Principles for RESILIENT INFRASTRUCTURE

UNDRR
UN Office for Disaster Risk Reduction

SENDAI FRAMEWORK
FOR DISASTER RISK REDUCTION 2015-2030

SUSTAINABLE DEVELOPMENT GOALS

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UNDRR
UN Office for Disaster Risk Reduction

Principles for Resilient Infrastructure

Foreword

Mami Mizutori

Special Representative
of the Secretary-General
for Disaster Risk Reduction

With the rapidly increasing risks of climate change, and far-reaching systemic hazards like the global pandemic, many critical infrastructure services are exposed and increasingly vulnerable. Critical infrastructure underpins our quality of life and social well-being because of the provision of essential services in a wide range of sectors from health and social care to education, transport, energy, telecommunications, public safety, security and emergency services.

For this reason, UNDRR has held consultations engaging over 100 countries, as well as business, academia and civil society, to develop Principles for Resilient Infrastructure. The aim is to support countries in a common understanding about infrastructure resilience, as well as steps and actions needed to achieve it.

The Principles for Resilient Infrastructure offer a holistic approach to ensure that resilience is embedded into the planning and implementation of infrastructure projects. They contribute to creating a common understanding of how to improve infrastructure resilience in a risk context of increasingly complex cascading disaster impacts that can occur across the whole infrastructure system.

The Principles for Resilient Infrastructure also introduce a new and innovative concept of "net resilience gain" which is an important pillar in achieving "net-zero" for carbon emissions. At the heart of this concept is promoting an approach where we ensure that everything we do is resilient, and that all infrastructure investments demonstrate enhancing the systemic resilience of infrastructure.

At the same time, the 'Principles for Resilient Infrastructure' directly make an important contribution to the implementation of the Sendai Framework for Disaster Risk Reduction 2015-2030 and Goal 9 of the Sustainable Development Goals. With the Midterm Review of the Sendai Framework underway, now is the time to take stock of progress and accelerate action to ensure critical infrastructure is resilient.

Frequent disruptions to critical infrastructure undermine livelihoods, reduce productivity, and damage businesses. The Principles for Resilient Infrastructure offer an opportunity to overcome these challenges, ensuring resilience infrastructure is at the core of decision making.

I invite all countries and actors to work together to implement the Principles for Resilient Infrastructure and key actions set out in this report so we invest in resilient infrastructure to save lives.

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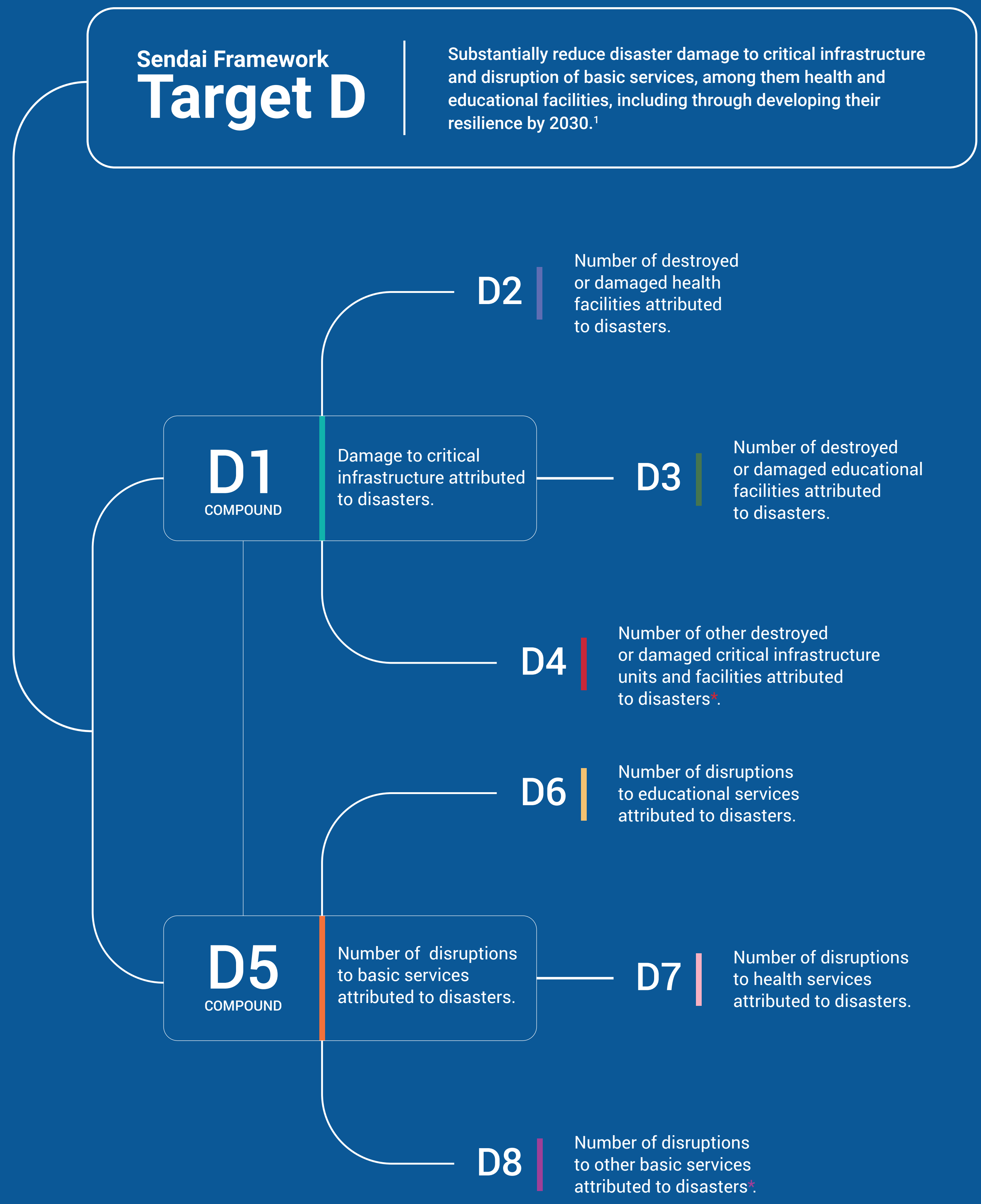
Overview

This report describes a set of principles, key actions, and guidelines to create national scale net resilience gain and improve the continuity of critical services provided by economic infrastructure systems: energy, transport, water, wastewater, waste, and digital communications; which serve as an essential backbone for the effective functioning of socio-economic infrastructure services such as health, education, business, food industry, etc.

The interconnected Principles for Resilient Infrastructure provide normative goals and desirable outcomes for systemic resilience of infrastructure, to meet the targets of the Sustainable Development Goals (SDGs) and the Sendai Framework for Disaster Risk Reduction (2015-2030). The key actions and governance guidelines for resilient infrastructure communicate the collaborative activities by which infrastructure will become more resilient, together with the mechanisms for improvement and monitoring infrastructure at national scale that will deliver net resilience gain and improved provision of critical services. The key actions define normative goals for what needs to be done to increase the resilience of critical services, and not how these might be achieved nor how they might be measured. Implementation of the principles and the specification of indicators for each of the key actions is the topic of the forthcoming Handbook for Infrastructure Resilience.

These Principles are intended for use by any level of government, institutions, donors, investors, owners, designers and contractors, service providers, and international organisations that are interested in implementing a set of actions that will improve national infrastructure resilience contributing to positive economic, social, and environmental outcomes.



* *The decision regarding those elements of critical infrastructure to be included in the calculation will be left to the Member States and described in the accompanying metadata. Protective infrastructure and green infrastructure should be included where relevant.*

* *The decision regarding those elements of basic services to be included in the calculation will be left to the Member States and described in the accompanying metadata.*

[1] For all Sendai Framework targets and their indicators see: https://www.preventionweb.net/sendai-framework/sendai-framework-monitor/indicators

1. Introduction

1.1 The significance of resilience

A 2016 report by New Climate Economy [1] calculated the need for approximately US$90 trillion investment into infrastructure over a period of 15 years, more than the what is in place in the entire current stock today. By 2019, Global Commission on Adaptation had highlighted the urgent and global environmental and economic imperatives to address the resilience and adaptation of infrastructure systems [2]. COP26 [3] the United Nations Climate Change Conference held in 2021, further highlighted the increasing urgency for action.

If mobilised, infrastructure investments would not only replace ageing infrastructure but also establish new and much needed infrastructure systems. However, the current approach to infrastructure planning, financing, design, development, operations and decommissioning, does not fully take into account either the interdependent nature of infrastructure and services, or the increasingly complex nature of risks and the cascading impacts that a disaster can have across the whole infrastructure system. A "think resilience" approach would address these concerns, encouraging a more comprehensive way of looking at risks and interlinkages, adaptable to specific national risks to resilience, and de-risking infrastructure investments and changes by implementing these principles for resilient infrastructure. A proactive approach is required in which investment is needed upfront to avoid potentially massive downstream costs relating to recovery, rebuilding, and replacement. Higher upfront costs should not lead to systematic rejection of resilience promoting improvements. Risk reduction and risk prevention is critical. These principles can help identify and build a pipeline of projects on what constitutes as a resiliency project, i.e. projects that have direct and indirect benefits to public and private stakeholders. The principles can set out critical factors to help prioritize projects. For example, treating the pipeline as a portfolio with some kind of scoring based on established criteria of the principles can help governments to de-risk investments.

Today, more people than ever are dependent on the services delivered by critical infrastructure systems, covering energy, transport, water, wastewater, waste, and digital communications. Social infrastructures, such as health and social care, education, police and prisons, fire and emergency services, rely on critical services. The role of critical infrastructure is to sustain the supply of critical services, protecting society and the environment, by acting as a buffer to extreme events. Our society is heavily dependent on the effective and efficient operation of critical infrastructure systems to deliver public services, enrich living standards and stimulate economic growth. National infrastructure (see section 2 for definitions) is the backbone of a modern economy, and critical infrastructure resilience is essential to develop sustainably. Robust and resilient infrastructure is a key driver of local and national economic growth. The reliability, performance, continuous operation, safety, maintenance, and protection of critical infrastructures are national and local priorities around the world.

The Sustainable Development Goals (SDGs) [4] especially SDG9, Sendai Framework for Disaster Risk Reduction 2015-2030 (Sendai Framework) [5] particularly target D ("substantially reduce disaster damage to critical infrastructure and disruption of basic services"), and the Paris Agreement [6] have unequivocally called for sustainable and resilient infrastructure, to mitigate the effects of climate change, and, future-proofing existing assets while building new ones. Climate change and other global trends [7] are driving an increase in the breadth, number, frequency, and intensity of hazards. Such hazards not only cause direct harm and damage (e.g. flooding), but they further exacerbate the challenge to maintain the systemic resilience of infrastructure. The threat of multiple hazards, hazards that occur together or soon after each other (as detailed in the Sendai Framework) are also increasing.

The COVID-19 pandemic and extreme weather events have highlighted potential vulnerabilities and exposure of our infrastructure systems across the globe. Existing infrastructure systems and the services they provide are increasingly being affected by disasters with a natural hazard origin as well as man-made hazards, and from the impacts of climate change. Evidence shows that infrastructure disruptions impose costs between $391 billion and $647 billion a year in low and middle-income countries [8]; and that investing €1.6 trillion globally from 2020 to 2030 in risk reduction activities could avoid as much as €6.4 trillion in future losses [9].

1.2 Recognising the gap

Policies, strategies, and regulatory frameworks need to be based on evidence of risks and on a clear understanding of the vulnerabilities of national infrastructure systems. To enhance the resilience of infrastructure through strengthened governance, there is a need to understand the performance of existing infrastructure, its exposure, current regulatory environment, challenges and barriers, coordination across various stakeholders and options to integrate resilience. This process also requires that common understanding of "critical infrastructure resilience" is built, based on certain criteria that can serve as a compass for governments and private sector.

One of the key gaps is the lack of understanding of what "resilient infrastructure" actually means and entails in terms of policy, planning, and practical measures, which public and private sectors can refer to when planning and managing infrastructure policies and projects. The work in this report builds on a variety of findings and recommendations: including those from the Global Commission on Adaptation [2], Global Center on Adaptation [10], G20 Principles for Quality Infrastructure Investment [35], and the World Bank [8], [11].

Through engagement with member states, the United Nations Office for Disaster Risk Reduction (UNDRR) has recognized that one of the key gaps in the infrastructure resilience arena is a shared view of: what infrastructure is in scope; the extent of resilience; the scale and ambition for resilience; the definition of resilience; and what can be done to improve infrastructure resilience. These items may vary greatly from country to country, and sector to sector, and so the proposed Principles for Resilient Infrastructure embrace the nuances of national resilience in different countries and sectors whilst assisting in raising awareness and setting a common basic understanding, but not a one-size-fits-all approach to resilience.

1.3 Addressing the gap

This report establishes the Principles for Resilient Infrastructure, mindful of the unique nature of infrastructure, the increasing contextual challenges to resilience, and the increasingly interconnected nature of infrastructure systems. The principles have been developed using extensive literature review and expert consultations. The literature review identified 14 principles which are now consolidated into 6 principles based on the input received from expert consultations. The Principles for Resilient Infrastructure have been widely consulted through global consultations with National Sendai Framework focal points, expert group meetings, workshops, presentations to regional platforms, other international and national events including individual interviews. The valuable inputs received from these engagements mean that the revisions, improvements, and clarifications implemented into the principles and key actions, which are grounded in scientific theories and evidence from global case studies, are now feasible for implementation into operational practice. A handbook along with key performance indicators (KPIs) is under development to support the operationalisation of the principles.

The principles are a system of goals with the requisite variety [12] to address resilience challenges of national infrastructure. Each principle is defined by a set of key actions. Implementing the key actions will adopt the principles and improve outcomes from national infrastructure. Key actions are grounded in past knowledge and so they provide robust guidance. The key actions are brought to life with global examples. Although the key actions are intended to be reasonably distinct there are some interdependencies. See Appendix A for the primary interdependencies between key actions.

The key actions contained in this report are not intended to limit interventions and improvements but to foster innovative thinking that solves resilience challenges to infrastructure that are unique to different nations across the world. As our economic infrastructures become more varied, interconnected, and innovative, and as our environments (e.g. natural, social, built) become more diverse, new key actions are expected to emerge over time. Furthermore, as with all innovation systems targeting improvement, there is a risk of unintended consequences. This demands continuous assessment of the national efficacy of these principles.

The principles for resilient infrastructure and the key actions underpinning each principle, are presented in this report as hazard agnostic. Each will require tailoring to the needs of specific nations and their unique circumstances in respect of hazards and vulnerabilities [13] thus they are formulated flexibly and without specific hazards in mind. Whilst every attempt is made to mitigate unintended consequences from implementation of key actions, infrastructure resilience performance must be continuously re-assessed to ensure undesirable outcomes are curtailed. Furthermore, we do not indicate the weighting or priority of any of the key actions: the priorities of each nation will define the urgency of adopting specific key actions.

1.4 Key contributions

This report introduces 6 principles and key actions for each principle. It also introduces a new commitment to 'net resilience gain', similar to Net Zero, that all interventions into infrastructure, not just those specifically targeted at enhancing the resilience of that system, must demonstrate that they enhance the systemic resilience of infrastructure and not damage the wider context.

Principles for Resilient Infrastructure will:

I. Assist in raising awareness and setting a common basic understanding of what "resilient infrastructure" constitutes;

II. Form the basis for planning and implementation of infrastructure projects that take resilience as a core value;

III. Raise engineering designs based on available and reliable data so parameters of safety and disaster risk mitigation are in place on new and retrofitting projects;

IV. Set out the desired outcomes of national infrastructure systems to establish resilience of critical services; and,

V. Assist the public and private sectors in making risk-informed policy and investment decisions.

1.5 Report structure

The rest of this report is structured as follows: Section 2 presents key definitions for: national infrastructure; systemic resilience; and net resilience gain. The economic case for infrastructure resilience is described in Section 3 focusing on expected savings across the whole lifecycle of infrastructure. Initial steps toward governance of resilient national infrastructure are proposed in Section 4 together with a theory of change to indicate how inputs, derived from key actions, deliver outputs, outcomes, and impact. Section 5 provides an overview of the six principles and shows how examples are drawn from across the world to bring the key actions to life. The key actions are strongly aligned with the UN SDGs and Sendai Framework as shown in Section 6. The next section 7 provides the bulk of the report and contains detailed descriptions of each principle, its key actions together with global examples. Section 8 provides a conclusion, together with next steps period.

2. Definitions

2.1 National Infrastructure

National infrastructure consists not just of the physical assets that deliver essential products and services but the set of systems, organisations, processes, technologies, etc. that enable critical services to be delivered inclusively and fairly to all users in a nation regardless of location. National infrastructure often has historical and cultural value, with iconic components which may limit what can be changed for better resilience.

Definition

National Infrastructure is an open complex interdependent system comprised of the: a) physical built infrastructure networks, buildings, and assets, b) governance structures; c) regulatory frameworks; d) management processes associated with the six economic infrastructure sectors of which it is comprised (energy, transport, water, wastewater, waste, and digital communications); e) interdependencies within and between each of the above; f) interdependencies between each of the above and the dynamic external context within which it is embedded [14]; g) the systems and technologies that control and deliver outputs; h) human factors, such as skills, knowledge; and i) the natural environment's resources and features with which it is integrated and allows it to deliver the goods that provide people and organisations with critical services.

By the production of a predictable flow of products (such as energy, potable water) and services (such as heating and cooling, wastewater treatment, mobility, connectivity, communication and digital services, flood risk management) national infrastructure makes possible the provision of social infrastructure services (such as hospitals, schools, fire services), and enables wider societal and economic activity, by supporting organisational and city value chains. Therefore, national infrastructure catalyses societal and economic multiplier effects, and supports the realisation of societally beneficial outcomes that simply could not occur without it [14].

The Principles for Resilient Infrastructure are targeted at national (or large territory/region) scale because it is at this scale that there is political accountability for infrastructure systems. At the national scale it is also possible to consider the diversity of ways in which infrastructure as a whole system can sustain critical services, and to assess national level resilience outcomes as a result of interventions. It is not intended that these principles are used at asset level, network level, or sector level. Others have written about service levels of infrastructure sectors in the context of resilience, for example [15]. The Principles for Resilient Infrastructure are intended to complement service level performance and do not replace operational service level agreements.

2.2 Systemic Resilience

National infrastructure resilience demands a systems' focus that straddles all sectors and activities within its scope. Systemic resilience provides a trans-disciplinary scope for the resilience of national infrastructure, recognising that a sectoral focus on resilience is inadequate. Systemic resilience is created when the whole system of systems that makes up national infrastructure is resilient to hazards outside the boundary of national infrastructure as well as the hazards created by the ways in which national infrastructure is organised (its components, its structure, its processes, etc.)

Definition

Systemic Resilience is a property of an infrastructure system that arises dynamically when the national infrastructure is organised in a such a way that it can provide agreed critical services (power, heat, communications channels, mobility services, potable water, and wastewater and waste removal) despite endogenous and/or exogenous hazards, and despite the addition, modification and removal of infrastructure components.

Over the last decades, the number and types of interdependencies between infrastructure systems and the wider dynamic, global external context in which infrastructure is embedded, have grown significantly. The consequences of more and diverse interdependencies are unknown: a national infrastructure system may respond in unexpected and emergent ways especially when infrastructure is stressed or disrupted. In complex interdependent systems such as national infrastructure, systemic incertitude (unknowns that cannot be classified, managed or governed as risks) has become a feature of infrastructure and traditional bounded approaches to risk management become much less relevant. Systemic approaches are needed to achieve systemic resilience.

The systemic resilience of national Infrastructure is a critical determinant of the frequency, scale, intensity and duration of disruption to the flow of infrastructure products and services it produces; and the social infrastructure services, economic and societal activity, and societally beneficial outcomes these enable [14]. Infrastructure systems with low systemic resilience can initiate a downward spiral in which more frequent disruptions undermine quality of life, reduce productivity and GDP, damage business, and investor confidence, and channel resources into responsive expenditure and away from other strategic priorities [16]. By contrast, infrastructure with high systemic resilience initiates a long-term virtuous cycle, leading to a more attractive and lower risk place to live, do business, and make investments. Damage to infrastructure systems (including people, organisations and physical assets) and damage created by loss of critical services can both be mitigated.

Building in systemic resilience however is often at odds with the lean, Just-in-Time, efficient, and optimising philosophies that drive most decision-making processes. Whenever, a complex interdependent system is governed and/or managed for short term efficiency, the long-term resilience of that system is inevitably undermined and eroded. The governance challenge is to create the right systemic conditions to enable the emergence and growth of systemic resilience. This requires a long-term commitment to a diverse long-term, collaborative, dynamic, multi¬faceted, multi-scale, cradle-to-cradle and synergistic portfolio of systemically targeted interventions focused on transforming the wider systemic drivers of low resilience.

2.3 Infrastructure Resilience

Infrastructure resilience is generally presented by describing the phases of disruption management: to prevent, absorb, recover, and adapt after disruptions caused by a hazard, in a timely and efficient manner (see Section 6 for more details on the phases of disruption management). The definition used in this report builds on the United Nations definition of resilience [17] by recognising that delivering resilient infrastructure needs both the creation of capacity for each of the phases of disruption management, as well as to recognise (1) the changing nature of risks and uncertainties; (2) the increasingly challenging nature of multi-hazards; (3) the need to use trans-disciplinary, systemic methods that consider both the life-cycle of national infrastructure and its interdependent, multi-sectoral nature. The definition is focussed at the national level and is concerned with making national level impact.

Definition

Infrastructure Resilience is the timely and efficient prevention, absorption, recovery, adaptation and transformation of national infrastructure's essential structures and functions, which have been exposed to current and potential future hazards. Implementing resilience across all disruption phases should be done through collaborative risk and uncertainty management, multi-hazard assessment, and methods that embrace the systemic nature of national infrastructure.

2.4 Net Resilience Gain

To assist in moving toward highly resilient infrastructure systems we introduce the commitment of net resilience gain which requires that all interventions into infrastructure, not just those specifically targeted at enhancing the resilience of that system, must demonstrate that they enhance the systemic resilience of infrastructure and not damage the wider context, contributing to more risks. Interventions must avoid reducing systemic resilience and aim to enhance systemic resilience. The level of systemic resilience of an individual nation's infrastructure will reflect its ambitions for uninterrupted critical services.

Definition

Net Resilience Gain is a long-term collaborative commitment to both (a) address systemic resilience loss, which reduces or removes actions that erode, reduce or undermine systemic resilience; and (b) to enhance systemic resilience, which prioritises actions that create systems intrinsically resilient to potential disruptions.

The prefix 'Net' signifies that it is acceptable for an action to have a negative impact on the resilience of the system into which it is introduced provided it either (a) also generates a resilience gain (has a positive impact) of sufficient scale to offset any negative impacts caused or (b) it is undertaken simultaneously as part of a wider portfolio of actions, which collectively generate a net resilience gain for national infrastructure. Therefore, any intervention into the infrastructure system that does not give rise to net resilience gain should not be considered. Alternative interventions should be identified. Net Resilience Gain should not be interpreted as opening the possibility of purchasing resilience offsets. This is because resilience is a system-specific quality, and a resilience loss in one system cannot be meaningfully offset by enhancing the resilience of another system.

Net Resilience Gain enables the application of a 'net gain' approach and is intended to be both complementary, and analogous, to the better known widely used Biodiversity Net Gain [18], Environmental Net Gain Principles [19], and Net Zero ambitions [20]. Biodiversity Net Gain is established as making a positive contribution to biodiversity. It was recently adopted in the Dasgupta Review on the Economics of Biodiversity which requires a net gain in biodiversity whereas offset seek no net loss [18].

Helm, in his book Net Zero [19] identifies The Net Environmental Gain Principle, The Polluter Pays Principle, and The Provision of Public Goods as the three key principles to motivate action on the natural environment and net zero. In their report Natural Capital and Environmental Net Gain [21] the UK National Infrastructure Commission adopted the Environmental Net Gain principle to shape their thinking on the relationship between Natural Capital and Economic Infrastructure; and provide a detailed explanation of how they plan to apply the concept to their work.

There are many global initiatives supporting the goal of Net Zero greenhouse gas emissions, insofar as net emissions of carbon dioxide (CO2) by human activities must approach zero in order to stabilize global mean temperature [20], but there are none for resilience which is a critical pillar to support Net Zero. Net resilience gain needs to match the urgency of Net Zero. There needs to be fundamental and profound mindset shift toward resilience.

A commitment to Net Resilience Gain for a national infrastructure system is a commitment to: ensure that: a) all infrastructure interventions should leave critical services in a measurably more resilient state than pre-intervention baselines; b) resilience frameworks and analysis are incorporated into all infrastructure decision making processes; c) infrastructure investors, developers, providers and operators, policy makers follow the resilience mitigation hierarchy to ensure their actions deliver net resilience gain by: i) prioritising actions that enhance overall systemic resilience, ii) avoiding actions expected to cause resilience losses (have negative impacts); iii) ensuring any action(s) that expected to lead to resilience losses are only undertaken as part of a wider portfolio of actions, which simultaneously generates a quantity of resilience gains greater than or equal to the expected resilience losses; and iv) In only exceptional circumstances, where the scale of benefits is sufficient to justify expected resilience losses, the benefits can be achieved in no other way, and all higher levels of the resilience hierarchy have been considered, and it is possible to do so as a last resort insure against the expected societal impacts of resilience losses.

3. The Economic Case for Infrastructure Resilience

The economic case for better resilience has never been stronger and these are covered in more detail below. Economic interventions are critical to support and promote the design, planning, development, maintenance, etc. of more resilient infrastructure systems. When financial resources are insufficient, at each stage of the infrastructure lifecycle, the resilience of infrastructure is likely to be compromised and suffer. Even if total spending is appropriate, allocating insufficient resources for planning, constructing, maintaining, recovering, or upgrading would lead to poor resilience and reliability [8]. So, resources must be distributed appropriately across the various needs and essentials of infrastructures over their lifecycle. This may require incentives in different parts of the infrastructure value chain, as the one who pays may not be the one that benefits from the investment. Implementation of these principles will lead to resilience of overall life cycle outcomes of national infrastructure, not individual cost benefits, which are better able to address the uncertainties of future hazards.

3.1 Early-stages

Adequate funding for risk and resilience analysis is required at early stages of project design and planning. As the early stage in the lifecycle of infrastructure projects, preparation budgets tend to be small, making it difficult to conduct the sophisticated studies and analyses needed for improvement in designing and decision making, while they can generate massive savings over the lifetime of infrastructure systems [8]. Initial evaluation and assessments can be applied as evidence of low-risk investment and high profitability to attract funds from private sectors and support requirements of resilient infrastructures across their lifecycle [22].

For example, in Bangladesh, accounting for climate change in the design of infrastructures, increased capital requirements by $560 million for additional flood protection but could save up to $1.6 billion [23]. Another example is related to the Federal Highway pilot project in the US, which evaluated the cost efficiency of the design of bridges and culverts in a different location under a range of sea level rise and storm surge scenarios, cumulatively over time, to find the most efficient design and suitable location that could save up to £0.5 million [24].

Considering additional up-front costs will build more reliable infrastructures in the long-term. The additional up-front costs for more resilient assets can prevent damage from future hazards and generate significant benefits in terms of lower repair costs and maintenance needs over the lifetime of infrastructure systems [8]. It will also improve mitigation in the event of compensation for environmental impact and the costs to reverse damage to biodiversity.

Modular bridge solutions may encase the deck structure of a bridge in stainless steel. This approach results in a significantly longer design life of up to 100 years with lower maintenance costs. Construction costs are also lower because a standardized formwork can be delivered to a site in a container, with deck casting conducted in a single pour, as opposed to the longer times and complex formwork needed for traditional in situ structures [25]. The other example is related to a study showing that $6 million spent on the seismic strengthening of transmission and distribution infrastructure resulted in a $30 million to $50 million reductions in direct asset replacement costs. This mitigation work was also highly effective in limiting damage in the earthquakes as very little major or structural damage occurred to any of Orion's 314 substations, afterward [26].

3.2 Operations

Allocating sufficient financial resources for acceptable operation and maintenance is vital for boosting the resilience of infrastructure assets while reducing overall costs [8]. It helps to move toward a preventive operation schedule and away from reactive approaches to repair. However, underinvestment in operation and maintenance is common because it is generally easier to raise resources to finance new investments or a major rehabilitation than to cover continuous operation and maintenance costs. Maintenance is also less visible than new investments and can usually be delayed, which makes it an easy target for budget cuts [27]. But to be resilient, assets not only need to be strong; they also need to be well maintained, which requires a steady flow of resources as well as processes and systems.

According to the analysis of OECD countries in 2019 every additional $1.0 spent on infrastructure maintenance is as effective as $1.5 of new investment [28]. There is also strong evidence that good maintenance increases the lifetime of assets. In Salzburg, most water pipelines are more than 100 years old, but they suffer very low water losses because of an effective strategic maintenance plan [29]. In addition, maintenance is critical for ensuring that assets can withstand extreme events, for example, improved road maintenance against risk of disasters with a natural hazard origin could reduce asset losses by 12 percent in Belize and 18 percent in Tonga [25].

Earmarking funds to reinforce the resilience of infrastructures for emergency and unforeseen incidents is essential. No infrastructure asset or system can be designed to cope with all possible hazards because there is great uncertainty about the probability and intensity of the most extreme events. Post-disruption financial roles of stakeholders for recovery activities need to be clarified up-front.

The Fukushima nuclear incident demonstrated that even if large dikes are supposed to protect a nuclear power plant against all possible tsunamis, some unexpected events may exceed the level of protection [30]. In these cases, infrastructures can take different approaches like producing additional vulnerability-reducing options and being prepared for the required response and recovery. Implementing these approaches require sufficient backup funds.

3.3 End of life

Banks, governments and other investors have a role in assigning budgets for necessary upgrades, maintenance, rehabilitation to prolong life and improve reliability, and for replacements at end of life. Lack of investments in technical upgrades can also lead to a lack of resilience to shocks and stresses, shortening the life of infrastructure components. New technologies and advanced materials can be deployed to improve construction, operation, maintenance, and recovery at a low cost [8]. Sensors in the water supply are already being deployed to monitor pressure and flow, minimising losses, and improving system maintenance.

The ePulse system was used in Washington, DC, during pipe replacement works. Condition assessment found that 32 kilometres of pipe were in good condition, whilst numerous leaks were located, and $14 million in investments were saved [8]. It enabled the system to pinpoint leakages and dispatch teams to specific areas instead of scouting wider areas to locate problems. Hurricane Sandy caused catastrophic damage in New York City, with kilometres of copper cables rendered useless. Estimating the loss at approximately $1 billion, Verizon did not see the value in repairing the existing network. Instead, it replaced the copper networks with fibre-optic cables, which are more resilient to water damage [31].

4. Governance

Governance is an essential component in achieving desired outcomes from resilient infrastructure. The OECD [32] have proposed a policy toolkit on governance of critical infrastructure resilience. It requires governments to address seven interrelated governance challenges: 1. Creating a multi-sector governance structure; 2. Understanding complex interdependencies and vulnerabilities across infrastructure systems; 3. Establishing trust between government and operators; 4. Building partnerships; 5. Defining the policy mix to prioritise cost-effective resilience measures across infrastructure lifecycles; 6. Ensuring accountability and monitoring implementation; and 7. Addressing the transboundary dimension of infrastructure systems. These challenges must be embraced within a method of governance that supports the implementation of the principles and key actions, and to demonstrate that they provide the anticipated outputs: benefits, outcomes and impacts. A theory of change is developed to provide a golden thread connecting the implementation of the principles and key actions (inputs) to their consequences (outputs), shown in Figure 1.

The implementation of the principles and its actions requires a national level decision. Nations may implement the principles in a voluntary manner, through national legislation, regulation, or policy instruments. It is proposed that key government ministries and agencies implement the principles into their approvals mechanisms, signalling that this is now part of national policy.

Governments must mandate investors to implement these principles otherwise governments will have to pay for lack of resilience, and ultimately citizens will pay. This would make it acceptable for investors to load additional costs for the purposes of resilience. If governments mandate investors to do this, governments must at least introduce these principles in regulations and standards.

The principles, through an assessment of the results of the key actions can be used to indicate the degree of national resilience of operational and future infrastructure, and to highlight the areas for improvement. Changes may be put into practice through implementation of the principles across the whole lifecycle of national infrastructure: new infrastructure projects, operational practices for maintenance, emergency and recovery plans, regulations (for monitoring, reporting), investment decisions (e.g., public-private investment), infrastructure decommissioning, and so on. The principles may also expose areas that currently constrain resilience, for example, tendering and procurement processes that constrain the ability of a nation to have more resilient infrastructure. There will be tensions and trade-offs in selecting the principles and key actions to implement first which will need to be resolved at national level.

Infrastructure regulator(s) and public authorities may set up mechanisms to gain insight on the effectiveness of the principles by continuously tracking: hazards; the changing landscape of demand; the emerging capability of the integrated national infrastructure system to maintain its resilience; the social and economic implications of outages of critical services; etc. Monitoring and reporting information will provide evidence of progress toward net resilience gain and of achieving national level targets for infrastructure resilience, allowing for more continuously more ambitious targets to achieve better socio-economic and environmental outcomes. Monitoring and reporting should also consider non-compliance and its effect on infrastructure resilience.

These principles can be incorporated into Environmental, Social, and Governance (ESG) reporting for impact investing [33]. Compliance with these principles would be a good way to reduce insurance premiums and there could be opportunities for the insurance sector to innovate to align with these principles. For example, depending on the location of infrastructure some insurers can take part of a premium and reinvest in the company's active risk management which means they will pay out like a cash fund to support de-risking of assets.

Positive impacts will be delivered through better resistance and absorption of hazards, through timely and efficient minimisation of disruptions by accommodating, and recovering appropriately, and by adapting and transforming when the appropriate action is to bounce forward. The nation should experience reductions in harm to people and assets, increased business and investor confidence, improved natural environment, and less interruptions and inconveniences. A comprehensive understanding of infrastructure resilience should include knowledge on absorptive capacity before disturbances, restorative capacity during disturbances, and adaptive capacity after disturbances [34]. Feedbacks from nations on the effectiveness of the principles as a whole and on specific key actions, connected with national contexts, will enable the principles and key actions to be revised periodically for greater global good. The governance and practices outlined above are shown visually in a standard theory of change representation demonstrating how Inputs, lead to Outputs, lead to Outcomes, lead to Impact. See Figure 1.

Figure 1 Principles for Resilient Infrastructure – Governance and Theory of Change

Direction of Change ↑ / Feedback ↓

IMPACT	Greater continuity of services, and better public health and wealth	Greater investor confidence	Less environmental harm and less wasted resources	Less inconvenience
OUTCOMES	Fewer failures, losses and near misses through better resisting and absorbing hazards	Rise in national resilience of critical services by better accommodating, adapting, transforming and recovering in the face of hazards		Increased knowledge
OUTPUTS	Infrastructure projects and enhancements are delivered "resilient ready"			Regulator reporting
INPUTS practice	Infrastructure changes, projects, operations, processes, investments, etc. demonstrate how they implement the principles			Regulator monitoring
INPUTS policy	Principles adopted into national approval mechanisms		Targets for national infrastructure resilience and net resilience gain are established	

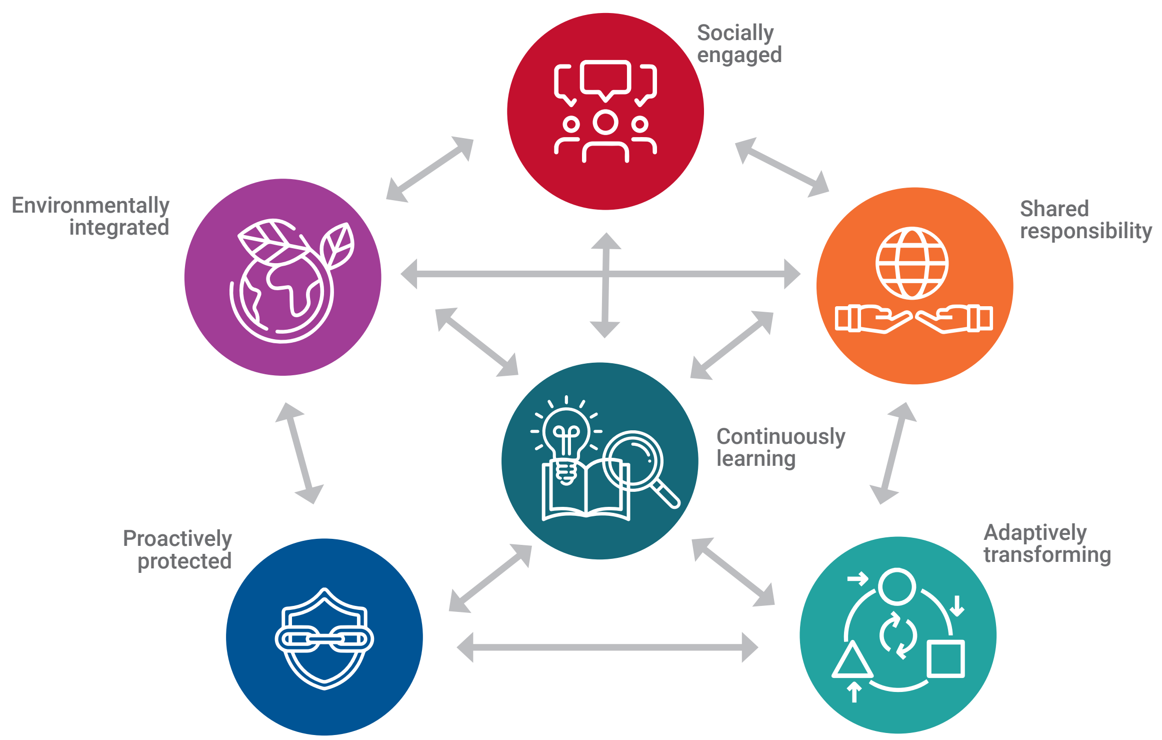
5. Overview of the Principles for Resilient Infrastructure

A set of six interconnected Principles for Resilient Infrastructure as shown in Figure 2 and listed below.

- Continuously learning
- Proactively protected
- Environmentally integrated
- Socially engaged
- Shared responsibility
- Adaptively transforming

Each principle has a normative goal, similar to sustainable development goals [4] and the Sendai Framework for Disaster Risk Reduction [5], enabling continuous improvement of national infrastructure resilience. Together the six goals form a system of goals that achieve net resilience gain across all lifecycle stages of infrastructure (design, build, operate, de-commission) assuring the continuity of critical services through all phases of disruption management (preparation, absorption, recovery, and adaptation). Given this focus on assuring critical services, and thus being infrastructure centric, it is outside the boundary of this work to consider for example how society might be resilient without critical services, or how communities can be resilient to critical services.

Figure 2 Principles for Resilient Infrastructure



6. Sustainable Development Goals, Sendai Framework alignment, and Resilience Phases

The Principles for Resilient Infrastructure embrace the ambitions of the Sustainable Development Goals [4] especially SDG9.

The principles Shared responsibility and Continuously learning encourage research expansion as well as technology development (9.5, 9.b, 9.c). Environmentally integrated reduces environmental impact (9.4) while Socially engaged supports societal engagement and blooming (9.1, 9.c). Proactively protected emphasises providing financial, technological, technical, and natural supports (9.a, 9.4).

The principles directly support the Sendai framework [5] in particular Global target D to substantially reduce disaster damage to critical infrastructure and disruption of basic services.

In respect of supporting the United Nations resilience definition [17], Shared responsibility aids the transition toward information-based approaches to prevent failure and enhance the recovery process. Proactively protected and Adaptively transforming can be applied to prevent, absorb, and resist failures as well as enhance the recovery process. Continuously learning is about preventing risks. Environmentally integrated has a focus on integrating with the natural environment to prevent, absorb, and resist disasters with a natural hazard origin (note this is not the same as 'natural disasters' which implies incorrectly that disasters occur naturally). Socially engaged encourages societal engagement to prevent, resist, and recover from facing failures. See Appendix B for a mapping of the inter-linkages with SDGs, the Sendai Framework and the capabilities in the United Nation's definition for resilience.

Furthermore, the Principles for Resilient Infrastructure complement the G20 Principles for Quality Infrastructure Investment [35], particularly its principle 4 which relates directly to Sendai Framework, and advocates disaster risk management when designing infrastructure, and disaster and risk finance and insurance mechanisms.

This report also refers to the phases of disruption management. The phases are Preparation, Absorption, Recovery, and Adaptation [36], [37] which are strongly connected to resilience capabilities. Preparation is about planning for and preventing disruptions and is the phase before any disruption event occurs. Absorption is the phase during which a disruption arises and requires infrastructure to resist and absorb (or limit) failures so that critical services can continue being provided with least interruption. The recovery phase starts when the hazard has ceased and repairs and reconstruction are implemented. The adaptation phase is about changing or transforming infrastructure provision so that its resilience is improved. Bouncing forward is an adaptation when used in the recovery phase.

7. Principles

Principle 1 (P1)

Continuously learning

The goal to develop and update understanding and insight into infrastructure resilience.

SUMMARY

This principle highlights the challenges to understand infrastructure resilience due to the internal complexity and external hyperconnectivity of related systems and sectors. It aims to develop understanding and insight into infrastructure resilience through key actions that: expose, and validate assumptions which may create future risks to critical services; monitor and intervene into the real-time performance of infrastructure to keep it resilient; identify and validate strategies before implementing them ensuring they work in multiple future scenarios and consider historical disaster records; and undertake stress testing to identify and remedy key vulnerabilities.

BACKGROUND

The internal complexity and external hyperconnectivity of infrastructures make it difficult for stakeholders to clearly grasp the status of resilience in national infrastructure, which undermines the ability of system operators to prevent, absorb, and recover from outages. Therefore, in addition to understanding and summarizing past disaster risks according to the Sendai Framework for Disaster Risk Reduction 2015-2030 [5], it is also necessary for planners to actively prepare for the scale of potential hazards that infrastructures may suffer, for operators to sense the dynamic changes in the operating status of infrastructures to detect anomalies rapidly, and for decision makers to learn and continuously devise strategies to optimize infrastructure resilience by disaster mitigation and rapid recovery.

P1 Continuously learning is concerned with improving knowledge on future vulnerabilities and so can support the business case for improving resilience. The lifecycle-integrated smart mechanisms of planning, monitoring, recovering, and learning provide infrastructure stakeholders with specific approaches to improve resilience literacy and comprehensive understanding of infrastructure resilience and its capacities. The results of continuously learning will serve as feedback to support other principles such as P2 Proactively protected and P6 Adaptively transforming. P1 Continuously learning is a principle to be adopted by all infrastructure stakeholders.

DEFINITIONS

- Smart mechanisms, enabled by organisations and intelligent technologies on infrastructures, allow planners, operators, decision-makers, wider stakeholders, and ultimately autonomous infrastructure components to learn from historical disturbances and be prepared for future hazardous or uncertain situations; they include: smart planning mechanisms for preparedness, smart sensing mechanisms for monitoring and flexible adjustment, and smart responding mechanisms for iterative and optimal recovery strategies; industry 4.0 and emerging technologies are increasingly enabling the realization of smart mechanisms.
- Resilience literacy is the ability of a people to engage with resilience advancements and support transition plans toward renovating, modernising, and smartness. Improved awareness may support the development and integration of novel programs related to the integration of privately-owned resources into resilient grid operation like vehicle-to-grid technologies and virtual power plants [38].
- Early Warning Systems are an integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities systems and processes that enables individuals, communities, governments, businesses and others to take timely action to reduce disaster risks in advance of hazardous events [39].

NET RESILIENCE GAINS

- Absorptive capacity is improved by embedding the findings of knowledge discovered through smart planning and smart sensing. Through improved understanding of resilience limits and safety margins, buffers can be developed to overcome potential future disruptions. Resilient infrastructures with absorptive capacity can absorb the negative impacts of disruptions and minimize consequences with little effort [40].
- Restorative capacity is increased through a better understanding of successful and timely strategies for recovery. Resilient infrastructures with restorative capacity can recover or bounce back from a disruptive event and timely return to normal or improved operating conditions [41]. Smart learning mechanisms can make infrastructure decision makers learn better and more timely actions for system response, using accumulated feedback, experience, and lessons from experimenting.
- Adaptive capacity is created by monitoring physical status, operating status, and service level performance of infrastructures with smart sensing mechanisms. Infrastructure operators build adaptive capacity by learning to adjust to undesirable situations by undergoing some changes in real time [34].

KEY ACTIONS

P1.1 Expose and validate assumptions

Expose and validate assumptions about the resilience of infrastructure to potential threats in order to assess the future risks to critical services.

Using scientific evidence and research, infrastructure planners, policy makers and scenario analysts must expose assumptions about infrastructure resilience, and validate them through scenario analysis (computationally, mathematically, using qualitative analysis, professional engineering, and other engagement tools, etc.) to characterize potential hazards of anthropogenic or natural origin, and assess future risks to critical infrastructure services. Investments to improve infrastructure resilience must use the evidence and insights from testing and validation to make the case for net resilience gain.

Morocco hazards modelling: The government of Morocco's disaster risk management program developed a tool "Morocco natural hazards Probabilistic Risk Analysis (MnhPRA)", which provides an inventory of the country's assets at risk and the hazards that threaten these assets and incorporates Morocco's population, the entire built environment of Morocco—all buildings, roads, bridges, railways, ports and airports, electric generation and transmission, and other infrastructures. MnhPRA combines these asset databases with databases of hazards (currently, earthquake, flood, tsunami, and drought) that threaten these assets, and then links these two with vulnerability functions to estimate fatalities, injuries, and direct economic costs due to all possible disaster exposure [42]. The assumptions exposed by using this tool (such as the magnitude and frequency of hazards, the assets and their condition) provides the assumptions made in the assessment, and can highlight gaps as knowledge and experience changes.

P1.2 Monitor and intervene appropriately

Monitor performance to sense real-time infrastructure performance and to intervene at an appropriate time scale.

Monitoring performance in real time through qualitative, quantitative, and hybrid approaches and intervene at an appropriate time scale will provide information for early warning and disaster mitigation. Infrastructure operators monitoring the status of national infrastructure to sense system performance and to identify system sensitivities to various hazards in real time will trigger early warnings, rapid risk assessment, and support decision making for interventions at an appropriate time scale. Where possible, aligning with Sendai Framework Target G will increase the availability of and access to multi hazard early warning systems and disaster risk information and assessments [5]. Smart sensing mechanisms can be implemented using technologies, people, and the monitoring of service levels as perceived by users.

Rising Main Monitoring Project for wastewater: A burst on a wastewater network and the impact of its pollution is a problem with significant consequence for social, natural and built environments, therefore increasing resilience. The rising main monitoring and analysis service from Syrinix improves knowledge of asset issues such as blockages, sticking/passing non-return valves, worn pumps and burst mains. This project had been truly ground-breaking in its ability to deliver early value to a wide range of stakeholders within the utility. Asset planners can now look at the effects of plans on rising main performance and inform future standards. In May 2019 early detection of a burst rising main at Anglian Water in the east of England, meant a repair bill of £1,100 as opposed to the £24,000 repair bill received 6 months earlier, prior to the monitoring and the burst alarm implementation [43].

P1.3 Analyse, learn, and formulate improvements

Formulate strategies for infrastructure resilience improvements that are based on learnings, feedback, scientific research, and analysis of previous disturbances, data, and models.

Infrastructure decision makers should formulate strategies for infrastructure resilience based on the learning of historical feedback of infrastructures after disturbances using disaster risk records and the assistance of the latest research and technologies from fields such as knowledge management, data science, and information management. Past disturbances can be evaluated, and thought/model experiments run, to determine how disruption to critical services might have been avoided. Analyses of data using Industry 4.0 tools and techniques in disaster management [44] will support smart learning mechanisms toward insight, mastery of risk evolution, theory development, and the creation of strategies to improve resilience of critical services. Improvements to risk assessment of infrastructure projects must focus on ensuring the useful life of the infrastructure and the continuity of the services to which it is oriented.

Transport system climate-resilience: Freetown is one of the world's most vulnerable cities to the impacts of climate change, with floods and landslides compromising its transport system, which is so important for its economic development. Lack of data and a poor understanding of the vulnerabilities of the transport system to climate-related hazards is preventing city planners from improving and developing a sound and resilient transport system to meet the growing demand. To address those challenges, the government of Sierra Leone worked to gain a better understanding of the roads' vulnerability to floods and landslides and how climate change would affect the patterns and characteristics of those events. They collected data on public mobility on formal and informal transport systems and identified interventions to enhance the resilience of transport systems. Mobile applications such as the RoadLabPro were used to map 4,038 km of formal and informal transportation systems. Flooded areas and the locations of critical road infrastructures, such as drainage and culverts, were also mapped. With this information, together with climate change projections for rainfall and sea level rise, this work resulted in the first comprehensive climate risk-informed transport map of Freetown and will support decision making on everything from infrastructure and policies to journey planning [45].

P1.4 Conduct stress tests

Develop strategies to continually assess resilience and expose system weaknesses through collaboration with relevant stakeholders and the public.

To cope with potential hazards, develop strategies to continually assess resilience and expose system weaknesses. Regular stress testing and compliance testing exercises must be conducted collaboratively with relevant stakeholders and the public. Testing must be standardised where appropriate and common practice. Disaster preparedness exercises and emergency drills will establish best practice in risk and crisis management and will also improve community resilience. Exercises should extend beyond sectoral and geographic boundaries to engage with all relevant stakeholders.

Efforts are being made to develop quantitative and qualitative methods to assess and measure resilience in systems and sub-systems [46]. These include both metric-based and model-based approaches. Standardising such methods and integrating these into infrastructure planning and operation can able a more robust and coordinated strategy for resilience. UNDRR has developed a stress testing tool for critical infrastructure based on a methodology by Linkov and Kott [47] that proposes a three-tier approach to resilience modelling, growing in complexity with each tier. In tier one, screening models or indices can be used for identifying easy improvements and areas for further analysis, and tier two sees decision analysis used to prioritise system performance and investments. Finally, complex models in tier three consider interdependent systems and sub-systems and use robust scenario analysis. Selecting which tier of modelling is required depends on the scenario being modelled as well as available data and resources.

The Great ShakeOut is an international organisation educating the public on earthquake preparedness. They run an annual International ShakeOut Day, where millions of participants undertake an earthquake drill, and provide resources for individuals, schools, and workplaces, including drill manuals, safety action guides, and earthquake science educational material [48].

Principle 2 (P2)

Proactively protected

The goal to proactively plan, design, build and operate infrastructures that are prepared for current and future hazards.

SUMMARY

The goal for Proactively Protected is to be prepared for hazards in the recognition that infrastructure is exposed to various hazards both known and unknown, and the nature of hazards is constantly changing. Key actions including raising the baseline for system safety, protecting critical components and critical interdependencies of national infrastructure, embedding mature emergency management planning, ensuring that systems can fail safely, building in resilience at multi-scales, and making a commitment to infrastructure maintenance.

BACKGROUND

Infrastructure is exposed to various hazards both known and unknown. And the nature of hazards is constantly changing. This includes amplitude and frequency of hazards, multi- hazards occurring concurrently or close after each other, and even new hazards such as climate change, sea level rise, and nuclear pollution. The best time for investment in readiness for hazards is at the early phases of the infrastructure lifecycle to satisfy risk return requirements, which must proactively consider and assess potential negative impacts of disturbance events and disasters on the full lifecycle of infrastructure provision.

Based on the results of Continuous learning, resilient design provides planners, structural engineers, contractors, operational staff, and decision makers with: systematic infrastructure network planning (such as interdependence planning), resilient structure schemes (such as hazard-resistant design and construction), operational schemes (such as regular maintenance schedule), and emergency plans (such as emergency evacuation and rescue plans). These aim to proactively raise system baseline safety to better absorb, accommodate, resist, adapt to, transform and recover from negative effects of ever-increasing hazards in the operation and maintenance phases by providing infrastructures with foresighted and proactive solutions considering the complex behaviour of and interactions among subsystems, the built environment, and humans [49]. Pre-design (options/strategy analysis) and post-design (construction and operations) must both ensure compliance with designs for infrastructure resilience through monitoring, provision of human capacity and skills, etc.

Design for resilience is supported by mature theories and numerous engineering practices. Engineering designs must support the commitment to resilience as a core value and must be raised based on available and reliable data, so parameters of safety and disaster risk mitigation are in place on new and retrofitting projects. Comprehensive risk management and risk-informed organisations and methods (O&M) align with prioritising maintenance resources toward the most critical assets, considering their performance in both normal and emergency or stress conditions, and responding to dynamic risk, e.g., changes in climate risk due to seasonality and long-term climate change.

These must be continuously revised based on P1 Continuously Learning which creates insight and scientific risk assessments based on stress testing, scenario testing, monitoring, examination of disaster records, etc. P1 takes into account the past, the present and futures, and futures analysis considers fluctuations in the built, natural, and social environments. A proactive approach is needed toward upfront investment in the design to avoid potentially massive downstream costs relating to recovery, rebuilding and replacement. This will involve stakeholders in all lifecycle stages of infrastructure, including private and public investors. See P5 Shared Responsibility and in particular P5.6 Share risk and return information.

DEFINITIONS

- Resilient design of infrastructures, including pre- and post-design planning and execution, is the intentional design of the form, configuration, operation schemes, and emergence plans of infrastructures that considers various negative impacts of hazards including natural and manmade disasters and disturbances, as well as long-term changes resulting from climate change [50].

- System safety, as the primary goal of resilience engineering, focuses on providing infrastructures with the capacities to proactively manage various uncertain disturbances [51]. Considering the degree of system safety will change continuously over time, resilience engineering exploits insights on failures in complex systems, organisational contributors to hazards, and human performance drivers to raise safety baseline in advance [52].

- Safe-to-fail infrastructure remains safe in the event of a partial or complete failure that renders it unable to provide its usual services [53]; this is different from fail-safe infrastructure, which is designed to prevent failure from occurring. When fail-safe infrastructure does fail, the consequences can be severe [54].

NET RESILIENCE GAINS

- Resilient infrastructures with robustness features can improve absorption and resistance to hazards, and also mitigate the spread of damages.

- Resilient infrastructures with redundancy features can deliver continuous services using remaining available resources in case of disturbances. Infrastructure interdependence planning can realize efficient internal transfer of infrastructure functions to improve system redundancy in the resistance and recovery phase of disturbances [55].

- Resilient infrastructures that are well-prepared with a rapid inflow of emergency resources can recover rapidly in the face of interruptions. Mature emergency management plans for different disturbances can effectively improve system rapidity in the recovery phase.

- Resilient infrastructures with resourcefulness feature can mobilize needed resources and services more appropriately. Environmental solutions (see P3 – Environmentally Integrated) with full use of local and renewable resources can make infrastructures equipped with more available sustainable resources in the recovery and adaptation phase of disturbances.

KEY ACTIONS

P2.1 Raise essential safety requirements

Plan infrastructure systems to have higher essential safety requirements.

Raising essential safety requirements for infrastructure systems at the planning and options stages will ensure that designs and solutions are prepared for future hazards (assuming that there is compliance with implementation of existing standards in line with localised risks and recognising that this is not always the case and must be addressed). Designs for new infrastructure systems and their upgrades need to be pessimistic in terms of the potential for lifecycle hazards given the longevity of most infrastructure components and the increased probability of multiple hazards such as attacks, pandemics, and climate change arising concurrently. Designs should apply a holistic approach combining results of scenario testing and stress testing from P1 Continuously learning with national needs and local circumstances to provide evidence to ensure the comprehensiveness of safety requirements to known and potential hazards. The adoption and enforcement of compliance with locally specific design codes and standards can be used to increase the safety of infrastructure to relevant hazards using locally available materials.

Pakistan Shelter Design guide for improved flood resilience: Since 2010, extreme flooding in southern Pakistan has affected 35 million people, damaging or destroying 2.5 million homes. In response, the International Organization for Migration as the national lead shelter agency in Pakistan created the shelter design guide based on scientific evidence, physical testing, surveys, and expert analysis. The guide raises essential safety requirement of structural designs (such as foundations, walls, and roofs) and provides design decision tools including material specifications,

hazard assessments and settlement guidelines, which is intended to inform best practice in the planning, design, and construction of flood resilient shelters in southern Pakistan [56].

P2.2 Exceed basic requirements for critical components

Increase design standards for critical components of national infrastructure to exceed basic reliability and durability requirements.

It is necessary to differentiate critical components within national infrastructure systems and make them more resilient and prepared for future hazards. Critical components play a vital role in the whole infrastructure system operation. Raising design standards for critical components means identifying a higher threshold for basic reliability and durability requirements than the threshold for standard components. This is not about overbuilding or gold-plating; it is about preparedness and providing redundancy for future hazards. Exceeding critical components' basic reliability and durability requirements rather than a holistic upgrade to all component standards recognises that priority can be given to critical components (and there are several methods to identify the critical components which have greatest negative effect in the event of their outage [57]). This targeted investment will achieve higher system-level reliability and durability helping to absorb and adapt to disturbances, which can effectively delay performance degradation, reduce system cascading failure probability, and improve adaptability to long-term hazards using the lowest cost. It will also identify those critical components in need of upgrading and retrofitting to mitigate critical service delivery failure or cascade failure.

Composites for improved reliability and durability: The American Road and Transportation Builders Association found that 46,000 bridges are structurally deficient and another 81,000 should be replaced. Composites can play a key role in rehabilitating crumbling infrastructures to achieve resilient design. In 2020, fibre-reinforced polymer bridge decking was used to rehabilitate two pedestrian overpasses in Atlanta, Georgia, U.S., replacing heavy, decaying concrete. The lightweight, zero-maintenance composite decks allowed contractors to use the original steel trusses, avoiding large disruption and downtime that would have been incurred with steel and concrete upgrades. The 100-year life of durable corrosion-resistant composites compares well to the 25-year life of steel-rebar-reinforced concrete [58].

P2.3 Consider complex interdependencies of connected networks

Design infrastructure to avoid the risk of cascading failures and provide redundancy using complex interdependencies.

Review critical infrastructure and uniformly plan all infrastructure to mitigate the risk of cascading failures from complex interdependencies. When alternative networks, such as road and rail, are available to deliver the same or similar critical services, they provide systemic resilience. But when different networks such as power and transport are coupled, vulnerabilities to failures can increase. The complex interdependencies of connected networks should be considered in the (re-)design for new infrastructure investments to reduce the risk of cascading failures and to provide redundancy. Critical interdependencies, that is those that create the most disruption in the event of failure, can be a focus for prioritisation and investment.

Infrastructure upgraded design considering the effects of interdependencies: Durban (eThekwini), South Africa is undertaking infrastructure design actions considering infrastructure interdependencies to mitigate risks of flooding from the city's river. The city is now designing their stormwater infrastructures and drainage infrastructures as an integrated system and has worked with the University of KwaZulu-Natal, which has provided downscaled global climate model data to the regional level and the city's catchment level. The university has estimated a 15% increase in rainfall by 2065, a time frame that is gradually becoming a design standard for infrastructure. Whenever the city receives complaints of flooding or waterlogging in the city, it checks for maintenance and time capacity; wherever it finds shortfalls (generally in older parts of the city), it is upgrading all interconnected systems and designing for the rainfall increase [59].

P2.4 Embed emergency management

Embed mature emergency management plans with sufficient financial support and strong governance.

Emergency management plans must be designed, tested and deployed in advance to respond to different disturbances and to provide back-up and dispatch of critical services to meet basic human needs. This includes travel to disaster zones by first responders as well as access to data and communications channels. The design of embedded emergency management plans must include regular testing and a refresh process to achieve continuous optimization and adaption to future requirements.

Redesign of emergency management plans considering the pandemic: In the midst of the outbreak of COVID-19, India experienced two major cyclones in May and June, 2021. Considering that the coupling of disasters with natural hazard origin and pandemics is showing an increasing trend in India and managing the competing demands of a lockdown with an evacuation is very challenging, transportation infrastructure designers should work with epidemiologists to set more exits and revise the standard operating procedures for evacuation to realize the efficient transfer of people. Meanwhile, food and water infrastructure designers should redesign access of emergency supplies to mitigate the risk of cross infection in the context of pandemics [60].

P2.5 Design infrastructure to fail safely

Design infrastructure so that when it fails, it is still safe.

Designing infrastructure so it is safe-to-fail focuses on sustaining safe conditions during disasters and disruptions. Safe-to-fail infrastructure accepts that there may be circumstances in which the infrastructure is no longer able to provide the services it was designed for but ensures that this failure occurs in such a way that safety is not compromised. The continuation of the basic services required to sustain safe conditions should be prioritised in the event of failure. A failed system should still offer a survivable environment. This should consider provision of heat, water, and shelter, as well as evacuation routes and access for emergency services. This key action is a reminder that systems will still fail despite proactive efforts, so when they do fail, they need to fail safely.

Flood Management: In the 1960s, the community of Scottsdale, Arizona, and the Army Corps of Engineers had differing opinions about how to best manage flooding in a rapidly urbanising area along the Indian Bend Wash. The traditional approach, advocated by the Army Corps, was to turn the wash into a concrete-lined channel. The Scottsdale community successfully fought the Army Corps to design and build an 11-mile-long greenbelt, consisting of parks, ponds, and golf courses, that allows the wash to flood without damaging the surrounding property [61].

P2.6 Design for multiple scales

Design for multiple scales to maximize the value of resilience investments.

Preventive and adaptive design solutions to achieve resilience should be addressed at different disaster scales, geo-political scales (including individual infrastructures, communities, cities, local and regional government (LRG) and national scales), and different time scales (from immediate to long-term), to maximize the value of resilience investments.

Design for resilience at every scale: The Resilient Houston project aims at linking existing infrastructures with new ones through integrating different system scales and time scales, which will collectively work to protect Houston against future disasters, from hurricanes to extreme heat waves, and chronic stresses such as aging infrastructure, poor air quality, and flooding. Resilient Houston is organized by different scales, to encourage every Houstonian, to use this framework for resilient infrastructure designing and planning at every scale. This project requires the newly designed infrastructures to achieve the following goals at five scales: prepared and thriving Houstonians, safe and equitable neighbourhoods, healthy and connected bayous, accessible and adaptive city, and innovative and integrated region [62].

P2.7 Commit to maintenance

Improve and commit to maintenance and operations.

Developing infrastructure asset management schemes at multiple levels including an inventory of assets, operating conditions, as well as all the strategic, financial, and technical aspects of management across their lifecycle, will create commitment to maintenance. Combining routine maintenance (e.g., annual frequency) with periodic maintenance (e.g., every 5 years) based on condition monitoring will improve reliability and extend the lifetime of infrastructure and provide better performance over time.

Maintenance to reduce water leakage: In 2005, Vietnam's largest city, Ho Chi Minh City, did not have enough water supply to meet demand because more than 40% of the water produced was lost as leakage of water infrastructures. To increase supply to customers, the state-owned water utility, Saigon Water Corporation procured a contractor for regular maintenance and leakage repair. After six years, more than 15,000 leaks were repaired and 122 million litres per day of water were saved, which improved reliability of supply and allowed new customers to be connected with water [63].

P2.8 Devise long-term investments

Plan strategically for the long-term so that investments are protected from challenges to resilience.

In order to protect investments and future proof the infrastructure against future resilience challenges, stakeholders must devise long-term investments that include strategies to protect investments and avoid negative impacts from their decisions. Long term thinking today is needed to protect investments for the lifetime of infrastructure systems [8]. Strategies and optioneering must focus on low-risk investment, and more certain chances for high profitability, to attract funds from the private sector and support requirements of resilient infrastructures across their lifecycle [22].

The National Infrastructure Plan (NIP) ensured the UK had an integrated strategy for how it would prioritise, finance, and deliver critical projects and programmes in the key economic infrastructure sectors: transport, energy, communications, flood defence, water, waste, and science. Through successive updates the NIP developed, responding to feedback from investors and the supply chain, to become a more mature and effective plan for UK infrastructure, underpinned by the National Infrastructure Pipeline. Besides, the new National Infrastructure Delivery Plan (NIDP) represents a further milestone reflecting a new approach to long-term infrastructure planning [64].

Principle 3 (P3)

Environmentally integrated

The goal is to work in a positively integrated way with the natural environment.

SUMMARY

The Environmentally integrated principle highlights the importance of the natural environment to both provide solutions to resilience and to be a risk to critical services' provision. The key actions aim to minimize harm to the natural environment which help to avoid rebound effects, to provide green and blue infrastructure that works with grey infrastructure, to support decision making using ecosystem information, and to reduce threats posed by the natural environment, such as trees falling on power lines.

BACKGROUND

This principle recognises the importance of working in a proactive and positively integrated way with the natural environment: biological (flora and fauna) and physical (land, air, water). Engaging with the social environment is addressed in principle P4, while acknowledging that some hazards in the natural environment are created by society. Principle P3 acknowledges the consequences of environmental degradation, some of which is caused by critical infrastructure itself, in raising vulnerability to hazards of a natural origin such as extreme weather events. This includes climate change which critical infrastructure both contributes to and attempts to reduce. Also, the consequences of having grey infrastructure can lead to greater investment needs in the natural environment.

Environmentally integrated also aims to identify opportunities of working with the natural environment in a positive way, such as planting trees to reduce the speed of flood water spread and protect critical infrastructure. Integration with the natural environment to employ natural capital in favour of building grey infrastructure must add value to natural ecosystems and not harm them. The natural environment provides a way to transform the resilience of critical services.

DEFINITIONS

- Natural capital consists of values and benefits produced by natural environments [65]; natural capital is the land, air, water, living organisms, and all formations of the Earth's biosphere that yields a flow of valuable ecosystem goods or services [66].
- Ecosystem services are the benefits of nature to households, communities, and economies [67]; they involve the conditions and processes through which ecological systems, and the species that make them up, sustain and fulfil human life [68].

NET RESILIENCE GAINS

- Reliability is improved through using green and blue infrastructures to provide ecosystem benefits. Disregarding natural capital can increase the risk of environmental irreversible damages.
- Reducing the risk of environmental damage by minimising the effect of infrastructure projects on the ecosystem to reduce rebound effects that impact infrastructure services delivery.

KEY ACTIONS

P3.1 Minimise environmental impact

Minimise the harmful effects of infrastructure projects and operations on ecosystems to minimise impact on the natural environment.

Minimising the effect of infrastructure projects and operations on the ecosystem will reduce the risk of harmful impact on the natural environment. Infrastructure systems can make changes on the natural environment with long term negative impacts in a way that alter the likelihood and magnitude of hazard events like pollution and climate change. Altering the characteristics of the built and natural environment changes the future risk profiles, the likelihood and magnitude of hazard events, and the vulnerability of society to those hazards. The resilience of infrastructure systems can be diminished by the redirected cumulative effects of hazards returning to infrastructures.

Thus, minimising environmental impact serves also to protect infrastructure from hazards in the natural environment.

Greenhouse gas emissions: The report, Infrastructure for Climate Action, looks in detail at the influence of infrastructure on climate action across energy, transport, water, solid waste, digital communications and buildings sectors. The findings highlight that infrastructure is responsible for 79 per cent of all greenhouse gas emissions, as well as 88 per cent of all adaptation costs [72]. Because past, current and future greenhouse gas emissions will influence the climate for decades, infrastructures need to act to ensure they can cope with: rising temperatures, changing rainfall patterns and rising sea levels, potential increases in extreme weather events, such as storms, floods and droughts, and possible changing patterns of demand [73]. In the winter of 2011, the UK suffered from disruption from snow on transport networks which cost the country over £600 million a day. Radical changes to how infrastructure is planned, delivered and managed are needed to make it suitable for a low-emission and resilient future and stop the worst effects of climate change.

Flooding: The formation of forest roads may increase floods by creating preferential paths of overland flow. In addition, the effects of deforestation to develop more indirect forest roads can include increased surface runoff on forest roads and increased soil erosion, and the development of gullies which both may enhance floods in steep terrain and increased snow accumulation and hence snowmelt in deforested regions [74]. However, preserving upstream catchments can mitigate flood risk, reducing the risk of road washout, and ensuring well-anchored vegetation above roads can reduce landslide risks [75]. For example, establishing plantations of appropriate trees between roads and rivers around the large Cambodian rivers, or in belts on the river side of roads, wherever there is a danger that rivers may eventually cut their way closer to roads, is a logical long-term strategy [76]. Another example is the poor location of an aluminium smelting factory between two rivers, the Takahashi and the Shimpon. This location posed a risk of flooding to the factory which happened in 2018, leading to the explosion of the factory, another nearby factory, and neighbouring houses [77].

P3.2 Use environmental solutions

Incorporate environmental solutions to provide the best suitable mix of grey, green, and blue infrastructure.

Infrastructure solutions that involve working with natural capital to address societal challenges, provide benefits for both human well-being and biodiversity as well as resilience for infrastructure systems. Incorporating mechanisms from the environment such as ecosystem services and nature-based solutions for disaster risk reduction [78] will support the resilience of infrastructure systems by increasing their hazard protection, and functional substitutability [8]. Any integration with the environment must ensure that the environment is protected from harm and restores natural and modified ecosystems wherever possible. Combining blue-green infrastructure like coral reefs and mangroves with grey infrastructure can provide lower cost, more resilient, and more sustainable infrastructure systems [44].

Green roofs and coral reefs: The implementation of green roofs [79] not only increases roof longevity because the membrane is protected from weather conditions by the soil layer, but it also has a direct impact on air quality improvement and energy saving [80]. The presence of coral reefs, which are one of the most biodiverse ecosystems on Earth, halve the risk of damages from flooding and divide the costs by three from frequent storms [81]. The projected savings were greatest for Indonesia ($639 million); the Philippines ($590 million); Malaysia ($452 million); Mexico ($452 million); Cuba ($401 million); and the United States ($94 million)—a combined savings of more than $2.6 billion for those six countries [82].

In addition to economic, environmental, and technical benefits, providing nature-based solutions in the wider landscape can boost important ecosystem services for societies such as the provision of clean water and air, food production, and nature-based tourism and recreation [75]. The Seychellois government has been moving to improve resilience along its coasts and a significant step in this direction was the endorsement of the national Coastal Management Plan (CMP) in 2019. The CMP proposes coral reef management and rehabilitation in 5 out of 18 priority areas, alongside other nature-based solutions and grey infrastructures (such as dams, seawalls, roads, pipes or water treatment plants) to reduce vulnerability to flooding and erosion while maintaining the beauty of the coastline. And in most locations, coral restoration is combined with artificial structures to deliver significant coastal protection. Blue barriers involve the construction of a submerged structure using natural non-toxic materials that can serve as a stable and hard substrate for coral colonization, supporting coral recovery and the development of more biodiverse benthic communities. Nature-based approaches that combine engineering with rehabilitating coral reef systems represent a new tide of innovation to build coastal resilience while protecting natural capital and boosting the economy, especially in small island developing states, which are among the most vulnerable globally to disasters with a natural hazard origin and climate change [83].

Design with green spaces for climate resilience: The informal settlement of Mukuru, in Nairobi, Kenya is suffering from higher temperatures and flooding due to its surface properties and close proximity to the flood-prone Ngong River. Cooler shelter and infrastructure design with the provision of green spaces (e.g. tree planting) not only reduces exposure to high temperatures due to cooling effects of vegetation and shading nut also reduces exposure to flooding as green spaces enable infiltration and slow runoff, as well as retaining excess water [87].

P3.3 Integrate ecosystem information

Integrate ecosystem information into decision-making processes to avoid hazards from the natural environment.

Integrating ecosystem information into decision-making processes is necessary to mitigate risks and conflicts between natural and built environments in and around the site of the project. Including ecosystem information in decision-making helps to mitigate development losses from ignorance of ecosystem functionality as well as reducing the likelihood of infrastructure investments causing large ecosystem losses for small development gains. Providing ecosystem information facilitates the selection of projects with less ecosystem-related conflicts and more synergies across sectors [75].

Copenhagen urban green spaces: Ecosystem information, specifically Volunteered Geographic Information (VGI) via social media, can be used to document spatial tendencies regarding citizens' uses and perceptions of urban nature with relevance for urban green space governance. The purpose of the ecosystem information is to support accessible, transparent, democratic, inclusive, and locally-based governance situations of interest to planners, citizens, politicians, and scientists. In 2014, the City of Copenhagen collected data consisting of geo-referenced images from Instagram, categorised according to their content and analysed according to their spatial distribution patterns. The results support scientific and democratic interaction, however VGI data is challenged by practical, technical and ethical concerns.

P3.4 Maintain the natural environment

Proactively maintain the natural environment around infrastructure locations to reduce exposure to vulnerabilities.

Proactively managing the natural environment (overgrown vegetation, risk of flooding, etc.) at and around infrastructure locations will reduce exposure to vulnerabilities [8] and return the natural environment closer to its initial conditions. It can also help to improve biodiversity and net environmental gain which is a win-win approach to mitigate the consequences of grey infrastructure that could lead to greater investment needs in the natural environment. Management and maintenance of surrounding natural environment is a no-regrets option for boosting the resilience of infrastructure assets [8].

Natural Vegetation: Good maintenance of the vegetation on each side of power transmission lines is crucial to reducing vulnerability to strong winds since vegetation is the primary cause of pole damage, not the strong winds themselves. Therefore, reinforcing poles is less efficient than trimming trees. In September 2017, Hurricanes Irma and Maria severely damaged the power grid in Puerto Rico, largely because of trees falling on the transmission lines. As a result, 100 percent of Puerto Rico Electric Power Authority customers lost power for more than a week after the storm, and the slow pace of recovery left many customers in the dark for several months [84]. Besides trimming trees, some utilities in the United States are encouraging native low-growth vegetation. Such vegetation management thus comes at a lower cost to the utilities, more resilience to damages, and can create a network of wildlife corridors under transmission lines [85].
Wildfires: Electricity transmission and distributional lines can trigger wildfires which damage everything including infrastructures. In California in 2007, San Diego Gas and Electric was found liable for $2 billion in damages from three fires that led to two deaths and the destruction of 1,300 homes [69]. Making safer infrastructures and good natural environment maintenance, like forest maintenance, can prevent this kind of hazard [8]. The other example is a dam failure in Zimbabwe in 2014. Chivi District, the origin of the Tokwe-Mukosi communities, receives an average annual rainfall of 400 mm typically, but between January and March 2014, received 850 mm of rainfall. While some resettlement efforts were underway, the incessant rainfall breached the dam walls under construction, causing the largest water release by failure in the world and inundating 5,793 families upstream and downstream [70], [71]. Embankment failure by flooding during construction is often overlooked but has been and remains a very serious risk. Failures have been linked with construction delays and have happened when the reservoir was quite full [71].

P3.5 Use local sustainable resources

Use local and sustainable resources to avoid the risks of single-sourcing, distant, non-renewables resources.

The availability and sustainability of resources required for infrastructure operations is improved through a resilient design strategy preferring the use of local, sustainable resources. Resources, especially single sourced, non-renewable, and distantly located, are easily affected by disturbances. Abundant local sustainable resources (such as solar energy, annually replenished groundwater, and local food and materials) should be chosen.

Sustainable and local energy: The Green Village Electricity project is a rural electrification scheme designed to provide clean and reliable energy locally to off-grid rural communities in Nigeria. Stand-alone solar PV mini-grids offer sustainable and resilient solution today as either the sole source of generation or in hybrid configuration with other generation sources [86].

Principle 4 (P4)

Socially engaged

The goal to develop active engagement, involvement, and participation across all levels of society.

SUMMARY

The Socially engaged principle aims to actively engage with people and communities so that they have a better understanding of how they can help to prevent and respond to disruptions. Infrastructure stakeholders, particularly local and regional governments and private enterprises who have these relationships, will: create better information about disruptions; increase the literacy of the public about resilience; communicate incentives to reduce demand, especially in disruption situations; and, encourage community participation and a sense of ownership in planning and development of infrastructure and in avoiding intentional damage and theft.

BACKGROUND

The Socially engaged principle will support people and communities to contribute to infrastructure resilience. Community resilience in the event of disruptions (including disruptions to critical services) is outside the scope of these principles, as it is covered by civil contingencies and other community resilience guidance.

Social responsibility is becoming increasingly prominent as an alternative mechanism to prevent and respond to system's failure [88]. Being socially responsible relies on infrastructure stakeholders increasing their social awareness, taking a more active role, and improving self-management skills, resulting in more consciousness about how our decisions and actions can affect the whole system [89]. Infrastructure systems are socio-technical systems which face challenges that can be addressed by improving social responsibility to make more resilient systems. This includes aspects of awareness, activism, and incentivisation of people for all concerns [90]. But essential to stakeholder engagement is trust, and this needs to be developed over time and reinforced by setting out and meeting the expectations of critical services' users.

Infrastructure stakeholders (particularly local and regional government, small to medium enterprises, construction companies) with responsibilities for engagement with critical services' users and communities must develop trust and work to increase awareness, understanding, co-responsibility, and participation of society to improve infrastructure resilience. Critical services' users and communities can bring local experience and native expertise into infrastructure planning and development; they can respond more effectively to requests to reduce or defer demand, and can be supportive during disruptions and disasters. Evidence of mechanisms for private sector engagement with the community on infrastructure construction projects [91] is just one example.

More understanding can be achieved through social engagement of the communities' need for more resilient alternatives and greater willingness, as necessary, to pay more (e.g., via taxes, where relevant) for resilient infrastructure. Support by a community for the resilience of its critical services can result in human flourishing which is the fundamental purpose of infrastructure [92].

DEFINITIONS

- Social responsibility is the ideological notion that individuals and organisations should not behave unethically or function amorally, and should aim to deliberately contribute to the welfare of society or societies, comprised of various communities and stakeholders, that they operate in and interact with [93].

- Socio-technical systems are an approach that consider human, social, and organisational factors, as well as technical factors in the design of organisational systems [94]; they apply an understanding of the social structures, roles, and rights from social science to inform the design of systems that involve communities of people and technology [95].

- Critical services' users are people, businesses, industries, government, organisations who benefit from the products and services provided by national infrastructure usually in exchange for a fee [96]. We avoid the use of consumer terminology and the marketisation of infrastructure because critical infrastructure services are a unique class of goods that should be available and accessible to everyone, including those with disabilities and impairments.

NET RESILIENCE GAINS

- Providing public support for resilience of infrastructures across the whole life-cycle.

- Ensuring the public awareness and acceptance of technical advancements and transition plans.

- Diffusing sense of belonging and trust among people for greater willingness to engage in demand response especially during disruptions and disasters.

- A healthy and wealthy community supported by resilient infrastructure will demand continuous improvements in resilience to meet their evolving needs.

KEY ACTIONS

P4.1 Inform people about disruptions

Inform people about upcoming or ongoing disruptions to reduce pressure on critical services' provision.

Informing critical services' users, about upcoming or ongoing disruptions to reduce pressure on the operating systems is essential. The majority of critical services' users have little awareness of the consequences of their consumption behaviour of critical services. This is especially true during disruptions and disasters with demand and supply mismatches where critical services' users do not know if their consumption behaviour challenges the resilient operation of infrastructure systems. So, the active responsibility for matching demand and supply is assigned to operators with critical services' users have no role in maintaining resilient operation of infrastructures [38]. In this regard, both local and regional government (LRG) and private sectors must be informed and involved to take necessary actions toward informing critical services' users, managing disruptions and disasters, providing information on changing service levels (pre- and post-disaster). Joint decisions with the community are important to understand risk appetites and implement comprehensive risk management so the service base levels of investments are based on realistic expectations.

In the aftermath of Hurricane Isaac, which came ashore in Louisiana in August 2012, there was unprecedented demand for customer interaction, along with the physical challenge of restoring service. For the first time ever during a major event, Entergy, the electric utility company, interacted with the public via social media, communicating with more than 32,000 customers. More than one million hits were recorded on the company's website. Traditional communications were also heavily used, with more than one million calls from customers and nearly 1.4 million texts to customers during the storm [97]. In times of disasters, social media sites are "digital habitats" where users converge to gather information and resources [98]. A case study of the 2011 Thailand Floods found that people tended to use social media because other sources of information such as mainstream news media and journalists did not provide updated or needed information [99].

P4.2 Raise resilience literacy

Educate the public with necessary information on resilience to create well-informed and engaged people.

Developing resilience literacy, by educating the public including future critical services' customers, and sharing information will enhance a two-way dialogue between the public and infrastructure stakeholders and create deeper empathy for plans and interventions around resilience, and the motives behind these. Well-informed people acknowledge the necessity of technical advancements and support transition plans toward renovating, modernising, and smartness. Moreover, public emotion of a resilience-aware community can create leverage for necessary changes. Education through the development of literacy and technical skills of citizens is the most important factor influencing resilience [100]. This key action will involve education providers who will need to be informed by infrastructure stakeholders about infrastructure resilience.

Solar energy technologies in the Americas: Inclusion of homeowners is necessary to make blockchain based distributed solar networks and battery storage viable in Puerto Rico as a backup for power outages after hurricanes [101]. However, this requires greater understanding and cultural acceptance of the new technologies among local people. A similar study conducted in Santiago, Chile [102] emphasised on increasing customer knowledge on technologies and services as one of the critical factors affecting societal uptake of household solar photovoltaic technologies.

No Code, No Confidence: the Federal Alliance for Safe Homes (FLASH) has created a tool to make it easier for customers to understand building codes. The non-profit alliance's No Code. No Confidence initiative makes finding the local residential code status easy for anyone wishing to learn more [103]. FLASH found that two-thirds of participants stated they would be very or extremely concerned to learn they had no code at all, using words such as "terrified" to describe the scenario. New awareness on this issue has led state leaders to propose state-wide adoption of the International Residential Code (IRC) [104].

P4.3 Incentivise demand behaviour

Incentivise people to reduce demand to reduce pressure on critical services' provision.

Incentivising the behaviours of critical services' users provides the capacity to make adjustments in consumption behaviour to reduce demand and provide demand response. The most common way of motivating people for participating in measures to improve infrastructure resilience is based on monetary benefits. The most prominent examples for such approaches are real-time pricing, time-of-use rates, and critical peak pricing, where critical services' users can save money by adjusting the points of use in time of non-peak hours when they consume power or transportation services [38]. The idea of responsible transport recognises the importance of individual behaviour and collective responsibility to protect personal and public health during the Covid crisis when forming transport infrastructure policies [105]. There are also social reward approaches act based on moral and intrinsic values, sense of achievement, and sense of comparison. The private sector such as utility companies as well as public authorities can be involved to implement the necessary actions but will need information from infrastructure stakeholders. The regulators of critical services also have a role to balance community demand for critical services with infrastructure resilience.

Dynamic pricing schemes have the power to adjust energy consumption behaviour within households. They require timely notifications of price changes, but often the success of the pricing scheme depends also on other factors, including that the end users should be engaged with them [106]. Providing data and information for power grid users in a way which is understandable for them can derive actions that both support their own interests and the overall resilience of the grid [38]. In Chile, subsidies are an important pillar for successful household adaptation, financing the initial installation of solar photovoltaic panels [102].

The public understanding of the importance of energy security helped to avoid power cuts after an earthquake in Japan in March 2022. Japanese energy users turned off neon signs, dimmed their lights and dialled down thermostats after the government issued an urgent call to save energy to avoid blackouts after earthquakes caused a serious power shortage [107].

In Africa, with recent substantial cost reductions, solar photovoltaic (PV) offers a rapid, cost-effective way to provide utility-scale electricity for the grid and modern energy services to the approximately 600 million Africans who lack electricity access. With the fall in solar PV costs, solar PV mini-grids offer important economic opportunities today as either the sole source of generation or in hybrid configuration with other generation sources. Stand-alone solar PV mini-grids or solar PV-hybrid mini-grids have installed costs in Africa ranging from USD 1.9 to USD 5.9/W for systems greater than 200 kW which came with higher costs in 2012 and earlier [108].

P4.4 Encourage community participation

Encourage community participation to create shared responsibility for infrastructure.

Inclusive decision-making with communities and monetary and non-monetary participation of people can increase the sense of belonging, ownership, and trust. The early participation of people and working toward co-responsibility throughout the infrastructure lifecycle – from the design and options selection to de-commissioning and post disaster actions and expectations - can provide opportunities to address trust through place-based engagement and targeted measures to improve inclusiveness and accessibility and enhance resilience of infrastructure systems. Community participation can also mitigate vandalism, damage [109], and theft [110] [111], and other undesirable behaviour that compromises infrastructure resilience.

The relationships with people and the community are often managed by local and regional government (LRG) and the private sector (e.g. waste removal, utility billing) who need to work with infrastructure operators, contractors, and national government to provide successful intermediation with communities. Note that P5.5 considers the necessity of remaining vigilant about the sensitivity and confidentiality of the information shared with the public. Conversely, the public may be willing to their data on national infrastructure and their data may even be collected without explicit consent (e.g. by Closed Circuit TeleVision – CCTV, or urban sensors). Any personal or sensitive data must be protected according to national legislation.

The Peru Rural Roads Program (known as PCR) is an example of how community participation in a large-scale rural roads program can contribute to rural transport, local economic development, and local governance. The PCR was initiated in 1995 under a central agency within the Ministry of Transport and Communications (Provias Descentralizado), to support the decentralization of rural roads management to local governments. The first phase focused on the rehabilitation and maintenance of rural roads in the country's 12 poorest departments, representing about 70 percent of the rural population of Peru. By 2008, the program was scaled up to cover the entire country. Communities and their local representatives identify and prioritize the roads to be rehabilitated and maintained, providing accurate information on which transport routes are important for communities, then communities, organized into microenterprises (MEMV), carry out the maintenance of rural roads. Community participation generates ownership and ensures sustainable maintenance (and consequently access) of rural roads, since communities using and living close to the roads have a direct interest in maintaining them [112].

In Zambia at Nkana Water and Sewerage Company an integrated approach to reducing vandalism in low-income communities was devised. They increased the community's sense of ownership by introducing a fair financial contribution to construction costs, bringing about the desired change in behaviour [113].

Principle 5 (P5)

Shared responsibility

The goal to share information and expertise for coordinated benefits.

SUMMARY

Shared responsibility is about infrastructure stakeholders taking shared accountability for infrastructure resilience by sharing information and expertise for coordinated benefits. This includes engaging with social infrastructure stakeholders. The key actions will create transparency and insights for organisations with common interdependencies through: sharing information using common standards and practices; cultivating collaboration, including with technical and financial organisations, via appropriate governance mechanisms; establishing shared responsibilities through clarity of roles and accountabilities; implementing mechanisms and platforms for sharing; making sure that shared data on resilience is secure and trusted; and collaborating on risk and return information.

BACKGROUND

In order to move away from the traditional siloed and sectoral approach to management, a collaborative approach must be encouraged for the sharing of data, knowledge, and expertise. Organisations with common interdependencies should be able to share data in a standardised way and generate shared insights into how to handle common threats. Shared knowledge across sector boundaries can also be in the form of human skills and expertise. To facilitate the sharing of resilience information, it is important to establish high levels of resilience literacy among all stakeholders (not just for P4.2). A cooperative approach to management and planning, including technical cooperation and financing, generates benefits from diverse knowledge and experiences, bringing both confidence and insight. Clear designation of roles and responsibilities enables a clear and coordinated approach to infrastructure resilience management, whilst ensuring transparency and accountability. Information sharing facilitates learning from mistakes and preparing a coordinated response to shared hazards or vulnerabilities.

A shared approach to resilience must involve international and cross-sectoral efforts, accounting for complex interdependencies between systems which will mitigate risks to critical services' provision. P5 is aligned with the vision of SDG17 [114] to "strengthen the means of implementation and revitalize the global partnership for sustainable development", and its ambition for improved and more equitable trade, as well as coordinated investment initiatives given the global interdependencies of infrastructure. This means to embrace the strong relationships with, and the consequences for, social infrastructure resilience (health, education, fire service, financial sector, food supply industry, etc.) and community resilience.

NET RESILIENCE GAINS

- Sharing of information develops more accurate resilience models, and enables a reduction in the frequency, duration, and impact of disruptions [115].
- A collaborative approach with defined responsibilities and accountabilities enables early identification of potential threats and facilitates a timely response to disruption.
- Engagement will increase diversity in resilience planning, developing more robust solutions.

DEFINITIONS

- Multi-level governance describes a system of continuous negotiation among nested governments at various territorial tiers (local, regional, national, international etc.) [116], [117].
- Polycentric governance is a system in which multiple governing bodies work together to create and enforce rules within a specific sector or location [118]; this contrasts with multi-level governance which has been effective at multi-level dialogue to define investment priorities for regional development [119]. Polycentric governance is less hierarchical than multi-level governance, with many independent centres of decision-making that interact within and across jurisdictional levels [120]. Local and regional governments, rather than national bodies, may take on a more significant role in the development and implementation of resilience policies under this approach.
- Data stewardship is the process by which an independent organisation facilitates safe access to sensitive data; these data institutions control who is allowed to access the data they steward, what data those people are allowed to access, how those people may access or interact with that data, and what those people are allowed to use that data for [121].

KEY ACTIONS

P5.1 Harmonise open standards

Develop and follow common standards and practices for straightforward sharing of information.

Harmonised open standards will facilitate the sharing of data across sectors [115]. Measures should be in place to ensure compliance with necessary standards and regulations, and to encourage adoption of, and continued adherence to, optional but beneficial standardisation initiatives. Information should be designed and usable by infrastructure stakeholders. Resilience literacy will be improved through harmonisation and agreement on terminology for open standards.

Standardised Information Sharing Protocol (ISP): The Wider Eastern Information Stakeholder Forum (WEISF), UK, is a partnership network of information governance professionals supporting good information governance and best practice. It helps partners with GDPR (General Data Protection Regulation) compliance and transparency in data sharing. The partners work together to develop a standardised ISP template and publish ISPs on the WEISF Portal for transparency. The protocol details how and what data partners share. It also explains the legal basis for the sharing [122].

P5.2 Cultivate collaborative management

Cultivate collaborative management and encourage sharing of expertise across boundaries.

Fostering open communication within and between sectors and enabling inter-sectoral exchange (e.g. between the power industry and public transport organisations) will provide opportunities for learning and experimentation. Encouraging and developing polycentric governance will result in broader levels of participation, creating modularity and redundancy that minimizes and corrects errors in governance [118]. Developing technical cooperation including financing across infrastructure stakeholders will encourage a shared understanding of governance and investments. Working with social infrastructure stakeholders to understand their needs of critical infrastructure systems will develop better engagement and empathy. Traditionally financed and operated infrastructure projects using resources from taxes and levies and led by the public sector can cause problems known as government failure including: slow and ineffective decision-making, inefficient organisational and institutional augmentation, and lack of competition and inefficiency. Whilst purely private approach can cause problems such as market failure through inequalities in the distribution of infrastructure services. To overcome both government and market failures, and successfully deliver sustainable infrastructure projects, a collaborative public-private collaboration strategy is advocated which incorporates the strengths of both polarised positions [123].

The Architecture, Engineering and Construction (AEC) sector: The Eastern Harbour Crossing Tunnel in Hong Kong was procured through a BOT (build-operate-transfer) arrangement of 30 years. A BOT arises when a public entity, usually a government, grants a concession to a private company to finance, build and operate a project for a long period of time with the goal of recouping its investment, then transfers control of the project to the government. For the Eastern Harbour Crossing Tunnel construction started in September 1986, and was completed half a year ahead of schedule and within budget. The success of the project was attributed to an established and equitable legal and regulatory system [123].

P5.3 Establish shared responsibilities

Proactively establish a shared understanding of resilience goals, giving explicit consideration to acceptable outcomes, thresholds and timelines.

Identifying the responsibilities of different stakeholders and organisations in terms of their objectives, operations, and assets, and putting these responsibilities at the centre of communication and engagement efforts, will create transparent and explicit pathways to ensure accountability. Delineating responsibility highlights failings in actors' (such as an asset owners or operators, or land use planners) processes/behaviours and helps to re-align incentives so that these parties change their practices/behaviours to improve resilience. Establishing collaborative engagement will enable the sharing of unified stakeholder responsibilities. Engaging a diverse, cross-sectoral group of stakeholders, including from across scales of government, the private sector, academic and expert groups, and community organisations, and collaboratively reviewing responsibilities and objectives with the support of infrastructure regulators will allow setting of acceptable outcomes, timelines etc. International partnerships may also be appropriate for infrastructure projects where countries face shared or similar threats, or where a methodology adopted by one country may be applicable in partner nations. Where possible aligning with Sendai Framework Target F will enhance International cooperation with developing countries to support their implementation of the Sendai Framework and to improve global resilience of infrastructure [5].

Polycentric governance of irrigation in Kenya: Kenyan farmers are regularly affected by drought, with upstream and downstream farmers vying for limited resources. Prior to the 1990s, water resources in Kenya were governed by formal rules that limited the ability of local farmers to share their concerns. Persistent poverty among tenants of large irrigation schemes undermined livelihoods, and farmers began to implement their own approaches to water governance which were, in some cases, violent. In response, Kenya has reformed its water and irrigation laws to facilitate participation of local water users in the resource allocation process. Kenya has adopted a polycentric approach, giving local communities the autonomy to implement locally appropriate approaches to water governance, and creating institutions to encourage communication and coordination between communities, and promote shared decision-making among local, regional, and national authorities. This approach, with the government actively encouraging locally- led solutions, has been able to mitigate shortcomings in water governance and promote learning and adaptation over time [124].

P5.4 Enhance connectivity for information sharing

Enhance connectivity to enable the sharing of valuable information including data, knowledge, and operational practices.

Providing adequate platforms that infrastructure stakeholders can access and understand is important for sharing information on disaster risk reduction. While digital connectivity is crucial for the sharing of data, it is also important to establish an environment in which relationships can be developed for the sharing of resilience knowledge across boundaries, including technical and specialist expertise. Information should be shared through accessible channels, in a way that is clear and understandable. Connectivity should extend beyond operators to include relevant authorities and institutes, infrastructure system users, and resilience networks such as membership-based groups. Those using this information to make decisions must be made explicitly aware of how to interpret any given information for their specific needs.

Information Sharing and Analysis Centres: In the US, Information Sharing and Analysis Centres (ISACs) have been established to help critical infrastructure owners and operators protect their facilities, employees and customers from cyber and physical security threats and other hazards. ISACs collect, analyse, and disseminate actionable threat information to their members and provide members with tools to mitigate risks and enhance resiliency. The National Council of ISACs (NCI) oversees the work of ISACs to facilitate cross-sector coordination, particularly during security incidents and disasters with natural hazard origin [125].

P5.5 Assure data safety to develop trust

Assure data safety to develop trust between organisations and the public.

Secure data practices encourage sharing of data between organisations and improve resilience to malicious attacks. While data sharing brings many benefits, it can only be achieved if infrastructure stakeholders and critical services' users have confidence that their data is secure. Implementing data governance, accountability, privacy, security, etc are essential to build trust which is essential during disruptions and disasters. Data stewardship organisations, government regulation, and technologies such as secure gateways are some of the ways data security can be improved [115].

The Open Data Institute works with companies and governments to build an open, trustworthy data ecosystem. They have published a Trustworthy Data Stewardship Guidebook, which provides a systematic way of examining how an organisation collects, manages, uses, or shares data. The guidebook describes the importance of documenting data practices and demonstrating data trustworthiness [126].

P5.6 Share risk and return information

Share risk and return information for risk assessment and investment in resilience.

Securing investments into resilience will happen more readily by sharing risk and return information, and building on technical cooperation established in P5.2. The disclosure of high-quality information related to risk assessment, financial reports, regulatory filings, accounting information, etc is critical for effective decision-making by investors and other stakeholders. Investor demand for greater transparency also includes increasing requests for the disclosure of non-financial information, such as governmental, social, and environmental and climate change data, that allows the resilience of infrastructure to be assessed more accurately. This needs to bring (evolving) climate and disaster risk considerations into methodologies on calculating internal rates of return and to ensure predictable and sustainable financing at multiple levels: national, regional, local, community and organisational.

Collaboration between the public and private sectors must be promoted and strengthened through the transparent exchange of necessary risk information. Effective strategies must align public and private investments, such as public-private sector partnership initiatives. Central to this demand is the argument that the disclosure of such data improves the ability of investors to evaluate and understand a company's long-term risks and that it is therefore relevant to investment-related decision-making. It is not only vital for the functioning of efficient capital markets but also provides a wider audience beyond investors, such as Governments, employees and other stakeholders, with information that is useful for assessing stewardship and making economic and policy decisions [127].

In 2019, the NAIC's Center for Insurance Policy and Research (CIPR) and Capital Markets Bureau collaborated on an infrastructure study for the insurance industry. The purpose of the study was to develop a better understanding of infrastructure investments and the dynamics of that market as it relates to the U.S. insurance industry as an institutional investor [128].

P5.7 Mitigate avoidable resilience losses

Avoid resilience losses and mitigate the impact of risk.

Strategies and pre-design plans for infrastructure projects that take resilience as a core value must consider the consequences of failures. Avoiding losses due to lack of resilience requires a transformation that focuses on systemic resilience. Some losses may be acceptable if they can offset against system specific resilience gains. Mitigation of the impact of risk through following the mitigation hierarchy and minimising compensation for losses will provide a focus for resilience investment and related insurance. The mitigation hierarchy [21] sets out rules for avoiding losses. In the first instance, infrastructure investors, developers, providers, and operators should work to determine their impact on natural assets and take the appropriate steps to avoid, mitigate or compensate against any negative impact by restoring and enhancing the condition of surrounding natural capital assets. Next, they should avoid negative impacts as far as possible, minimising unavoidable impacts. As a last resort, they may compensate for unavoidable losses wherever the greatest benefits can be delivered, either locally or nationally, first considering compensating for losses within the development footprint.

Mitigation at options stage: A Federal Highway pilot project in the state of Maine, USA, evaluated the cost-efficiency of the design of bridges and culverts in a different location under a range of sea-level rise and storm surge scenarios, cumulatively over time, to find the most efficient design and suitable location that could save up to £0.5 million [129].

Principle 6 (P6)

Adaptively transforming

The goal to adapt and transform to changing needs.

SUMMARY

The principle adaptively transforming enables systems involved in the planning, design, construction, and delivery of critical services to adapt and transform. The key actions contribute to net resilience gain by: creating adaptive capacity to reduce failures; responding to the unexpected; going beyond regular system boundaries when required; and enabling infrastructure systems to bounce forward when needed.

BACKGROUND

Adaptive transformation is the ability to change the ways in which infrastructure systems are run, or to change the desired outputs of these systems, in response to changes in the wider context within which they operate. This principle recognises that, in a world facing the evolving hazard of climate change, the requirements placed on our infrastructure systems in the future may look different from those placed on them today. Creating the ability to operate outside normal conditions improves infrastructure resilience by absorbing the unexpected and changing when needed in order to maintain operational/service continuity and flexibility. Ideally, infrastructure systems must be developed with this in mind, encouraging stakeholders to incorporate flexibility into supply chains, delivery methods, organisational structures, and operational methods including early warning, evacuation, etc. However, adaptivity must go beyond the design phase, forming part of an ongoing cycle where the outcomes of continuous learning are implemented as changes in relevant infrastructure, management, and information systems.

Wherever possible, a proactive approach is preferred, anticipating potential threats to infrastructure systems through appropriate monitoring and modelling. The principle Continuously Learning provides the ability to anticipate future challenges, changes, threats, and disruptions, creating an awareness to change. However, some of these future challenges may be unexpected, requiring infrastructure to adapt beyond expected boundaries in order to absorb the disruption. It may be that these necessary adaptations become the 'new normal', transforming the system into one better able to respond to potential hazards.

Adaptively transforming provides the capabilities not just to recover or bounce back, but to adapt and transform when (unexpected) challenges or changes are already happening. Transformations must be relevant to country needs, e.g. Small Island Developing States (SIDS) may prefer replaceable infrastructure based on frequency of hazards. Transformations may involve socio-institutional change [130].

Transformations may need to be radical, such as abandoning infrastructure that is no longer fit for purpose. However, it cannot be assumed that all attempts at adaptive transformation will succeed. This highlights the importance of the P1 Continuously Learning principle and to learn from experiences of failures and avoid maladaptation.

DEFINITIONS

- Adaptivity capacity is the ability (or capacity) of a system to modify or change its characteristics or behaviour so as to cope better with existing or anticipated external stresses [131].
- Adaptive transformation is the outcome of implementing adaptive capacity which leads to transformed infrastructure that has better systemic resilience.
- Extensibility is the ability of a system to extend its capacity to adapt when surprise events challenge its boundaries [132].

NET RESILIENCE GAINS

- Consideration of adaptive capacity enables infrastructure to adapt to changes brought about by stressors such as climate change and population growth. This increases the ability of infrastructure to absorb disturbances and, depending on methods used, can increase system redundancy.
- Infrastructure systems with manageable solutions, manual override capacity, and flexible management structures are able to respond in a timely way to threats and disturbances.
- Flexible and extensible infrastructure can mitigate disruption and evolve beyond system boundaries to ensure resourcefulness in the face of unexpected disturbances.

KEY ACTIONS

P6.1 Choose manageable solutions

Select solutions based on skills and resources availability, and the fitness of the solution to the changing environment.

Solutions to provide critical services need to be fit for local contexts and have buy-in. Viable solutions must be able to handle the variability of a changing environment [12]. Interdependencies mean that all critical infrastructure systems are inherently complex, so appropriate solutions that use available operational and maintenance skills are needed. This key action recognises the limits to controllability of socio-technical systems [133]. A simple or modular approach may be more suitable for restructuring or adaptation later in asset life, and also has benefits for maintenance and repair. Manageability and feasibility of solutions must be considered, helping to establish buy-in from the community served by the infrastructure. It may be appropriate to adjust the complexity of solutions in response to any unexpected changes to operating conditions, transforming the infrastructure as the availability of resources and needs of users evolve.

The Sand Bag House was the first qualifying solution into the 10 x 10 Housing Initiative of the South African based design organisation, Design Indaba. They developed the housing project to build 10 pilot homes within a squatter area on the outskirts of Capetown in a bid to address the area's housing shortage in a way that would conserve money and resources. The home uses inexpensive local materials which cuts down on transportation, a local 'future-resident' community workforce, and a construction method that replaces traditional brick-and-mortar with sandbags (developed by ecobeams) to create a strong, safe and cheap way of delivering affordable housing. The system is reported to be just as strong as a brick system and uses less timber than traditional construction. Standing on two-storey timber frame, with the sandbag infills, the house is energy efficient, requiring no electricity or skilled labour to construct. It is a very scalable prototype that can serve larger families and grow to multifamily structures. The Sand provides very good thermal quality and prevents moisture from getting through. Aside from being waterproof, the sandbags also create soundproof and fireproof spaces and allow for a rapid pace of construction, saving time and money. It took about 12 weeks to erect 8 of the 10 homes. The blueprints and designs were compiled into a manual and donated to African Governments for royalty free use in developing similar projects as solutions to housing shortages [134].

P6.2 Create adaptive capacity

Build adaptive capacity into infrastructure systems at all life-cycle stages to allow flexibility in decision making, transitioning, and problem solving.

Flexibility in systems' designs and operation is key as disaster and climate risks cannot be eliminated and therefore actions to reduce socioeconomic impacts and loss of life is paramount. Adaptive capacity must be monitored and reviewed during design and operational stages, and multi-year planning cycles. Adaptive capacity must be created through selection of projects and actions based on the latest science and in anticipation of any projected shift in supply or demand. Adaptive capacity must be addressed in business continuity planning and operations management including early warning and evacuation systems. A simple example of this would be utilising cloud computing, rather than onsite data banks, to mitigate the risks of failure of co-located data storage and infrastructure delivery.

In Indonesia, adaptive capacity has been created by looking for opportunities at the water-food-energy nexus. With a focus on increasing water security, a flexible approach to land use has been adopted, utilising integrative planning tools such as LUMENS (land use for multiple environmental services) to promote resilient agroforestry solutions [135].

P6.3 Develop flexible management

Develop dynamic and flexible management/organisational structures to enable the workforce to adapt in the event of a disturbance.

Flexible management is needed so that a workforce that can adapt dynamically to the changing needs of disturbances. Teams must be developed with an emphasis on transparency, establishing an environment in which there is room for constructive and challenging discussion. This approach can go beyond organisation boundaries to include a dynamic and evolving relationship with critical services' users, regulators, civil authorities, and other system operators. Ensure that decision-making teams are diverse and representative and provide feedback channels to ensure active engagement with management.

Tucson Water is a municipally owned and operated water utility that supplies drinking water to the Tucson Metropolitan Area in Arizona, US. In the early 1970s, Tucson was an 'oasis' city. In 1976, to fund much-needed new infrastructure, Tucson Water increased rates. The Tucson Citizens' Water Advisory Committee (CWAC) was created to increase transparency, eventually getting residents to support a rate increase and improve public education and peak flow reduction, which saw Tucson adopt conservation values and transform from an 'oasis' to a 'desert city' with native, low-water vegetation. In 1992, when residents blocked a plan by Tucson Water to switch from groundwater to Colorado River water, the CWAC was crucial to public acceptance of the eventual solution. Tucson is now able to bank six months of its water supply annually, reducing the risk of future shortages. Consumption rates continue to drop and are among the lowest in the USA. Not only has Tucson improved its supply and demand capacity, but it has fostered capacity for transformation, capacity for learning, change and collaborative action [136].

P6.4 Enable capacity for transformation

Allow for deviation beyond standard operational practices, recognising that national legislation and regulation may need to be improved to become fit for purpose.

Capacity for transformation allows infrastructure to adapt beyond its primary purpose recognising that the adaptive capacity of any unit at scale is finite. Extending beyond system limits, known as extensibility, requires organisational structures to support the decisive and timely adoption of a new approach and resist defaulting to the 'status quo' approach in exceptional circumstances. Small scale failures or near-failure events should be analysed as learning opportunities and used to revise management strategies. Organisations should expect that operational best practice will change with new evidence, and anticipate that events will occur that saturate adaptive capacity [137], requiring alignment and coordination across multiple interdependent units in a network. While proactive transformation is ideal, it is also important that, should system failure occur, transformation resulting from lessons learned is a key part of the recovery process. Systems must not just build back, but build back better, having addressed the vulnerabilities that allowed failure to occur. This allows flexibility in future use and can prevent or mitigate potential failure scenarios. Transformation capacity focuses on knowing the boundaries of existing infrastructure systems and how infrastructure systems might be viable beyond the boundaries. It is a reminder that preventing system failure requires thinking beyond traditional infrastructure system boundaries.

Assiniboine River dike: In 2011, during a period of extreme weather in Winnipeg, Canada, officials broke through a section of the Assiniboine River dike to facilitate the controlled release of floodwaters. The dike was surrounded with large limestone boulders, or rip rap, to absorb the impact of the water and reduce the speed of flow. The breach consisted of a cut less than a meter in depth. The aim of the breach was to allow water to disperse slowly across fields, fill behind roads and spill at low points along roads, before ultimately spilling into the La Salle river. This was done to prevent an uncontrolled breach downstream, which could affect 850 homes and an area of 500 square kilometres [138]. While originally designed to protect the area's road network and nearby land, officials were able to utilise the dike for another purpose, in order to mitigate the risk of more severe disruption downstream.

P6.5 Allow for human discretion

Incorporate manual overrides and human-in-the-loop provision to allow for human discretion.

An emphasis should be placed on developing skills amongst operational staff at all levels, with appropriate training and testing to enable them to have the authority for autonomous intervention. Processes that contain human and digital systems must ensure operational safeguards. Avoiding a sudden collapse or failure when events push the system up to and beyond its boundaries for handling changing disturbances and variations. While automation may be more efficient in everyday operations, incorporating the capacity for manual control enable humans to respond to surprises by opening and closing paths for service flow, allowing infrastructure to function beyond designed thresholds, and switching on and off backup resources [132]. This can enable fast interventions in response to unexpected disturbances.

China Airlines Flight 140 crashed due to issues with autopilot manual overrides. An automated system was programmed to ignore manual controls in an aborted landing situation, but the human pilots tried to continue the landing. The conflicting signals resulted in the aircraft stalling and crashing. The autopilot for this aircraft type was reprogrammed so that it would never ignore a manual override [139].

8. Conclusions and next steps

The resilience of critical services provided by national infrastructure has never been more important. There is strong evidence that investment into infrastructure resilience is economically justified.

This report presents a set of six Principles for Resilient Infrastructure that will support national scale net resilience gain. Key actions are defined for each principle, making the implementation of the principles actionable. Global examples are provided for the key actions demonstrating their relevance to emerging, developing and developed nations.

The principles are recommended to nation states and would be suitable for large territories or devolved administrations where infrastructure is largely independent. The principles can be used to determine the resilience of national infrastructure. They are not intended for assessment of individual assets or components of infrastructure. An overview of the governance for the implementation of the principles is described in Figure 1.

Each of the six Principles for Resilient Infrastructure contribute in specific ways to delivering Net Resilience Gain. Implementation of the principles and key actions is proposed in nations ready to improve resilience outcomes. Implementing the principles in emerging, developing and developed countries would support the collection of data and improvement of the key actions, in time. It is also recommended to work with global infrastructure organisations to seek their endorsement and to create local opportunities for translation into best practice guidance.

Further steps to develop and measure the usefulness of the principles could involve setting up a global knowledge sharing platform for capturing practices, including experiences in implementing the principles, the development of international standards, national digital twins, and computational models. A knowledge platform can inform nations of successes and failures whilst digital twins can continuously monitor national infrastructure, providing early warning of potential vulnerabilities especially when linked to meteorological and other geo-physical systems. The models could be used to determine Net Resilience Gain which is expected to emerge as the key actions are integrated into national infrastructure. All further steps can aid continuous assessment of the national efficacy of these principles and detect unintended consequences before they spin out of control. Existing plans/pipeline for national infrastructure investment must be assessed before they are commissioned to assure compliance with Net Resilience Gain.

Implementation of the principles require building capacity and knowledge of various stakeholders engaged in all phases of infrastructure development, operation, and maintenance.

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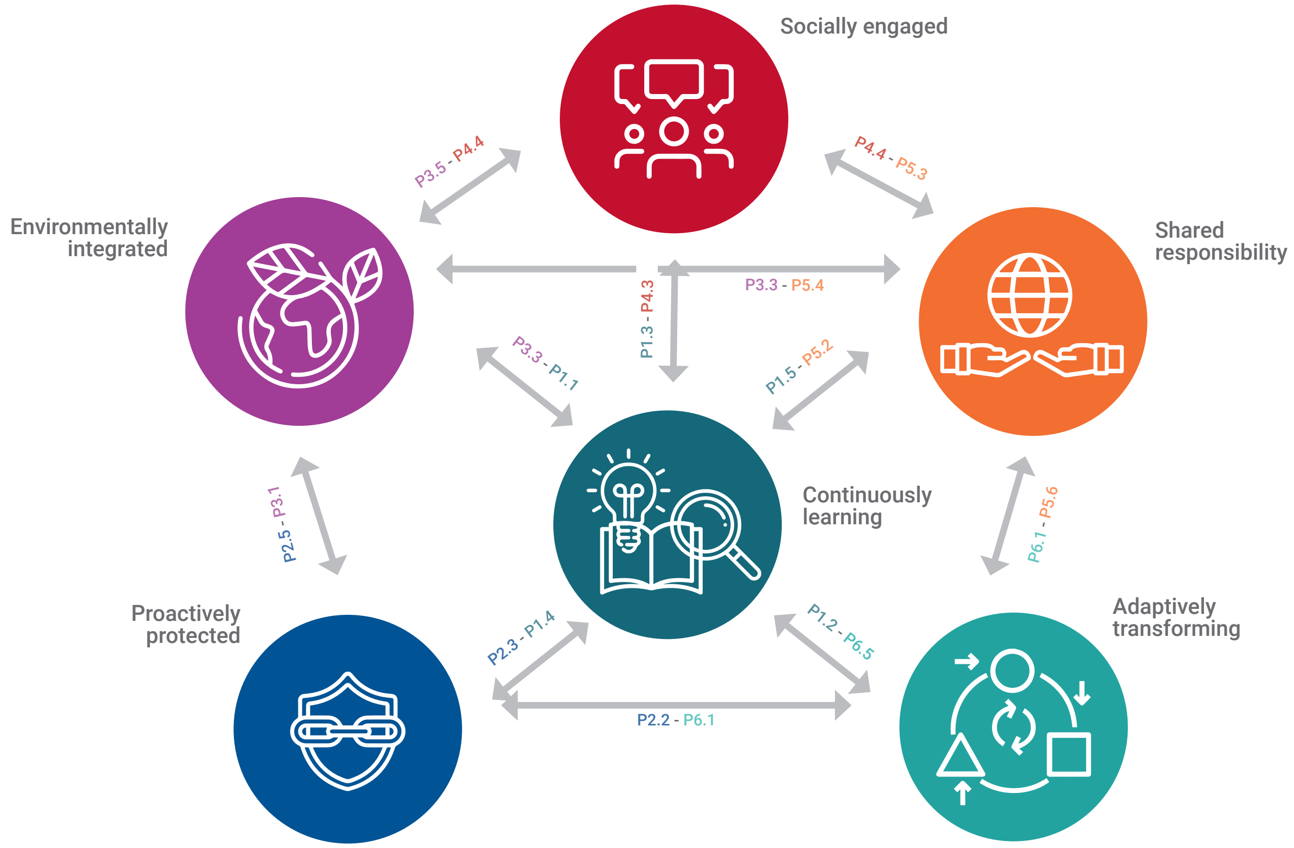
Appendix A Interdependencies

The Principles are a system of goals. The key actions underpinning each Principle are inevitably interdependent. Figure 3 highlights the primary interdependencies between the key actions. For example, P3.3 Integrate ecosystem information is interdependent with P5.4 Enhance connectivity for information sharing.

Figure 3: Interdependent Principles for Resilient Infrastructure



Appendix B
Mapping to SFDRR and SDG9

Key Activities mapping to Target D of Sendai Framework for Disaster Risk Reduction (SFDRR), Goal 9 of Sustainable Development Goals (SDGs) and Resilience capabilities

	Key Activity	Target D SFDRR	Goal 9 SDGs	Resilience Capability
Continuously learning	P1.1 Expose and validate assumptions	D4, D8	9.5.Taking these actions can enhance scientific research, upgrade the technological capabilities, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending.	Prevent all risks
	P1.2 Monitor and intervene appropriately			
	P1.3 Analyse, learn, and formulate improvements			
	P1.4 Conduct stress tests			
Proactively protected	P2.1 Raise essential safety requirements	D4, D8	9.1 Develop quality, reliable, sustainable, and resilient infrastructure	Prevent from all disasters
	P2.2 Exceed basic requirements for critical components	-		Prevent from all disasters
	P2.3 Consider complex interdependencies of connected networks	D4, D8		Absorb failures
	P2.4 Embed emergency management	D8		Resist and absorb failures
	P2.5 Design infrastructure to fail safely	-	-	Absorb failures
	P2.6 Design for multiple scales	D8	-	Enhance recovery process
	P2.7 Commit to maintenance	D4, D8	9.1 Develop quality, reliable, sustainable, and resilient infrastructure	Adapt to all disasters
	P2.8 Devise long-term investments			Prevent from all disasters

	Key Activity	Target D SFDRR	Goal 9 SDGs	Resilience Capability
Environmentally integrated	P3.1 Minimise environmental impact	D4, D8	9.4. Taking environmentally friendly measures and being more adapted to natural environment supports both sustainability of environment and resilience of infrastructure systems and reduced CO2 emissions.	Prevent the risk of disasters with a natural hazard origin
	P3.2 Use environmental solutions	D4, D8	9.4. Greater adoption of clean and environmentally sound technologies and industrial processes.	Resist in the face of risk of disasters with a natural hazard origin; Absorb effects of disasters with a natural hazard origin; Accommodate the natural environment
	P3.3 Integrate ecosystem information	D8	9.4. Taking environmentally friendly measures and being more adapted to natural environment can support both sustainability of environment and resilience of infrastructure systems and reduced CO2 emissions.	Prevent the risk of disasters with a natural hazard origin; Adapt to natural environment conditions
	P3.4 Maintain the natural environment	D4, D8		Prevent disruptions caused by disasters with a natural hazard origin
	P3.5 Use local sustainable resources	D8	9.4. Resource-use efficiency.	Resist failures
Socially engaged	P4.1 Inform people about disruptions		9.1. By providing requirements necessary for having more informed, educated, active and engaged people, not only is the resilience of infrastructures increased but human well-being and development can be improved. 9.c. Making people more familiar with technical advancement and providing more accessible communication technologies support resilience of both infrastructure and human societies.	Prevent unmanageable loads of usage; Resist in emergency situations with lower supply level
	P4.2 Raise resilience literacy			Support transformation to apply more technical advancements necessary for being more resilient
	P4.3 Incentivise demand behaviour			Prevent unabsorbable high loads of usage; Resist abrupt failures by manageable level of usage
	P4.4 Encourage community participation			Prevent man-made interruptions; Enhance recovery process through public participation

	Key Activity	Target D SFDRR	Goal 9 SDGs	Resilience Capability
Shared responsibility	P5.1 Harmonise open standards	D4, D8	9.5. Taking these actions can enhance upgrading the technological capabilities and encouraging innovation. 9.b. Support domestic technology development, research, and innovation in developing countries, including by ensuring a conducive policy environment for, inter alia, industrial diversification and value addition to commodities. 9.c. Significantly increase access to information and communications technology and strive to provide universal and affordable access to the Internet.	Resilience for whole lifecycle
	P5.2 Cultivate collaborative management	-		Prevent failure; Enhance recovery process
	P5.3 Establish shared responsibilities			
	P5.4 Enhance connectivity for information sharing			Support transformation to data-based approaches to be more resilient; Prevent failure; Enhance recovery process
	P5.5 Assure data safety to develop trust			Support transformation to data-based approaches to be more resilient
	P5.6 Share risk and return information	D8		Prevent failure
	P5.7 Mitigate avoidable resilience losses			
Adaptively transforming	P6.1 Choose manageable solutions	-	9.1: Develop quality, reliable, sustainable, and resilient infrastructure, including regional and transborder infrastructure	Adapt, transform, and recover more easily
	P6.2 Create adaptive capacity	D4		Resist and absorb failures; Adapt to failures; Enhance recovery process
	P6.3 Develop flexible management			Adapt to failures; Enhance recovery process
	P6.4 Enable capacity for transformation			Adapt to failures; Absorb failures
	P6.5 Allow for human discretion			Resist failures; Adapt to failures; Enhance recovery process

UNDRR
UN Office for Disaster Risk Reduction

7bis Avenue de la Paix, CH1211
Geneva 2, Switzerland

www.undrr.org
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