives aimed at improving understanding of resilience concepts, risk assessment methodologies and effective mitigation strategies.

- **Leveraging international support and funding.** Developing countries can leverage international support and funding mechanisms provided by donor agencies, multilateral development banks, and other international organisations. Collaborative projects funded by international donors can support the development of resilient infrastructure and provide opportunities for knowledge transfer and technology exchange.
- **Promoting South-South co-operation.** Developing countries can benefit from South-South co-operation initiatives, where countries with similar development challenges share experiences, expertise and resources to support each other's resilience-building efforts. South-South co-operation can facilitate the exchange of knowledge, technologies and innovative solutions tailored to the specific contexts of developing countries.

In conclusion, collaboration in building resilient infrastructure is crucial because no single entity or sector can effectively address the complexities of resilience alone. Through collaboration, stakeholders can leverage their strengths, minimise duplication of efforts, and establish a more robust and adaptive infrastructure system capable of withstanding and recovering from various shocks and stresses.

Box 2.3. The Fargo-Moorhead Flood Diversion Project in the United States achieved increased resilience to natural disasters through effective collaboration

Multi-stakeholder co-ordination. Efforts to address the flooding challenges in the Fargo-Moorhead area began with local stakeholders taking action. This led to the creation of an authority aimed at raising funds for constructing a 30-mile flood diversion channel. A significant milestone was reached when the US Army Corps of Engineers became involved, marking the point at which both local and federal governments became actively engaged. Eventually, the project expanded to involve the state government and local stakeholders from Minnesota, who were also affected by similar disruptions. Over time, the project garnered support from over 50 organisations across the public and private sectors, including 20 utility companies and 30 federal, state and local agencies. The co-ordination efforts involved navigating through 14 pieces of legislation, obtaining 200 permits (with over 2 000 conditions to be tracked), and establishing 70 memorandums of understanding, representing a massive co-ordination effort among government entities.

Funding sources. The Fargo-Moorhead Flood Diversion Project secured significant funding from various sources to support its implementation. A substantial amount of USD 750 million (United States dollars) was allocated by the federal government through a Project Partnership Agreement with the US Army Corps of Engineers, with USD 437 million of this funding provided by the Infrastructure Investment and Jobs Act of January 2022. Additionally, the project received state grants, including USD 850 million from North Dakota and USD 86 million from Minnesota, reflecting cross-border collaboration efforts. Local revenues also played a crucial role, with approximately USD 1.514 billion generated, primarily through sales tax. Furthermore, financing mechanisms such as a low-interest loan of USD 569 million from the US Environmental Protection Agency and USD 55 million in state Revolving Fund loans issued by the North Dakota Public Finance Agency were utilised. The project also benefited from USD 280 million in loans provided by the US Department of Transportation's Private Activity Bonds (PABS), contributing to its overall financing structure.

Source: Case study "United States: Fargo-Moorhead Flood Diversion Project" in Chapter 3 – Making infrastructure resilient to natural disasters: Learning from concrete projects in Africa, Asia, Latin America and the OECD.

Conducting risk assessment

Risk and impact assessment in infrastructure refers to the systematic process of evaluating potential risks, vulnerabilities and consequences associated with natural disasters and other disruptive events on infrastructure systems. This assessment aims to identify and understand the likelihood and severity of various hazards, such as floods, earthquakes, hurricanes and climate-related events, as well as human-induced risks like cyberattacks or terrorist threats, on infrastructure assets. The assessment considers multiple factors, including the vulnerability and exposure of infrastructure assets, the capacity of systems to withstand or adapt to disruptions, hazard characteristics and environmental conditions. It involves analysing historical data, hazard scenarios, and predictive models to assess the potential impacts on human life, economic activities, environmental assets and social well-being.

Through risk and impact assessment, decision makers can make informed choices about resource allocation, prioritise efforts, and develop proactive strategies to enhance the resilience of infrastructure systems (OECD, 2018[14]). This includes implementing preventive measures, improving emergency response and recovery plans, and integrating resilience considerations into infrastructure planning, design, construction, operation and maintenance processes. Overall, risk and impact assessment play a crucial role in building resilient infrastructure that can withstand and recover from various challenges, contributing to the sustainable development and well-being of communities.

Resilient infrastructure refers to the ability of a system or structure to withstand and adapt to changing conditions, shocks and stresses while continuing to provide essential services to the community. Furthermore, resilient infrastructure not only shields communities and the economy from disruptions caused by natural disasters but also fosters sustainable development in a changing world. By incorporating resilience into infrastructure planning and design, communities can better adapt to environmental changes and mitigate the impacts of disasters, thereby promoting long-term sustainability.

Risk assessment plays a fundamental role in this process by identifying:

- the expected probability of different natural disasters and their potential impact
- risk interdependence between sectors, such as an increased vulnerability to flood damage which creates risks to be considered in road and electrical distribution infrastructure
- the potential for simultaneous occurrence of natural disasters across regions.

Moreover, the assessment enables the implementation of prevention and mitigation activities to reduce the likelihood and severity of disasters. It also facilitates the development and implementation of appropriate preparedness measures, ensuring that communities are adequately equipped to respond effectively to disasters when they occur. Overall, a comprehensive risk assessment is a cornerstone of proactive disaster risk management and plays a vital role in enhancing infrastructure resilience and promoting sustainable development. Risk assessment significantly enhances prevention and preparedness capacities in case of natural disasters, and provides important information in the reaction and rebuilding phase by:

- **Providing information to assess vulnerabilities.** Risk assessment helps identify vulnerabilities within the infrastructure system, such as weak points, exposure and vulnerability to hazards, and potential points of failure. This understanding is essential for implementing targeted resilience measures to address these vulnerabilities effectively. By analysing historical data, hazard characteristics and environmental factors, decision makers can anticipate and understand the nature and magnitude of potential threats.
- **Enabling risk-informed decision making and increasing adaptive capacities.** Risk assessment provides decision makers with the information needed to make informed decisions about infrastructure resilience. By understanding the potential risks and vulnerabilities, decision makers can develop and implement resilience strategies that enhance infrastructure's ability to

withstand natural disasters and minimise their impact on communities and economies. Risk assessment facilitates adaptive planning by identifying evolving risks and vulnerabilities over time. As climate change and other factors contribute to changing risk profiles, ongoing risk assessment allows for adjustments to resilience strategies and measures to ensure infrastructure remains resilient in the face of new challenges.

- **Prioritising resilience measures and resource allocation.** By assessing the likelihood and potential impact of different natural disasters, risk assessment enables decision makers to prioritise resilience measures. High-risk areas or infrastructure components can receive more attention and resources to strengthen their resilience, leading to a more efficient allocation of resources. Risk assessment provides valuable information for allocating resources effectively. It allows decision makers to identify areas with the highest risk and allocate resources accordingly to mitigate those risks. This ensures that limited resources are directed towards the most critical areas to maximise their impact on infrastructure resilience. Understanding the magnitude of a disaster enables prioritisation of funding toward areas facing the greatest risk. While the long-term goal is to equip all vulnerable areas with adequate resilience measures, in the short term, it’s essential to allocate funds where they can have the most immediate impact. This targeted approach is crucial for swiftly minimising the disaster’s economic repercussions.
- **Enabling targeted prevention measures.** With a comprehensive understanding of the risks, preventive measures can be targeted and tailored to specific vulnerabilities. This includes infrastructure improvements, land-use planning, and the implementation of building codes and regulations designed to mitigate the impact of natural disasters.
- **Increasing community awareness and engagement.** Risk assessment fosters community awareness and engagement in disaster preparedness efforts. By communicating the findings of risk assessments to the public, communities can better understand their vulnerabilities and take proactive measures to mitigate risks, such as securing property, creating emergency kits, and participating in community resilience-building initiatives.

The risk assessment process involves three key steps:

- **Identifying the hazards that the infrastructure may face is essential.** These hazards encompass various natural events such as earthquakes, floods, hurricanes and climate-related phenomena, as well as human-induced risks like cyberattacks or terrorist threats. Once the hazards are identified, efforts and resources are focused on addressing them.
- **Estimating the likelihood or probability of each hazard is crucial.** Understanding the type of disaster faced, whether it's flooding, earthquakes, wildfires or others, guides the selection of appropriate resilience measures. For example, while drainage culverts are effective for managing flooding, they provide little protection against earthquakes. Additionally, considering the expected magnitude and physical characteristics of the disaster is vital to ensure that the chosen measures are suitable and cost-effective.
- **Measuring the potential impacts of the identified hazards to evaluate the costs and benefits of various activities.** This assessment includes evaluating the consequences on human life, economic activities, environmental assets and social well-being, that stem from the likelihood of a hazard to occur, as well as exposure and vulnerability to it. By combining information about potential impacts and likelihood, decision makers can prioritise risks and allocate resources accordingly. High-risk areas can receive more attention and resources during the planning and implementation of resilient infrastructure projects. These measures may include strengthening the infrastructure, improving maintenance practices, incorporating redundancy, and exploring nature-based solutions.

To ensure the effective assessment of infrastructure resilience, specific conditions must be established to ensure that the assessment process is thorough, accurate and useful for decision making:

- **Data collection.** A reliable and comprehensive dataset is essential for a robust risk assessment (OECD, forthcoming[15]). This should include historical data on past hazards, infrastructure performance, and their impacts. Additionally, real-time data collection systems can provide up-to-date information to assess current vulnerabilities.
- **Multidisciplinary skills.** Risk assessment for infrastructure resilience should involve experts from various disciplines, including engineers, geologists, climatologists, social scientists and economists. This multidisciplinary approach ensures a comprehensive understanding of the risks and potential impacts.
- **Stakeholder involvement.** Engaging stakeholders such as local communities, government agencies, private sector partners and non-governmental organisations is crucial. Their input provides valuable insights into specific vulnerabilities and priorities, enhancing the overall effectiveness of the assessment.
- **Consideration of climate change.** Given the increasing frequency and intensity of climate-related hazards, risk assessment should take into account climate change projections to understand future risks and plan for adaptation.
- **A targeted regulatory framework** that incentivises and mandates risk assessment may encourage infrastructure developers and operators to consider resilience in their planning and operations.
- **Risk awareness education.** Education and awareness initiatives among stakeholders about the importance of risk assessment and the benefits of investing in resilient infrastructure are essential components. However, it is crucial to note that risk assessment is not a one-time process; it should be regularly revisited and updated as conditions change, new information becomes available, or when the infrastructure undergoes modifications.

Developing countries face limited financial and institutional capacities for risk assessment, nevertheless they can and should establish an effective risk assessment system, in particular through the following actions:

- **Prioritising risk assessment.** Despite limited resources, governments should prioritise risk assessment as a foundational step in disaster risk management. By allocating available funds strategically to prioritise risk assessment for critical infrastructure and high-risk areas, countries can lay the groundwork for informed decision making. Multilateral development banks (MDBs) and development finance institutions (DFIs) can play a pivotal role in this respect.
- **Utilising existing data.** While developing countries may have limited resources for data collection, they can leverage existing data sources such as satellite imagery, remote sensing technologies, historical records and community knowledge. Governments can collaborate with international organisations, research institutions and NGOs to access and analyse available data to identify hazard-prone areas and assess infrastructure vulnerabilities.
- **Building institutional capacity.** Developing countries need to strengthen their institutional capacity by training local experts, establishing partnerships with academic institutions, and collaborating with international organisations and international partners to develop technical expertise in risk assessment methodologies. Governments can also prioritise capacity-building initiatives to enhance the skills of government officials and stakeholders involved in disaster risk management.
- **Promoting stakeholder engagement.** Engaging stakeholders, including local communities, government agencies, private sector partners, and non-governmental organisations, is essential for effective risk assessment. Despite the challenges to engage stakeholders in contexts of high poverty and inequality, developing countries need to foster collaboration and information sharing

among stakeholders to gather diverse perspectives, local knowledge and expertise, contributing to a more comprehensive risk assessment process.

- **Utilising available risk assessment tools.** Developing countries can leverage existing risk assessment tools and methodologies developed by international organisations such as the United Nations Office for Disaster Risk Reduction (UNDRR), World Bank, and other multilateral agencies. These tools provide standardised frameworks and methodologies for assessing infrastructure vulnerabilities and prioritising risk management interventions.
- **Seek international support.** Developing countries can seek international support and technical assistance from donor agencies, development partners and regional organisations to establish and strengthen risk assessment systems. International support can provide funding, technical expertise and capacity-building opportunities to enhance the effectiveness of risk assessment efforts in developing countries (Box 2.5).

Overall, risk assessment serves as a cornerstone for building prevention and preparedness capacities, enabling authorities and communities to proactively mitigate the impact of natural disasters and enhance their resilience to future events.

Box 2.4. Risk and impact assessments as success factors in the restoration of the Dique Canal in Colombia and in the MRT (Mass Rapid Transport) in Jakarta, Indonesia

The restoration of the Dique Canal represents a multifaceted endeavour aimed at revitalising a historically significant waterway while addressing contemporary challenges, restoring a degraded ecosystem and preventing flooding. By leveraging innovative solutions and collaborative partnerships, the restoration project has the potential to deliver lasting benefits in terms of transportation efficiency, environmental conservation and regional development.

The comprehensive risk and impact assessment and the understanding of the negative impacts of climate change and natural disasters, notably the significant flood in 2010/11 of the area surrounding the Dique Canal, provided a solid foundation for the project. A multitude of data and information from various sources have been meticulously analysed in this broad assessment, contributing to a nuanced understanding of the challenges and opportunities associated with the project.

In the MRT (Mass Rapid Transport) project in Jakarta, Indonesia, continuous risk and impact assessments were conducted to identify potential major disasters, such as assessments of the potential increase in flood levels (heavy rainfall due to climate change, sea level rise, land subsidence), earthquakes, fire, terrorism and power failure. Recent trends and long-term predictions were analysed to inform decision making for improvement in disaster-resilient design. Precise data necessary for assessment was collaboratively obtained from relevant institutions, and digital technologies were used for the risk and impact assessment analysis.

Effective co-ordination with the Meteorology, Climatology, and Geophysics Agency (BMKG) facilitated access to essential climate, meteorological, hydrological and seismic data. The installation of flood panels was based on hydrological and disaster studies against predicted flood levels under a 200-year rainfall return period. Updates in the hydrological study were based on additional considerations of heavy rainfalls due to climate change, sea level rises and land subsidence, conducted and co-ordinated with the Provincial Government of the Special Capital Region of Jakarta and other relevant organisations.

Source: Case study "Restoring a degraded ecosystem and preventing flooding in the Dique Canal in Colombia" in Chapter 3 – Making infrastructure resilient to natural disasters: Learning from concrete projects in Africa, Asia, Latin America and the OECD.

Box 2.5. International partnerships for enhancing risk assessment capacities in developing countries

The importance of international co-operation and collaboration in supporting risk assessment and resilience-building efforts to address the growing challenges posed by natural disasters cannot be underestimated. By working together, countries can enhance their capacities to assess, manage and reduce disaster risks, ultimately building more resilient communities and infrastructure. Below are some examples of international organisations active in the field:

United Nations Office for Disaster Risk Reduction (UNDRR): UNDRR facilitates international co-operation and co-ordination on disaster risk reduction through initiatives such as the Sendai Framework for Disaster Risk Reduction. UNDRR works with member states, regional organisations and other stakeholders to strengthen risk assessment capacities and promote resilience-building efforts globally.

World Bank Group: The World Bank Group supports risk assessment and resilience-building efforts in developing countries through various initiatives and projects. This includes providing technical assistance, funding and expertise to help countries assess disaster risks, develop risk management strategies, and implement resilience measures.

International Monetary Fund (IMF): The IMF works with member countries to assess the economic impacts of natural disasters and supports efforts to strengthen disaster risk management and resilience. Through technical assistance, capacity-building programmes and policy advice, the IMF helps countries integrate disaster risk considerations into their macroeconomic and fiscal policies.

Asian Development Bank (ADB): ADB collaborates with member countries in the Asia-Pacific region to enhance disaster risk assessment and resilience-building efforts. ADB provides financial and technical assistance for risk assessment studies, capacity-building initiatives and infrastructure projects aimed at reducing vulnerability to natural disasters.

European Union (EU): The EU supports risk assessment and resilience-building efforts in its member states and partner countries through various programmes and initiatives. This includes funding research projects, providing technical expertise, and promoting best practices in disaster risk management and resilience building.

International Federation of Red Cross and Red Crescent Societies (IFRC): IFRC works with national Red Cross and Red Crescent societies and other partners to support risk assessment and resilience-building efforts at the community level. IFRC provides training, resources and technical support to enhance community-based risk assessment capacities and promote local resilience-building initiatives.

United Nations Development Programme (UNDP): UNDP supports risk assessment and resilience-building efforts in developing countries through initiatives such as the Climate Risk Early Warning Systems (CREWS) programme. UNDP works with national governments, regional organisations and other stakeholders to strengthen early warning systems, enhance risk assessment capacities, and promote climate resilience.

Source: Official information from each organisation.

Monitoring and measuring impacts

Measuring the positive impacts of resilient infrastructure serves a dual purpose: to demonstrate to society the benefits of such infrastructure on economic growth, social welfare and sustainability, while also highlighting the costs avoided by mitigating the impacts of natural disasters. This rationale underscores the importance of disseminating information on the positive outcomes of efforts to enhance infrastructure resilience, thereby fostering acceptance and support from authorities and communities alike. Three key types of positive indicators support this goal and rationale:

- **Economic growth impacts.** These indicators highlight the contribution of resilient infrastructure to economic growth by reducing disruptions such as blackouts, thereby enabling businesses to continue operating and fostering overall economic development.
- **Social welfare impacts.** Resilient infrastructure ensures continuity of essential services, such as communication networks, even in the face of natural disasters, benefiting communities, especially smaller ones, and enhancing social welfare. Some resilience measures, notably nature-based solutions, also promote further societal benefits such as health improvements due to, for instance, improved air quality, and recreational activities (OECD, 2021[16]; OECD, 2024[12]).
- **Sustainability impacts**. Resilient infrastructure initiatives can also contribute to sustainability goals by reducing emissions and minimising environmental impacts, thereby promoting a more sustainable economy and environment.

Understanding the historical record of natural disasters and their impacts is crucial for enhancing social knowledge and acceptance of the necessity for investing in resilient infrastructure. This includes recognising the upfront costs associated with resilience measures and comparing them to the costs of inaction. Moreover, it involves considering infrastructure resilience investments in terms of their opportunity costs, and improving resource allocation efficiency by directing investments toward areas where they will have the most significant impact on mitigating the effects of natural disasters.

Monitoring the impact of disaster impacts over time provides valuable insights into recurring patterns and regional vulnerabilities, aiding in the development of informed disaster preparedness plans for better future event handling. It also enables authorities to allocate resources more efficiently, prioritising response efforts where most needed. Monitoring and impact measurement should be multi-dimensional, going beyond the impacts on infrastructure assets and taking into account impacts on livelihoods and diverse community needs. It is important that impact monitoring and assessment also takes into account local stakeholders’ perspectives to ensure community empowerment.

Monitoring and measuring impacts contributes to:

- **Rational resource allocation**. Allocating resources based on the severity and nature of disasters ensures proportionate and effective distribution, minimising unnecessary wastage.
- **Risk mitigation.** Historical data on the impact of disasters helps identify high-risk areas and implement targeted mitigation strategies.
- **Community awareness.** Measuring and tracking disaster impacts raises awareness among communities about potential risks, encouraging preventive measures and better emergency preparedness.
- **Research and innovation.** Data on disaster impacts is valuable for researchers and innovators developing new technologies and strategies to enhance disaster resilience and response.

Good practices in monitoring and measuring impacts of natural disasters include:

- Comprehensive hazard identification. Identify potential hazards that could affect infrastructure, including natural disasters, technological failures, cyber-attacks and human errors.

- Expertise utilisation. Engage engineers, risk analysts and subject matter experts to accurately process and present data.
- Effective communication. Communicate risk information to stakeholders, including the public, to raise awareness and encourage proactive efforts for resilient infrastructure.
- Clear resilience goals. Establish clear and well-defined goals and objectives for infrastructure projects, encompassing positive outcomes in social, economic and environmental domains. Identifying how infrastructure resilience to natural disasters contributes to the achievement of the Sustainable Development Goals (SDGs) is of particular importance (UNDDR, 2023[17]).
- Stakeholder engagement. Involve diverse stakeholders, including communities, local authorities, experts and the private sector, in the decision-making process to identify relevant indicators and gain consensus on their importance.

Developing countries often face limitations in setting up effective monitoring and measurement systems due to lack of expertise and resources. International partnerships can be key to scale up capacities in this field. International partners can be key in supporting access, deployment and development of mechanisms and tools for comprehensive data collection, covering physical infrastructure performance, socio-economic factors, environmental impacts, and community feedback.

Box 2.6. Monitoring and measuring the impact of disasters is key for better prevention, reaction and rebuilding: The experience of Mozambique

In Mozambique, the national road network faces significant exposure to natural hazards, particularly flooding and cyclones. With 40% of the country situated less than 200 metres above sea level and a coastline stretching over 3 000 km, Mozambique is vulnerable to the impacts of intense rainfall and frequent cyclones. Historically, the reliance on outdated data for preventive measures, such as building embankments, has proven insufficient in mitigating the risks exacerbated by climate change, leading to increased vulnerability.

To address these challenges, Mozambique has taken proactive steps to identify risks and hazards through collaboration with the National Meteorological Institute and the development of hazard maps. By utilising new data and spatial forecasting techniques, the country has been able to pinpoint areas most at risk and direct response preparation actions accordingly. Additionally, new design standards implemented in 2019 have introduced measures such as changing slopes, cutting trees and constructing levees and embankments to enhance road resilience and reduce vulnerability to natural disasters.

Source: Case study "Increasing road network resilience through adapted standards and effective use of data in Mozambique" in Chapter 3 – Making infrastructure resilient to natural disasters: Learning from concrete projects in Africa, Asia, Latin America and the OECD.

Investing in capacity building and knowledge management

The construction, operation and maintenance of resilient infrastructure entail multifaceted responsibilities that demand sound data and capable individuals with the requisite expertise. Achieving resilience requires enhancing the knowledge and capabilities of all involved stakeholders. Governments need to allocate sufficient human resources to support processes conducive to resilient infrastructure development. Furthermore, adapting infrastructure to accommodate a dynamic and uncertain climate landscape will necessitate cultivating new proficiencies across various domains. Stakeholders in infrastructure should enhance their understanding of the performance of both structural and non-structural resilience measures.

The cost of maintaining and upgrading resilient infrastructure assets can be significantly minimised through a well-integrated plan developed by personnel equipped with technical expertise and an understanding of the associated risks. Such a plan should encompass all aspects of the asset management system, from policy and strategy formulation to leveraging key enablers and opportunities like nature-based solutions and technological innovations.

By enhancing the skills, knowledge and resources available to individuals, organisations and communities, capacity building empowers them to effectively tackle challenges and capitalise on opportunities. Equipping local professionals, communities and institutions with the requisite expertise and tools enables a country to autonomously plan, implement and maintain infrastructure, fostering enduring benefits and inclusive growth.

Capacities are needed in project phases including planning, design, construction, operation and maintenance. It is necessary to:

- Conduct a knowledge gap assessment. Infrastructure providers and contractors can serve as valuable partners in conducting a gap assessment to identify areas for improvement in terms of capacities needed.
- Capture, disseminate and leverage on knowledge gained from firsthand experience to enhance future infrastructure practices.

Capacity development efforts should also focus on enhancing the knowledge and skills of individuals and institutions in non-technical areas, such as disaster risk finance, policy frameworks for resilient infrastructure and other aspects related to infrastructure risk governance. This comprehensive approach ensures a well-rounded development of expertise critical for building resilient infrastructure.

A targeted approach to ensure that local communities have the capacities to plan and implement resilience-oriented actions is crucial, particularly at the local level in disadvantaged communities where the impact of disasters is often most severe due to their vulnerabilities and chronic underinvestment. These communities often lack the resources to hire professionals to plan and execute projects aimed at disaster resilience. It is essential to allocate resources equitably and build capacity within these communities to identify the challenges, develop effective solutions, and implement them. The technical assistance programmes specifically tailored to support capacity building are key components of lending strategies for infrastructure resilience. For example, the Build America Bureau in the US Department of Transport is an effective example of an institution that has evolved from financing to encompass targeted support, including training and capacity building to empower communities to take proactive measures to increase infrastructure resilience to natural disasters.

Equipping people in the public and private sector with adequate technical skills is crucial. For example, in Ghana, the Ministry of Roads and Highways has prioritised capacity building for staff through a range of training programmes to equip them with the necessary skills to effectively carry out their responsibilities. Newly recruited technical staff within the agencies undergo mandatory training programmes; this in-house training ensures that all staff, regardless of academic background, are well-prepared for their roles. Additionally, development partners such as the Japanese Development Cooperation Agency (JICA) and the African Development Bank play a significant role in supporting Ghana’s training programmes together with providing concessionary facilities for road projects. International technical cooperation, including South-South and triangular co-operation, play a crucial role in this field. Mobilising the private sector’s expertise is also crucial. For example, the International Federation of Consulting Engineers (FIDIC) carries out regular capacity building initiatives, including specialised tailored programmes for engineers and certification courses, including in developing countries.

Box 2.7. Knowledge management and impact assessment in the aftermath of disasters increases future prevention capacities: Examples from Indonesia and Japan

The Disaster Prevention Policy implemented by Indonesia aims to ensure the safe evacuation of passengers during emergencies, particularly focusing on the Mass Rapid Transit (MRT) system in Jakarta. A crucial factor contributing to the success of these projects was the emphasis on building knowledge, skills and capacities throughout the planning and construction phases, particularly regarding resilience to natural disasters.

MRT Jakarta actively engaged in capturing, disseminating and reusing knowledge gained from firsthand experiences to enhance their practices. They organised retrospective events to discuss the initial phase of the project, compiling valuable lessons learned at their Internal Knowledge, Information, Education Center (KINETIC). Additionally, MRT Jakarta published a series of books covering construction, and operation and maintenance aspects, providing valuable insights for future projects.

Furthermore, MRT Jakarta played a significant role in a study on flood management conducted by the Community of Metros Benchmarking Group (COMET). This initiative resulted in a comprehensive benchmarking report among all COMET members, allowing metros to compare their practices in flood management and learn from each other's experiences. By actively participating in knowledge-sharing platforms like COMET, MRT Jakarta contributed to the collective learning and improvement of flood management practices in metro systems.

Impact assessment studies are key components of resilience strategies. In Japan, the case study of the 2019 Abukuma River flood revealed the substantial damage incurred, including the inundation of 114 km², resulting in 29 fatalities and significant economic losses. The case study underscored the potential impact of unrealised investments, highlighting the importance of preventive measures in flood risk reduction strategies.

Source: Chapter 3 – Making infrastructure resilient to natural disasters: Learning from concrete projects in Africa, Asia, Latin America and the OECD.

Carrying out strategic preventive maintenance

Strategic preventive maintenance in infrastructure refers to a proactive approach aimed at preventing structural weaknesses and deterioration in infrastructure assets through regular inspections, monitoring and maintenance activities. This preventive strategy involves identifying potential vulnerabilities and addressing them before they escalate into significant issues that could compromise the integrity or functionality of the infrastructure.

The goal of strategic preventive maintenance is to mitigate the risk of structural weaknesses resulting from wear and degradation, which can lead to severe damages in the face of natural disasters. Major structural damage to infrastructure not only incurs high repair costs but also leads to significant downtime, greatly reducing operational capacity. Much of this damage is attributed to pre-existing structural weaknesses exacerbated by wear and degradation over time. Natural disasters exacerbate these vulnerabilities, resulting in more extensive and costly damage that necessitates extensive repairs. However, regular preventive maintenance can mitigate wear and degradation, thereby minimising the financial and economic toll of disaster recovery.

By implementing strategic preventive maintenance, countries minimise the risks of failures, extend the lifespan of assets, optimise performance, and reduce overall maintenance costs over the long term.

By monitoring the condition of existing infrastructure and conducting regular inspections and maintenance, structural weaknesses can be mitigated, significantly reducing the damage incurred during disaster events. Regular Preventive Maintenance (RPM) is estimated to decrease life-cycle maintenance costs by 32% compared to reactive maintenance (MLIT, 2018[18]). RPM contributes to improved infrastructure quality during operation by minimising wear and degradation. This becomes particularly crucial in the aftermath of disaster events, as the infrastructure can remain operational, albeit potentially at reduced capacity, facilitating broader relief efforts and aiding disaster recovery in affected areas.

RPM is also more manageable compared to extensive post-disaster repairs, as engineers perform similar tasks regularly. This streamlined process enhances efficiency, saving both time and money, and enables the infrastructure to remain fully operational for extended periods. Moreover, this accumulated experience allows for the development of strategies to minimise disruptions during repairs, further reducing the economic impact.

Enabling conditions for effective strategic preventive maintenance in infrastructure include clearly defining responsibilities among stakeholders and holding them accountable for both maintenance and repairs. For instance, in a public-private partnership (PPP), the private firm responsible for construction can also be held accountable for a portion of maintenance costs during the initial years of operation, incentivising them to prioritise preventive maintenance strategies from the outset.

Incentives play a crucial role in encouraging stakeholders to prioritise maintenance. One approach involves linking maintenance responsibilities to the construction phase, where those responsible for construction bear a share of maintenance and repair costs. Additionally, incentives can focus on promoting maintenance techniques that facilitate quick repairs with minimal disruption to service, thus ensuring continuous infrastructure functionality.

Furthermore, the development of innovative maintenance techniques that minimise disruptions is essential. With the need for more frequent repairs under preventive maintenance, there is a greater opportunity to invest in technologies and methods that streamline repair processes without compromising infrastructure operations.

Strategic preventive maintenance requires:

- **Clear accountability**. Defining clear responsibilities among stakeholders and institutions ensures that those responsible for maintenance are also held accountable for repairs. This accountability can be reinforced through contractual agreements, such as in public-private partnerships (PPP) where maintenance obligations are integrated into construction contracts.
- **Incentives alignment**. Aligning incentives with maintenance goals is crucial for promoting proactive maintenance practices. For example, linking maintenance responsibilities to the construction phase can incentivise construction firms to prioritise quality and durability, knowing they will bear a portion of maintenance costs during the operational phase.
- **Proactive investment**. Investing in preventive maintenance techniques and technologies is essential for minimising disruptions and extending the lifespan of infrastructure. By allocating resources to regular inspections, proactive repairs, and predictive maintenance strategies, stakeholders can mitigate the risk of major structural damage and costly post-disaster repairs.
- **Continuous improvement**. Emphasising continuous improvement in maintenance practices allows stakeholders to adapt and evolve their strategies over time. This includes investing in research and development to identify innovative maintenance techniques that minimise service disruptions and optimise infrastructure performance.
- **Collaboration and knowledge sharing**. Facilitating collaboration and knowledge sharing among stakeholders fosters a culture of best practices and lessons learned. By sharing experiences, successes and challenges, stakeholders can collectively improve maintenance efficiency and effectiveness across different infrastructure projects and sectors.

Box 2.8. Japan invests in preventive maintenance to enhance infrastructure resilience

Japan's regulatory framework advocates a life cycle approach to maintenance, emphasising proactive measures to address issues before they escalate. Adopting this approach can yield a 32% reduction in overall maintenance costs compared to reactive methods, enhancing infrastructure quality during its operational lifespan.

Clear legal and policy frameworks are pivotal in ensuring cohesive maintenance efforts across governmental levels. This clarity fosters efficient co-ordination and resource allocation for infrastructure upkeep.

Japan prioritises conducting repairs during operation to minimise disruptions, thereby mitigating economic costs associated with downtime.

Leveraging automated systems and sensors enables early detection of failures, facilitating prompt maintenance interventions and substantially reducing maintenance expenses.

Through a strategic mix of regulatory, legal and operational measures, Japan exemplifies the efficacy of proactive maintenance practices in safeguarding its infrastructure against natural disasters and the challenges of ageing assets.

Source: Case study "Investing in cutting edge technology and strategic preventive maintenance to build resilience in a cost-effective way in Japan" in Chapter 3 – Making infrastructure resilient to natural disasters: Learning from concrete projects in Africa, Asia, Latin America and the OECD.

Deploying cutting-edge technology and fostering new design and innovation

Advanced technology, digitalisation, innovation and novel infrastructure design contribute to increasing infrastructure resilience to natural disasters by making it more capable of withstanding natural disasters such as floods, earthquakes and hurricanes. This can reduce the risk of damage, disruption and loss of life during extreme events. In addition to increased resilience, they also contribute at the same time to:

- **Cost-effectiveness.** Some new design and innovations offer cost-effective solutions compared to traditional infrastructure designs. For example, nature-based solutions, such as water retention ponds or green roofs and walls, can provide multiple benefits, including flood mitigation and improved water quality, at a lower cost than conventional grey infrastructure (OECD, 2020[19]).
- **Sustainability.** Many new design innovations prioritise sustainability by incorporating eco-friendly materials, energy-efficient technologies, and nature-based solutions. This aligns with sustainable development goals and reduces the environmental impact of infrastructure projects in developing countries.
- **Adaptability.** Innovative designs often offer greater adaptability to changing environmental conditions and evolving risk factors. Modular construction techniques, for example, allow for the rapid assembly and disassembly of infrastructure components, enabling quick responses to disasters and changing needs.

Cutting-edge technology provides advanced monitoring, real-time data analytics and predictive capabilities, which can aid in identifying vulnerabilities, assessing risks and facilitating timely responses. Furthermore, leveraging advanced technologies can enhance various aspects of resilience, ranging from minimising disruption during maintenance to enhancing the physical durability of the infrastructure itself.

Resilient infrastructure equipped with advanced monitoring and maintenance capabilities can mitigate costly damages and minimise extensive repair and recovery expenses during disaster events. Despite potentially high initial investments in cutting-edge technology, the long-term benefits often outweigh the costs. In particular, the use of cutting-edge technology is at the foundation of increased preparedness, reaction and rebuilding capacity through:

- **Early warning systems.** Modern technology enables the deployment of early warning systems capable of detecting hazards and providing real-time alerts to authorities and the public. Sophisticated sensors can detect seismic activity, monitor water levels in flood-prone areas, and identify infrastructure wear and tear, allowing proactive measures to be implemented before disasters occur.
- **Data-driven and risk-informed decision making.** Cutting-edge technology facilitates the collection and analysis of large volumes of data related to infrastructure performance and environmental conditions. Leveraging data-driven decision-making processes enables optimal resource allocation and prioritisation of maintenance efforts.
- **Smart and adaptive Infrastructure.** Integration of smart technologies such as the Internet of Things (IoT), artificial intelligence (AI) and machine learning (ML) enables infrastructure to become more adaptive and self-modifiable. Examples include smart grids that automatically reroute power during outages and self-healing concrete that can autonomously repair cracks.
- **Energy efficiency and sustainability.** Advanced technologies, from materials to construction machines, often offer more energy-efficient solutions, leading to cost savings and reduced environmental impact. Incorporating renewable energy sources, energy storage systems and smart energy management systems allows resilient infrastructure to better withstand energy supply fluctuations and contribute to sustainability.

In addition to the use of cutting-edge and digital technologies, design and innovation play a significant role in making infrastructure resilient to natural disasters by integrating features that enhance its ability to withstand and recover from adverse events. Innovation and design can contribute to enhancing infrastructure resilience to natural disasters through:

- **Increasing adaptability and flexibility.** Innovative designs allow infrastructure to adapt to changing environmental conditions and unexpected events. Flexible designs can accommodate variations in load, stress and environmental factors, reducing the risk of structural failure during disasters.
- **Ensuring redundancy and backup systems.** Innovative designs often incorporate redundant systems and backup mechanisms to ensure continued functionality during disruptions. For example, redundant power sources or communication networks can maintain essential services even if primary systems are compromised.
- **Providing modularity and scalability.** Modular designs allow infrastructure to be easily expanded or modified in response to evolving needs or changing conditions. This scalability ensures that infrastructure can grow or adapt over time, enhancing its resilience to shifting environmental and socio-economic factors.
- **Harnessing the potential of nature-based solutions.** Innovative designs increasingly incorporate nature-based solutions that mimic natural processes to enhance resilience. Examples include green roofs, permeable pavements and constructed wetlands, which can mitigate flood risks, improve water management and enhance ecosystem services (OECD, 2020[19]; OECD, 2021[16]).
- **Fostering the use of advanced materials and construction techniques.** Innovations in materials, science and construction techniques enable the development of infrastructure that is more resistant to hazards such as earthquakes, floods and extreme weather events. High-performance materials and construction methods enhance structural integrity and durability, reducing vulnerability to damage and collapse.

- **Integrated risk assessment and design.** Innovative design approaches integrate risk assessment and hazard mitigation strategies into the design process. By considering potential hazards and vulnerabilities from the outset, infrastructure can be designed to minimise risks and enhance resilience.

Innovation and design play a critical role in enhancing the resilience of infrastructure to natural disasters by incorporating adaptability, redundancy, modularity, nature-based solutions, advanced materials and integrated risk assessment. By embracing innovative designs, infrastructure can better withstand and recover from the impacts of disasters, ultimately safeguarding communities and promoting sustainable development. Some examples include:

- **Floating buildings and bridges.** In flood-prone areas, engineers are designing buildings and bridges that can float during floods, reducing the risk of damage and allowing for continued functionality during and after the event. For example, the “Floating Pavilion” in Rotterdam, Netherlands, is a multi-purpose structure designed to rise with floodwaters, providing a resilient space for events and activities.
- **Nature-based solutions.** Incorporating green infrastructure elements such as green roofs, rain gardens and permeable pavements helps manage stormwater runoff and reduce flooding risks. These nature-based solutions enhance resilience by absorbing and filtering water, reducing the burden on traditional drainage systems (OECD, 2020[19]) .
- **Seismic-resistant structures.** In earthquake-prone regions, engineers are implementing innovative seismic-resistant design techniques to minimise structural damage and ensure occupant safety. Examples include base isolators, which decouple the building from the ground motion, and damping systems, which dissipate seismic energy.
- **Smart infrastructure.** Smart infrastructure systems leverage sensors, data analytics and automation to monitor and manage infrastructure assets in real-time. For example, smart grids in the energy sector use advanced sensors and predictive analytics to detect and respond to power outages, improving resilience and reliability.
- **Resilient coastal infrastructure.** Coastal infrastructure, such as seawalls, breakwaters and artificial reefs, are being designed with resilience in mind to withstand storm surges, erosion and sea-level rise. Innovative designs incorporate natural materials and bioengineered solutions to enhance coastal protection and preserve ecosystem services.
- **Adaptable modular construction.** Modular construction techniques allow for the rapid assembly and disassembly of buildings and infrastructure components, enabling quick responses to changing conditions and emergencies. Prefabricated modular units can be easily transported and assembled, providing flexible and resilient solutions in disaster-prone areas.
- **Earthquake-resistant bridges.** Advanced bridge designs incorporate seismic-resistant features such as flexible columns, energy-dissipating devices, and innovative materials to withstand ground shaking and ensure structural integrity during earthquakes. For example, the Akashi Kaikyō Bridge in Japan utilises seismic isolation bearings to absorb earthquake forces and maintain stability.

The main challenges that developing countries face in using cutting-edge technology to innovate and apply novel design to ensure infrastructure resilience to natural disasters include:

- **Limited resources.** Developing countries often face resource constraints, including limited funding, technical expertise and access to technologies, innovation and novel designs. This can hinder the adoption of new design innovations that require significant investment or specialised knowledge. In particular, cutting-edge technology often comes with high initial costs, which may be prohibitive for developing countries with limited financial resources.
- **Capabilities and know-how.** Developing countries may lack the necessary technical expertise and human resources to adopt and maintain cutting-edge technology for infrastructure resilience. Building

the capacity of local engineers, architect, and construction workers to implement new design innovations is essential but challenging in developing countries. Training programmes, knowledge-sharing initiatives and technology transfer partnerships are needed to address this capacity gap.

- **Access and availability.** Access to technology and expertise may be limited in developing countries, making it difficult to acquire and implement these solutions effectively. In some locations inadequate infrastructure and connectivity may hinder the adoption and integration of advanced technology solutions.
- **Regulatory barriers.** In some cases, outdated or rigid regulatory frameworks may pose barriers to the adoption of innovations. Streamlining approval processes and updating building codes and standards to incorporate resilient design principles can help overcome these regulatory challenges. A legal vacuum with respect to digital and other advanced technologies can also hamper their utilisation potential in developing countries.
- **Socio-economic factors.** Socio-economic factors such as poverty, inequality and informal settlements can complicate the implementation of new design innovations in developing countries. Addressing these factors requires comprehensive approaches that consider social, economic, and cultural contexts.

Box 2.9. The role of nature-based solutions (NBS) in the climate resilience of infrastructure

Different definitions of NBS exist. OECD defines NBS as measures that protect, sustainably manage or restore nature, with the goal of maintaining or enhancing ecosystem services to address a variety of social, environmental and economic challenges. NBS can contribute to the climate resilience of infrastructure by:

- Strengthening overall resilience of infrastructure networks and protecting people by complementing grey solutions. For example, around Tanzania's capital, Dar es Salaam, a combination of NBS (restoration of 3 000 square metres [m^2] of coral reefs and 1 245 ha of mangroves) and grey infrastructure (2.8 km of sea walls, groynes and sea defence structures) provide protection from sea level rise and rain-induced flooding, directly benefiting around 58 000 people (UNEP, 2022[20]).
- Protecting grey infrastructure assets, ensuring their safe functioning and enhancing their operable life. In the Philippines, mangroves act as living safeguards to avert more than USD 1 billion in damage to residential and industrial infrastructure, while protecting over 600 000 people from flooding annually.
- Providing flexible and adaptive solutions in the context of climate change. NBS also have the potential to recover their functions following extreme weather events. For example, coastal wetlands can migrate upwards in response to rising seas (if sea level rise is within certain limits and there is undeveloped space to expand) (Borchert et al., 2018[21]).

Estimates show that NBS for infrastructure can cost half as much as grey alternatives, while generating 28% more in added value (Bassi et al., 2021[22]). Moreover, through enhancing human well-being and the quality of life in diverse ways, NBS also provides important social co-benefits, including health outcomes. However, NBS solutions are still used largely at pilot scales. To promote wider uptake of NBS, national governments need to design innovative institutional, policy, regulatory and financial frameworks. These should enable the use of NBS by both public sector agencies and authorities, as well as private actors.

Source: Based on OECD (2024[12]), "Harnessing Nature-based Solutions for climate-resilient infrastructure" in *Infrastructure for a Climate-resilient Future*.

To overcome these challenges, developing countries need:

- **Financial support.** Financial assistance from MDBs and DFIs and donor countries to offset the initial costs of acquiring cutting-edge technology can be a game changer in facilitating the adoption.
- **Technology transfer and partnerships**: Establish partnerships with technology providers, research institutions and developed countries to facilitate technology transfer and capacity building.
- **Training and education.** Invest in training programmes and educational initiatives to build local capacity and expertise in utilising and maintaining cutting-edge technology for infrastructure resilience.
- **Policy and regulatory support.** Develop policies and regulatory frameworks that encourage investment in resilient infrastructure and incentivise the use of cutting-edge technology through tax breaks, subsidies and other incentives. A regulatory framework that mandates and incentivises the integration of advanced technologies into the planning and construction process. For instance, implementing a bidding system that rewards the utilisation of advanced technologies could be effective. Another complementary approach is the support provided by multilateral agencies and countries, which facilitate the connection between infrastructure providers and investors offering cutting-edge technology solutions.
- **Collaboration and knowledge sharing.** Foster collaboration among government agencies, private sector entities, academic institutions and international partners to share knowledge, best practices and lessons learned in implementing cutting-edge technology solutions.

Despite these challenges, the advantages of utilising new design innovations for resilient infrastructure outweigh the barriers. With strategic planning, investment and collaboration, developing countries can leverage innovative design solutions to build infrastructure that is more resilient, sustainable, relevant for the specific context and adaptable to the impacts of natural disasters.

Developing countries are often characterised by rich biodiversity and diverse ecosystems that provide vital services to local communities, including food security, clean water and climate regulation. However, rapid urbanisation, industrialisation and unsustainable land use practices have placed immense pressure on these ecosystems, leading to habitat destruction, deforestation and loss of biodiversity. As a result, many developing countries are experiencing heightened vulnerability to natural disasters, exacerbated by the degradation of infrastructure.

Preserving and restoring ecosystems in developing countries is therefore crucial for building resilience to natural disasters. Nature-based solutions (NBS) offer a sustainable approach to addressing this challenge by leveraging the inherent resilience of natural systems. For example, reforestation efforts can help stabilise slopes and reduce the risk of landslides and soil erosion in mountainous regions prone to heavy rainfall and seismic activity. Additionally, restoring mangrove forests along coastlines can provide a natural buffer against storm surges and coastal erosion, protecting coastal communities and critical infrastructure from the impacts of hurricanes and tsunamis.

Furthermore, developing countries often face significant infrastructure gaps, particularly in vulnerable regions where the need for resilient infrastructure is most acute. Traditional grey infrastructure solutions, such as concrete flood barriers and levees, are often costly to construct and maintain, and may have limited effectiveness in the face of increasingly unpredictable and extreme weather events. In contrast, nature-based solutions offer a cost-effective alternative that can complement or replace traditional infrastructure, providing multiple benefits such as flood control, water purification and carbon sequestration while enhancing ecosystem health and biodiversity.

By integrating nature-based solutions into infrastructure planning and development, developing countries can address both their infrastructure gaps and environmental challenges while building resilience to natural disasters. This approach not only offers tangible benefits in terms of disaster risk reduction and climate adaptation but also contributes to broader sustainable development goals by safeguarding ecosystems, promoting biodiversity and enhancing the well-being of local communities.

Digitalisation, innovation, and design play a critical role in enhancing the resilience of infrastructure to natural disasters by incorporating adaptability, redundancy, modularity, nature-based solutions, advanced materials and integrated risk assessment. By embracing innovation and modernisation, infrastructure can better withstand and recover from the impacts of disasters, ultimately safeguarding communities and promoting sustainable development.

Box 2.10. Re-building effectively through technology and international partnerships in Ghana

In response to the pressing need for a substation adjacent to Accra's thriving commercial hub, Ghana faced a dual challenge of land scarcity and heightened flood risk in available areas. To overcome this hurdle, Japan played a pivotal role through JICA, extending significant support in the form of a JPY 4.2 billion (Japanese yen) grant for the construction and retrofitting of the substation. Collaborating with the Ghanaian government, Mitsubishi took charge of the construction and retrofitting efforts, leveraging innovative technology and methods to minimise disruptions to commercial activities. These efforts included the use of underground drilling techniques and the installation of crucial flood and disaster mitigation technologies such as automated pumps and fire-resistant walls. These measures not only facilitated the station's construction but also proved instrumental in mitigating the impact of subsequent floods, ensuring uninterrupted power supply to the commercial hub.

The project's impact assessment revealed remarkable successes, with a 95% reduction in the rate of power shortages compared to 2013. Despite facing two major floods in 2020 and 2022, the substation remained resilient, experiencing no disruptions to its operations. This resilience underscores the efficacy of the implemented flood mitigation strategies, including the utilisation of automated pumps and other technological innovations. Japan's significant support, coupled with Ghana's collaborative efforts, exemplifies the benefits of international co-operation and the strategic integration of cutting-edge technology in bolstering infrastructure resilience against natural disasters.

Source: Case study "Building a bulk supply point in a flood-prone area in Accra, Ghana" in Chapter 3 – Making infrastructure resilient to natural disasters: Learning from concrete projects in Africa, Asia, Latin America and the OECD.

Conclusions

Ensuring infrastructure resilience to natural disasters is context- and time-specific. However, some general good principles apply and when implemented have significant impact on the quality, effectiveness and efficiency of the preventive, reaction and re-building actions. This project highlights the value of exchanging experiences to identify lessons learned and innovative approaches to enhance resilience to natural disasters. By sharing knowledge and identifying best practices that can be customised to local conditions, countries can effectively address their unique challenges while benefiting from proven strategies implemented elsewhere. The project has demonstrated that while each country faces distinct socio-economic, environmental and institutional realities, there are common principles and approaches that can be universally applied to improve infrastructure resilience to natural disasters.

By fostering a culture of knowledge sharing and mutual learning, this project contributes to building a repository of effective strategies and tools that can be adapted and implemented in diverse settings to enhance infrastructure resilience. In particular, seven good practices have been identified:

- Adopting a life cycle approach
- Ensuring interests' alignment through effective collaboration
- Conducting risk assessment

- Monitoring and measuring impacts
- Investing in capacity building and knowledge management
- Carrying out strategic preventive maintenance
- Deploying cutting-edge technology and fostering new design and innovation

Adopting a life cycle approach is essential for ensuring infrastructure resilience to natural disasters because it requires taking into account the various stages of an infrastructure project, from planning and design to operation and maintenance. This approach enables proactive measures to be incorporated into the project, leading to long-term sustainability and resilience.

Effective collaboration among stakeholders and countries is crucial as it ensures alignment of interests and promotes collective action towards resilience goals. By bringing together diverse expertise, resources and perspectives, collaboration facilitates comprehensive risk assessment and the development of robust mitigation strategies.

Conducting risk assessment and measuring impacts are fundamental steps in understanding natural hazard risks and vulnerabilities and identifying areas for improvement. These practices provide valuable insights into the potential consequences of natural disasters, guiding informed decision making and resource allocation.

Investing in capacity building and knowledge management is key to enhancing the resilience of infrastructure. By empowering individuals and organisations with the necessary skills and information, countries can strengthen their ability to plan, implement and maintain resilient infrastructure solutions.

Strategic preventive maintenance, coupled with the deployment of cutting-edge technology and fostering innovation in design, plays a critical role in minimising vulnerabilities and ensuring resilience and longevity of infrastructure assets. These practices enable proactive maintenance and upgrade activities by capitalising on new and more efficient technologies, designs and materials, reducing the risk of costly damages and disruptions during natural disasters.

These good practices provide actionable guidance for prevention, reaction and rebuilding operations, increasing overall disaster preparedness and response, enabling countries to mitigate risks and minimise damages. In addition, to improve national and local policy approaches in developing countries, international co-operation is vital for supporting developing countries in implementing these good practices. Developing countries often face significant challenges in terms of limited financial resources, technical expertise and institutional capacities. International co-operation can provide much-needed financial assistance, technical know-how and capacity-building support to help these countries overcome these barriers and effectively implement resilience-building measures. An increased collective effort of the global community, including national and international development banks, and financial institutions is needed to enhance developing countries' resilience to natural disasters, protect critical infrastructure, and promote sustainable development for the benefit of present and future generations worldwide.

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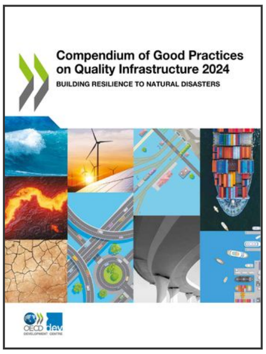

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