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Abstract

In many disciplines, the resilience concept has applied to managing perturbations, challenges, or shocks in the system and designing an adaptive system. In particular, resilient infrastructure systems have been recognized as an alternative to traditional infrastructure, in which the systems are managed to be more reliable against unforeseen and unknown threats in urban areas. Perhaps owing to the malleable and multidisciplinary nature in the concept of resilience, there is no clear-cut standard that measures and characterizes infrastructure resilience nor how to implement the concept in practice for developing urban infrastructure systems. As a result, unavoidable subjective interpretation of the concept by practitioners and decision-makers occurs in the real world. We demonstrate the subjective perspectives on infrastructure resilience by asking practitioners working in governmental institutions within the metropolitan Phoenix area based on their interpretations of resilience, using Q-methodology. We asked practitioners to prioritize 19 key strategies for infrastructure resilience found in literature in three different decision contexts and recognized six discourses by analyzing the shared or discrete views of the practitioners. We conclude that, from the diverse perspectives on infrastructure resilience observed in this study, practitioners' interpretation of resilience adds value to theoretical resilience concepts found in the literature by revealing why and how different resilience strategies are preferred and applied in practice.

1. Introduction

Improving infrastructure resilience, understood as increasing the capacity of infrastructure systems to resist, adapt, or respond to changes, disturbances, and shocks, is now critical to adapting cities to climate change (Linkov *et al* 2014, National Infrastructure Advisory Council 2010 and The National Academies 2012). Broad factors compound climate change impacts on cities, like accelerated urbanization, population changes, earth system interactions, land-use changes, technological shifts, and economic growth. This adds growing complexity in the ever-changing environments in which infrastructure must perform and persist. In the effort to understand the complexity of cities, resilience studies have been focused on the interactions of social and ecological systems (Grimm *et al* 2008, McPhearson *et al* 2016, Meerow and Newell 2019 and Suarez *et al* 2005), and more recently on the social, ecological, and technological systems interactions (Markolf *et al* 2018). The concept of resilience, which is a well-known materialistic ability in engineering science (Trautwine 1909) and system capacity in ecology (Holling 1973), has been employed in developing infrastructure systems. More specifically, strategies to manage resilience are meant to improve capacity of infrastructure systems to respond to external changes, and to develop and manage infrastructure systems with the ability to withstand or recover quickly from conditions brought about by climate change, even those that are not easily

foreseen (Biggs *et al* 2012, Linkov *et al* 2013, Meerow and Newell 2015 and Woods *et al* 2012). Numerous guidelines, from international and national climate-change adaptation plans to municipal planning documents, have emphasized the importance of increasing infrastructure resilience as a solution to tackle growing risks of extreme weather events. Still, there is a gap in understanding how practitioners interpret and embed the concept of resilience and the associated strategies pragmatically in infrastructure development. Infrastructure engineers, landscape planners, policy makers, and facility managers (i.e., practitioners, hereafter) are the actual experts who make decisions about infrastructure in state, regional, and municipal governments that lead to planning and managing infrastructure systems—not academic researchers. Previous studies on resilience demonstrate that the concept needs to be understood with an interdisciplinary viewpoint reflecting regional, environmental, economic, and social challenges of climatic risk-management decisions (Adger 2000, Cutter 2016, Hayward 2013 and Keating and Hanger-Kopp 2020). Yet, most resilience studies neither observe a practitioner's interdisciplinary viewpoint on infrastructure resilience and climate risks nor identify how their perspectives may differ from the academic literature. Furthermore, a straightforward standard that guides practitioners for their decisions about infrastructure resilience and a protocol for developing resilience strategies is lacking (Chester *et al* 2021). Thus, the application of resilience in practice often entails subjective interpretation of the concept identified in academic literature by local practitioners involved in infrastructure development and management decisions (DeVerteuil and Golubchikov 2016 and Huck and Monstadt 2019). To better understand how the concept of resilience is interpreted in practice and capture the interdisciplinary perspective of practitioners on climate-change adaptation, in this paper, we focus on the practitioner's view of resilience.

The emerging concept of safe-to-fail is a resilient infrastructure design approach that would benefit from capturing interdisciplinary practitioner perspectives (Ahern 2011 and Kim *et al* 2019). Safe-to-fail emphasizes incorporating resilience strategies that reflect the diverse adaptive capacities of infrastructure systems. By adaptive capacities of infrastructure systems, we mean the flexibility and agility of structured systems that enable systems to respond to external changes while they operate (Chester and Allenby 2019). The premise of safe-to-fail is that incorporating resilience strategies in infrastructure development increases flexibility and agility to mitigate adverse impacts of unpredicted extreme weather risks and potential failure of infrastructure systems to respond to predicted risks. Safe-to-fail infrastructure development entails an understanding and valuing of different consequences of a system's functional loss regardless of its cause. Knowing the impact of infrastructure failure in advance helps to manage the loss of different functions and enhance system performance in design to avoid catastrophic damage (Kim *et al* 2019). For example, a storm sewer system may be designed to have a vegetated buffer basin at its critical inlet nodes when the sewer system reaches its capacity due to heavy rainfall. The buffer would function to minimize the overflow and damage to other dependent systems. Research on safe-to-fail infrastructure suggests the involvement of multiple stakeholders to determine the current adaptive capacities of the region to climate risks and to identify which resilient capacities should be embedded in new infrastructure designs (Ahern 2011 and Kim *et al* 2017). Among the stakeholders involved in assessing and embedding adaptive capacity in infrastructure systems, city practitioners hold knowledge of the capacity for governmental and non-governmental organizations to maintain, operate, and adapt infrastructure systems to climate change via knowledge of current decision considerations, design criteria, and the development process of infrastructure. Although this knowledge is critical to successful implementation of a safe-to-fail approach for resilient infrastructure development, there is no work in the literature that links practitioner knowledge to theory to better understand how adaptive capacities identified by researchers would be implemented in a real-world context.

Previous studies on safe-to-fail suggest that practitioners' viewpoints must be understood to succeed at resilient infrastructure development, because these perspectives highlight a nuanced understanding of resilience that is not captured in academic literature (Aldunce *et al* 2015, Chang *et al* 2014, Hagemann *et al* 2020 and Kim *et al* 2017). In the study of safe-to-fail adaptation for Phoenix roadway flooding (Kim *et al* 2017), seven preliminary safe-to-fail adaptation perspectives were explored that represent contrasting fail-safe and safe-to-fail characteristics of infrastructure systems. These perspectives were derived from an academic literature review, and only captured researchers' distinctive interpretations on how a safe-to-fail design approach promotes different resilient infrastructure solutions for managing urban flooding. While the results of the Phoenix study demonstrate that differing resilience perspectives of researchers may change recommended solution rankings for infrastructure design, they also suggest that more nuanced perspectives that reflect real-world conditions on safe-to-fail development may be lacking from resilience literature. To investigate diverse and subjective perspectives on resilience and their application in safe-to-fail infrastructure development, this study utilizes the Q-methodology (see methods), which allows researchers to explore the subjectivity of perceptions on a subject. Definitions of resilience are debated in the literature (Meerow *et al* 2016) and the safe-to-fail approach has been developed and promoted by researchers (Ahern 2011, Hobbie and Grimm 2020 and Kim *et al* 2019), but incorporating practitioner perspectives

derived from their long-term experience has lagged behind although it could benefit the advancement of both concepts. Q-methodology is a leading approach for systematically elucidating diverse perspectives of human subjects by combining a quantitative factor analysis and a qualitative discourse analysis (Sneegas 2020). Via the Q-methodology, this study hypothesizes that the way practitioners prioritize safe-to-fail strategies for infrastructure development will vary depending on their knowledge and experience and from the academic literature.

This study aims to contribute to an understanding of practitioner's perspectives on resilience and safe-to-fail, thereby providing guidance for infrastructure development and adaptation under climate change; and demonstrate the non-traditional use of Q-methodology in assessing stakeholders' views on a transdisciplinary subject in various decision contexts. Current infrastructure design standards and engineering criteria manuals have not been explicitly asking practitioners to consider and integrate resilience strategies into the design. Still, practitioners have been on the front line of improving infrastructure performance to be resilient to a changing environment and last for decades. We infer that, to some degree, practitioners have been practicing resilience for developing these systems without explicit consideration of 'resilience principles or strategies'. Infrastructure development practices and strategies endorsed by practitioners may already embed inherent attributes of resilience. Given that the notion of resilience has a malleable and multidisciplinary nature, the objective of this study is to explore the pragmatic interpretation of the resilience concept by practitioners and to recognize diverse perspectives on adopting resilience strategies into safe-to-fail infrastructure development in various decision contexts.

2. Methods

2.1. Q-methodology

Q-methodology was used in this study to explore the diverse perspectives of practitioners on resilience and safe-to-fail. Q-methodology is a research technique used to study an individual's subjectivity (Brown 1993) by collecting tables of organized statements that represent participants' subjective perspectives. It was first introduced by the psychologist Stephenson in his article 'correlating persons instead of tests' in 1935, as a technique that inverts the common correlation analysis (i.e., correlating test variables (Spearman 1904)) by correlating among human subjects instead of the test variables (Stephenson 1935). The benefit of correlating study participants by Q-methodology appears in investigating questions about personal experience and opinions regarding insights, attitudes, values, and beliefs (Brown 1980 and Ellingsen *et al* 2010). Q-methodology incorporates both qualitative and quantitative research methods, and it allows researchers to explore shared and/or discrete views among participants by its study procedure and factor analysis technique. Also, Q-methodology has a benefit of feasibility in discovering significant viewpoints and the range of variability, with only a few participants needed to offer statistically meaningful results (as few as 12 participants, because each Q-sort product delivers a substantial amount of information (Barry and Proops 1999)). A Q-methodology study typically comprises: (i) developing a Q-sample—a list of statements related to the topic and the study question; (ii) conducting Q-sort—a hands-on activity of ranking the Q-sample of statements by study participants on a quasi-normal distribution table (i.e., Q-sort table); (iii) semi-structured interviews; (iv) performing factor analysis on Q-sorts (i.e., participants)—not on variables (i.e., statements); and (v) interpreting identified factors and constructing narratives (i.e., discourses).

To implement the Q-methodology for investigating perspectives on resilience and safe-to-fail infrastructure, study participants (i.e., practitioners in the metro-Phoenix in this study) were asked to perform a series of Q-sorting activities (i.e., ranking resilience strategies on the Q-sort table) by responding to three questions that reflect different decision contexts involving climate-change adaptation, urban infrastructure development, and past natural disasters:

- Question A. Which statements are more/less relevant for promoting infrastructure resilience in addressing climate and weather risks from your experience and perspective?
- Question B. Which statements are more/less relevant for promoting safe-to-fail infrastructure in addressing urban flooding from your experience and perspective?
- Question C. Which statements are more/less relevant for promoting resilience considering infrastructure failure consequences during the infrastructure development process in addressing climate and weather risks like Hurricane Harvey?

In addition to asking participants these questions, additional information of decision contexts was provided to participants to help guide Q-sorting activities and frame their subjective view on infrastructure's adaptive capacity to changes. For *question A*, participants were provided with a common definition and extended explanation of resilience for infrastructure found in the academic literature:

The National Academy of Sciences defines resilience as ‘the ability to plan and prepare for, absorb, recover from, and adapt to adverse events’ (The National Academies 2012). In response, resilient infrastructure systems have been extensively recognized as an alternative to traditional infrastructure in managing systems more reliable against unforeseen and unknown threats, i.e., ‘surprises’ (Woods *et al* 2012).

Before ranking the statements for *question B*, participants deliberated their decision contexts to guide their sorting on a specific infrastructure matter in the area either for an existing case or a hypothetical case. The decision context included a type of infrastructure, location within the metro-Phoenix area, and a type of weather events (e.g., a-100-years frequency rainfall). The metro-Phoenix area was selected for data collection given its increasing trends of extreme precipitation and flooding challenges. A general definition of safe-to-fail was given, while allowing practitioners to interpret the meaning of the term:

Safe-to-fail infrastructure are built systems designed to lose function in controlled ways, even when design threshold is exceeded in unpredicted hazards.

Question C considered failure consequences in the process of developing resilient infrastructure to the past flooding disaster in Houston experienced during Hurricane Harvey in 2017. To provide an explicit decision context for the third question, selected quotes used to describe the Houston case were provided:

‘But there is, and most Houstonians casually accept the enormous drainage system—the bayous, creeks and gullies—that keep it precariously dry in a former wetland. The only solution is to widen the waterways, which means buying up adjacent buildings and tearing them down; Brays Bayou, which has been widened in recent decades, surged over its banks in several spots, spilling feet of water into adjacent neighborhoods. The county engineer puts the price tag on a total upgrade at \$26 billion, which will not happen soon (Baddour 2016).’

2.2. Q-sample: collecting statements

The Q-sample in Q-methodology refers to the statements, objects, or other artifacts that study participants sort during each of the three sorting activities (Brown 1993). The Q-sample for this study is a collection of statements on describing various resilience strategies that reflect various adaptive capacities of the infrastructure system to respond to climate risks in certain ways. Since we were particularly interested in how practitioners’ viewpoints on resilience strategies differ from the academic researchers’, we adopted an unconventional way of developing the Q-sample by selecting the 19 resilience strategies as statements demonstrated in Kim *et al* (2017). We referred to previous studies on Q-methodology that discuss the use of secondary sources, such as relevant literature, media, or other sources for gathering statements instead of conducting interviews (Cuppen *et al* 2016 and Ellingsen *et al* 2010). We acknowledge that this modification from the traditional Q-methodology hinders capturing the uncontaminated subjectivity of participants on resilience. However, a deductive approach of Q-sampling was taken for this study due to the study condition that a majority of participants in this study were rather unfamiliar with the concepts of infrastructure resilience rigorously used in literature, but less discussed in practice. In addition, we intended to focus on maximizing the benefit of Q-methodology in capturing the variety of diverse stakeholder perspectives on resilience in various decision contexts for infrastructure development.

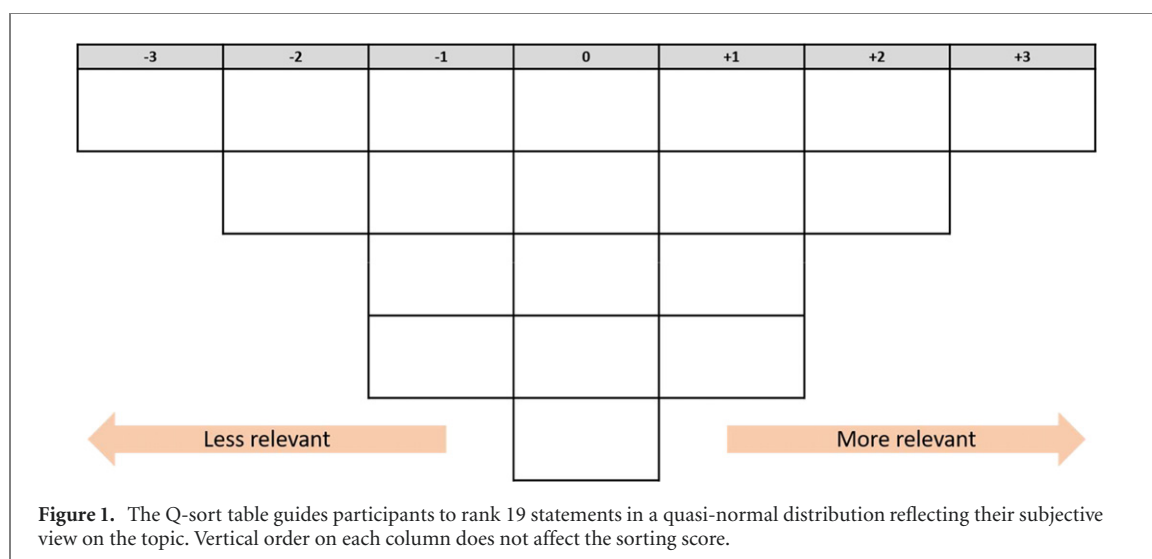
The 19 strategies make a comprehensive list encapsulating the discourse, or ‘the flow of communicability surrounding any topic’ (Brown 1993), derived from 10 studies on resilience and safe-to-fail infrastructure. Initially, in Kim *et al*, a total of 43 resilience strategies were collected from the literature related to infrastructure development. By combining similar strategies that shared similar definitions and descriptions among various authors, the initial list of collected statements was aggregated into 19 distinct strategies (see table 1). We adopted these 19 strategies and their descriptions as statements to form the Q-sample of this study.

2.3. Q-sort: ranking the statements and semi-structured interview

In the Q-methodology, participants are asked to rank the Q-sample using the Q-sort table (figure 1) based on their experience and perspectives. For this study, participants were identified via the urban resilience to extremes sustainability research network (UREx SRN) Phoenix practitioners’ network and directories on government websites. All potential participants received an invitation email explaining the purpose of the study. We invited the participants whose responses indicated that their work was related to infrastructure planning and flood management. The final study set included the total of 16 participants from state, regional, and city governments (3, 9, and 4 participants, respectively) working on the broad fields of sustainability, stormwater and flood control, water resource management, and transportation. Among 16 participants, four are female and 12 are male participants. A set of study materials including paper copies of a Q-sort table (figure 1), binning table, Q-sample (i.e., a list of 19 strategies with the descriptions, table 1), and a stack of cards with printed statements was distributed to each participant. Study participants completed a respective Q-sort table for each

Table 1. Q-sample: 19 resilience strategies for infrastructure development. Adapted from Kim *et al* (2017). Copyright © 2017, Springer Science Business Media B.V. With permission of Springer).

#	Strategy	How achieved...?
1	Adaptability/adaptive capacity	Increasing a system's capacity to change in response to new pressures and to manage known and unknown events
2	Adaptive planning & design/innovation	Opening existing analysis, design, and implementation practices to encourage creativity with the goal of gaining knowledge for future solutions
3	Anticipation	Improving the capacity to foresee and predict positive and negative future system states
4	Armoring	By hardening or stiffening a system or component to exogenous shocks via the addition of new components or functions
5	(Bio and social) diversity	By using solutions with a greater number of forms, behaviors, and responses across a wider range of conditions
6	Efficiency	Designing for system performance with modest resource consumption
7	Fail-operation	Enabling systems to continue to work despite failures and faults
8	Fail-silence	Developing a negative feedback mechanism to achieve system self-shutdown in case of component or human failure
9	Isolation	Reducing connectivity, interdependence, functionality, and interactions among system components and between systems where those interactions already existed
10	Learning/learning-by-doing	Creating retrospective feedback loops between response actions to assess and develop new knowledge and adaptive strategies
11	Multi-functionality/flexibility	Through the design of systems or components with extensible functionality, capacity for reconfiguration, intertwining/combined functions, and time-shifted functions
12	Networks/connectivity/cohesion	Creating linkages within systems that support and maintain functional connectivity
13	Oversizing	Increasing existing system and component tolerance, capacities, robustness, functionality
14	Redundancy/modularization	Providing provide the same, similar, or backup functions with multiple elements or components
15	Renewability/regrowth	Enabling the recovery of system or component function from endogenous and exogenous forces
16	Sensing	Improving the capacity by which new system stresses are efficiently and rapidly incorporated into current understanding
17	Strengthening	By hardening or stiffening a system or component to exogenous shocks via the upgrade of existing components or functions
18	Transdisciplinarity	Enabling dissimilar stakeholders to contribute to and benefit from a mutual experience
19	Transformability	Enabling the capacity to create an entirely new system when existing structures are untenable



question (*question A, B, and C*) in small groups and in three successive stages. This process allowed researchers to observe the changes in perspectives in different decision contexts with following semi-structured interview and discussion after each Q-sort activity. A single question stage consisted of three phases: (1) the facilitator explains the background and decision context of the study question to the group of participants; (2) the participants respond to the question by sorting the selected statements with given values in a Q-sort table from +3 (most relevant) to −3 (least relevant); (3) semi-structured interviews of each participant and the group are conducted to identify their reasonings for the Q-sort product. A quasi-normal distribution table (figure 1) for ranking the Q-sort table was used rather than asking practitioners to rate the statements individually to represent their perspective, i.e., the number of columns on each side of the Q-sort table corresponded to the other, with an increased number of Q-sample responses remaining in the middle (Brown 1993). The Q-sort table is meant to capture the viewpoint on a certain resilience strategy that practitioners think about in relation to others, rather than in isolation. 16 participants produced 16 Q-sorts for each of *question A* and *B*. 15 participants produced 15 Q-sorts for *question C*. One participant had to leave one meeting early due to a schedule conflict. As a result, a total of 47 Q-sorts representing diverse perspectives on employing resilience for infrastructure development were collected. Examples of the interview questions asked of participants after each stage for discussions are:

- Why did you choose <this strategy of the 19 in the Q-sample> as the most/least relevant strategy? Do you have a real-world example demonstrating your reasoning?
- Which of these resilience strategies are most difficult to categorize? Why?
- Which of these resilience strategies are most useful to guide decisions for infrastructure development? Why?
- Can you think of any other resilience strategies important for guiding infrastructure development not included here?
- What criteria did you have in your head for sorting strategies? Are your decision criteria the same for all three questions?

2.4. Factor analysis and constructing discourses

The collected Q-sorts were analyzed using factor analysis, a statistical correlation method. The publicly available Q-methodology software PQMethod-2.35 was used for the factor analysis (Schmolck 2014) on the sets of Q-sorts responding to each question. The following steps for factor analysis were repeated three times, once for each respective study question. The first step of factor analysis is to enter the Q-sorts into the program. Principal components analysis (PCA) was chosen for factor analysis as it is the most common and well-established method (Akhtar-Danesh 2017). PCA correlates every participant's Q-sort with every other Q-sort to test the correlation among collected data. In this study each question has 16 variables (i.e., 16 Q-sorts produced by 16 participants; except 15 for *question C*) and 19 observations (i.e., 19 statements of resilience strategies). With PCA, the variance of Q-sorts was observed and extracted as clustered factors representing shared or discrete perspectives, thus allowing researchers to explore the range of viewpoints responding to each question. By default, in the PQMethod, a maximum of eight factors are extracted due to computational limitations.

Table 2. The factor characteristics of each idealized sort for question A.

Factor characteristics for question A	Factor (idealized sort)
	A1
Eigenvalue	4.8102
Number of defining variables	5
Composite reliability	0.952
% Explanatory variance	26

Table 3. The factor characteristics of each idealized sort for question B.

Factor characteristics for question B	Factor (idealized sort)		
	B1	B2	B3
Eigenvalue	5.0659	2.7679	2.0350
Number of defining variables	4	3	4
Composite reliability	0.941	0.923	0.941
% Explanatory variance	22	15	19

The first factor had the highest level of explanatory variance in the dataset, the second factor had the second highest variance, and the rest of six factors thereafter. The resulting cumulative explanatory variances were 90, 91, and 91% with eight extracted factors for each question of this study, respectively. This means that 90%–91% of 15–16 Q-sorts can be explained with the eight extracted factors. The next step in the standard study protocol of Q-methodology is to ‘rotate’ the extracted factors to simplify the representation of each factor’s statistical values, which helps the interpretation of each factor into a discourse. Varimax rotation technique was used in this study to rotate the factors with eigenvalues higher than one. This process maximizes the number of Q-sorts associated with only one factor (Cousins 2017). In the next step, significant factors (i.e., ‘idealized’ sort) were determined that were considered as meaningful shared perspectives. The significance of factors was determined with the common Q-methodology criteria: i) the composite reliability is higher than 90%; and ii) the number of defining variables (Q-sorts) are more than three (Akhtar-Danesh 2017, Hagan and Williams 2016 and Watts and Stenner 2005). The composite reliability is calculated by the expression $R_{\alpha} = 0.80 * p / [1 + (p - 1) * 0.80]$, where p is the number of Q-sorts defining a factor (Brown 1980).

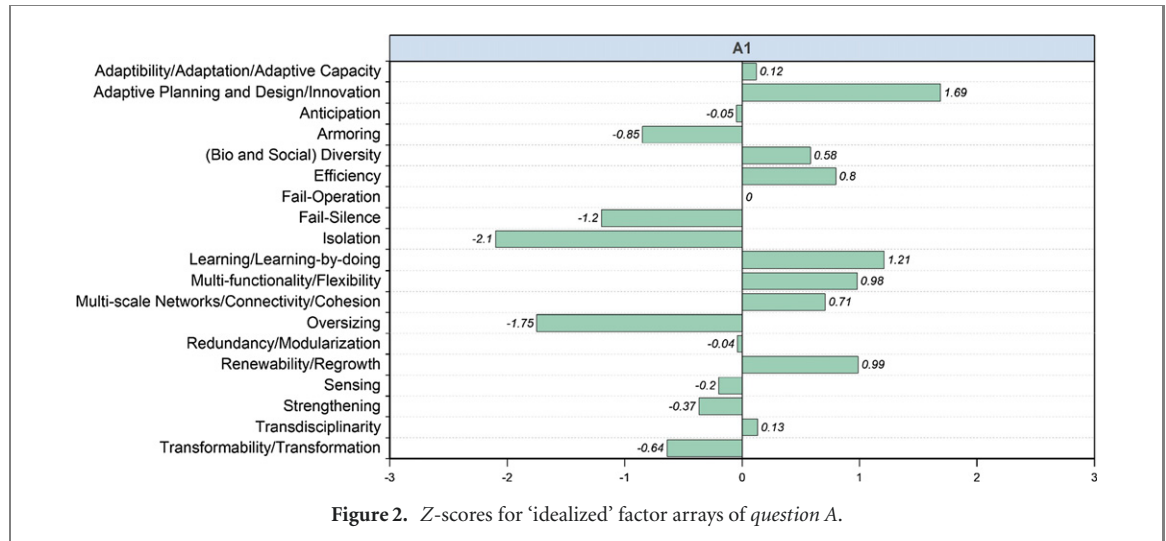
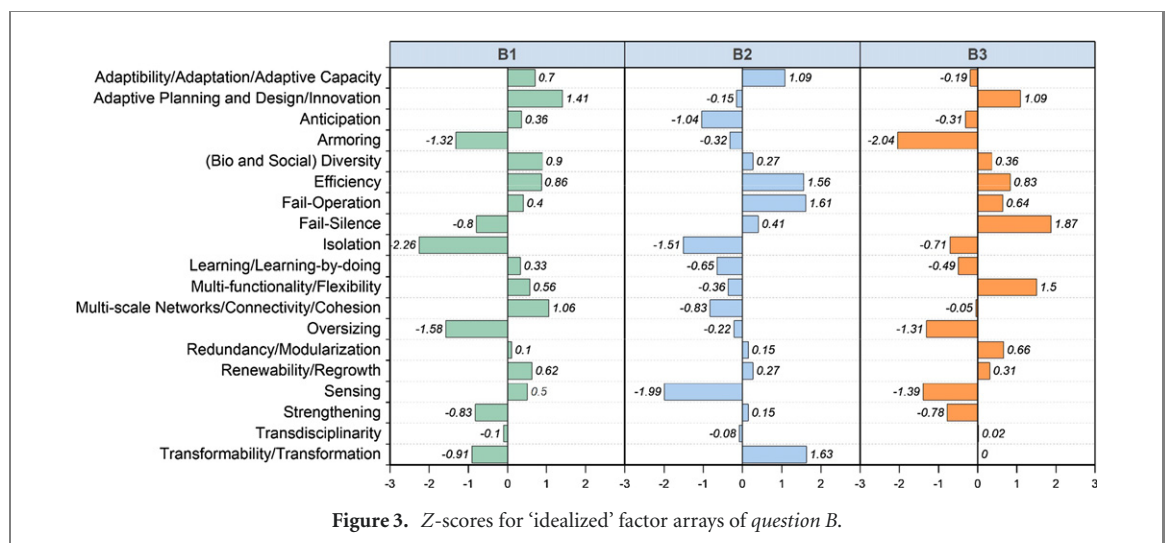
The results of idealized Q-sorts from the factor analysis were interpreted in combination with the interview data for the interpretative discourse construction, which helps understand the quantitative outcome of factor analysis. Interpretative discourse construction is meant to gain an in-depth understanding of the participants’ frame of reference and identify the reasoning behind their resulting Q-sorts as a narrative view, rather than a view with representational statements and the rankings. Results of factor analysis provided information on participants that had a statistical significance in producing respective idealized Q-sorts. Thus, participants’ interview data were selected and interpreted based on their significance of support for each idealized Q-sort. Also, distinguishing and consensus statements among idealized Q-sorts for each question were reviewed to construct discourses representing shared or discrete perspectives among participants. A distinguishing statement has a Q-sort score (i.e., Z-score ranging from -3 to $+3$) that is statistically unique for a specific factor, while a consensus statement does not notably distinguish in the Q-sort score between any pair of factors (Brown 1993 and Cousins 2017). Constructing discourses based on identified factors were subjected to interpretative analysis using interview data, while focused on capturing respondent’s subjectivity with respect to factor analysis without inferring investigator’s subjectivity. Hence, by combining the significant Q-factors (i.e., idealized sorts) and the interview data, we constructed discourses for each question that provide vital information for understanding diverse practitioner viewpoints. Discourses further elucidate participants’ thoughts on selected statements associated the given decision contexts and resilience strategies, as well as the reasoning that participants use for decisions to rank certain strategies in relation to others.

3. Results and discussion

The result produced ‘idealized’ sorts (factor arrays) that are significant to explain the shared and/or distinct perspectives for each question—one idealized sort for *question A*; three idealized sorts for *question B*; two idealized sorts for *question C*. The PCA characteristics of idealized sorts are summarized in tables 2–4.

Table 4. The factor characteristics of each idealized sort for question C.

Factor characteristics for question C	Factor (idealized sort)	
	C1	C2
Eigenvalue	4.8856	2.3745
Number of defining variables	3	3
Composite reliability	0.923	0.923
% Explanatory variance	26	13

**Figure 2.** Z-scores for 'idealized' factor arrays of question A.**Figure 3.** Z-scores for 'idealized' factor arrays of question B.

The factor scores (i.e., Z-score, a weighted average of the values given to each statement by participants defining the factor (Brown 1980 and Ellingsen *et al* 2010); range from -3 to $+3$ in this study) are shown in figures 2–4. The different numbers of idealized sorts for each study question confirm that decision contexts affect the variation of viewpoints in spite of applying the same set of Q-sample (i.e., 19 resilience strategies). This also shows the benefit of using the Q-methodology for exploring stakeholder's diverse perspectives, while traditional stakeholder study methods, such as surveys, are designed to present the popularity or importance of the test variables as a result among the randomized large number of study participants (Barry and Proops 1999 and Cuppen *et al* 2016). In other words, if R-methodology (e.g., survey) were used in this study, the study results would only produce a discrete ranking of resilience strategies with regardless of the sophisticated participants viewpoints. Via Q-methodology, the prioritization of resilience strategies enhancing infrastructure adaptive capacities demonstrates that various resilience strategies are considered constructively in relation to each other, rather than emphasized as a single, particular strategy. In the following sections, the discourses

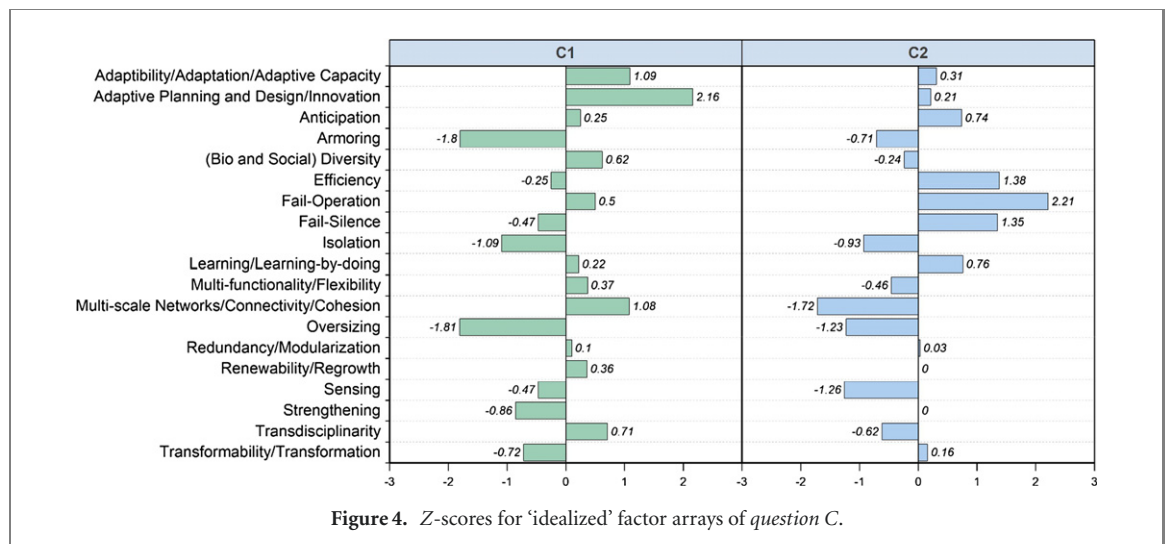


Figure 4. Z-scores for 'idealized' factor arrays of question C.

are illustrated for each study question by interpreting both the Q-factor analysis and the discursive analysis of interview data.

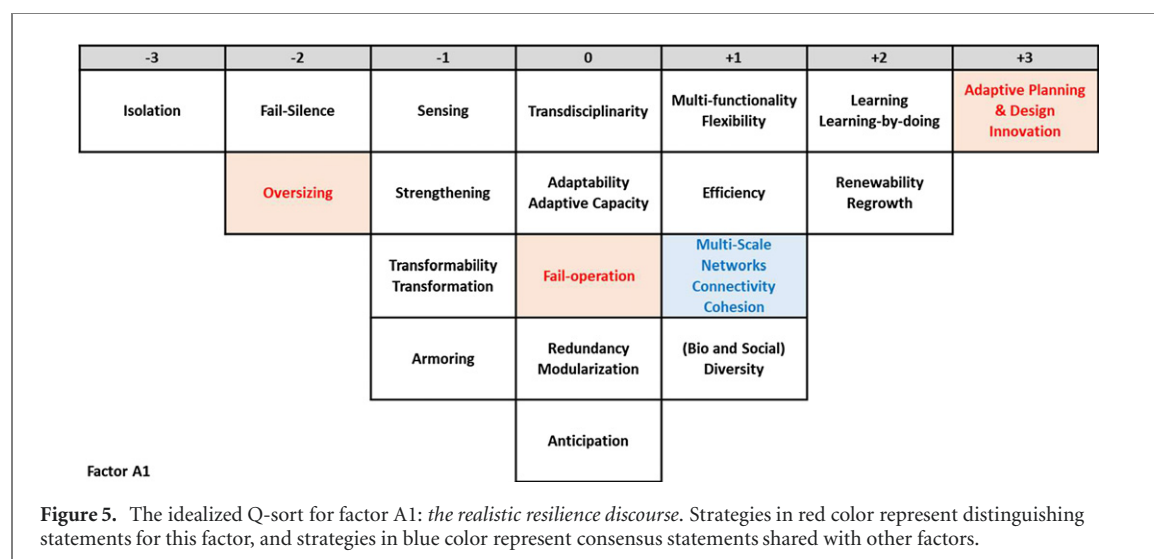
3.1. General perspective on resilience for infrastructure development (question A)

We define one idealized sort for question A as the *realistic resilience discourse* (table 2, figure 2). This discourse highlights a general perspective on resilience for infrastructure development. Practitioners' perspective on applying the concept of resilience for infrastructure development, in overall, is driven by their institution's current capabilities and needs in developing resilient systems. During the sorting activities, some participants (i.e., engineers in the department of public works) found the overall terminologies describing the statements very different from the terms that they often use in their infrastructure projects. They pointed out that their terms are rather limited in describing 'shades of gray infrastructure' indicating that infrastructure practices are often constrained by path-dependent technological decisions. Participants also found that the ends of the sorting table (i.e., +3 and -3) were easier to sort statements because they spoke more to realistic institutional conditions such as budget constraints. Among the 19 strategies, participants have a consensus on the statement of multi-scale networks/connectivity/cohesion as a moderate relevant strategy (strategy #12 in table 1, +1 in figure 1) to be considered across institutions and levels of government for encouraging collaboration to promote a coherent resilience strategy across interconnected systems. We find this consensus is partially attributed to the fact that practitioners thought this strategy as a non-structured approach that they have less influence or control over as individuals. Creating linkages across systems to maintain functional connectivity as well as to support coordinated management and maintenance across the various levels of governing institutions is observed to be relevant for promoting resilient infrastructure by practitioners.

3.1.1. The realistic resilience discourse

This discourse is based on the perspective of promoting resilient systems by pursuing new solutions for infrastructure design and management with a recognition that current systems may not be effective in responding to the changing environment with respect to urbanization, population increase, and climatic events (figure 5). The *realistic resilience discourse* embeds a strong concern that isolating the system (#9, -3) by reducing connectivity, interdependence, functionality, and interactions among system components and between systems where those interactions already existed is not pragmatic (table 1). Because maintaining interdependency, such as power-water and roadway-drainage dependencies, is critical to providing reliable infrastructure services to the region, practitioners in this discourse affirm that isolating systems is not realistic.

Three statements appear to distinguish this discourse from other perspectives, namely, adaptive planning and design innovation (#2, +3), fail-operation (#7, 0), and oversizing (#13, -2) (table 1, figure 5). This discourse highlights the need for institutions to allow adaptive planning and design to innovate existing analysis, design, and implementation practices with the goal of gaining knowledge for future solutions. Practitioners in this discourse acknowledge that being dependent on standard practices is less relevant to design and manage resilient infrastructure to changing climate. A practitioner identified as a key contributor to this sort mentioned that infrastructure resilience would derive from 'building upon past successes and failures to infuse new knowledge into the system and to be at the forefront of technology and innovation.' This discourse also acknowledges practitioners' viewpoints that financial constraints are one of the biggest considerations for



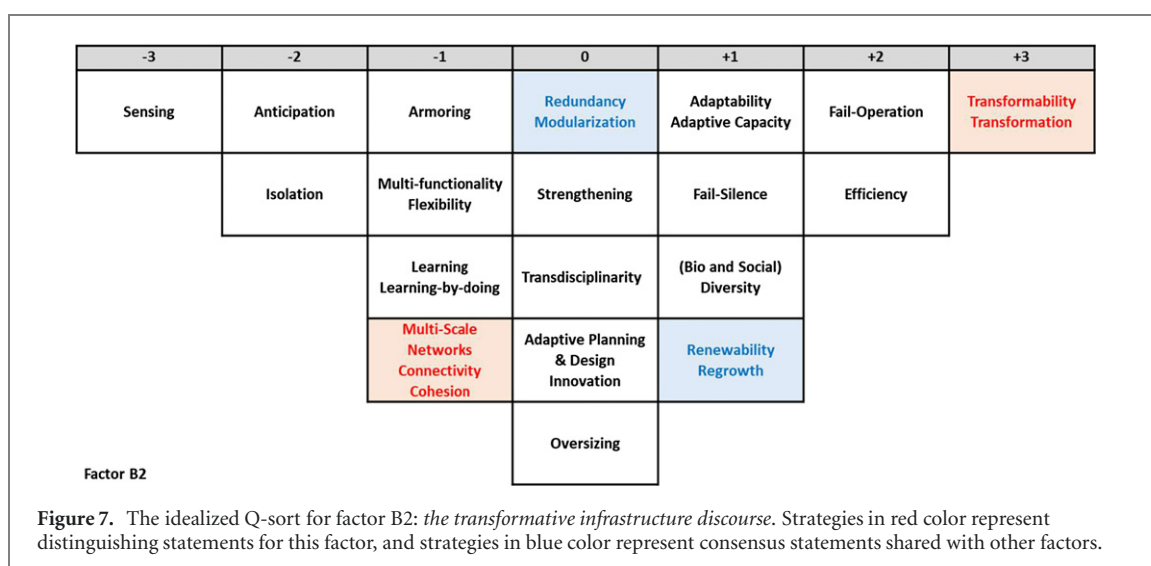
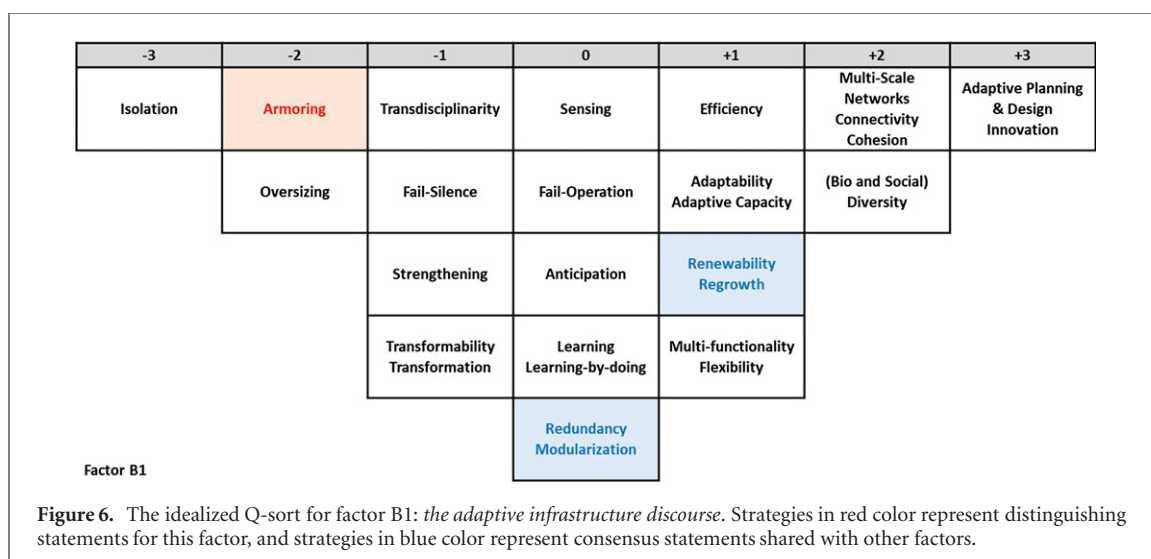
implementing infrastructure projects and cannot be ignored when increasing the resilience of an infrastructure system (Coffee 2020). Encouraging innovations in design is viewed particularly positively in this discourse, because changes in design and planning occur before institutions start investing money toward a project or physically altering the infrastructure in unaccustomed ways. In the same regard, even though oversizing is a common strategy used to increase infrastructure capacity to deal with adverse impacts in traditional infrastructure development, it is considered a less economical solution with the recent changing risk profiles and uncertainty of future climate. Statements positioned along the neutral score, such as fail-operation, transdisciplinarity, and anticipation (figure 5), are explained as strategies that practitioners have less technical or institutional capacity to implement, despite that those strategies are not negligible in resilient infrastructure development. This also emphasizes the practicality and challenge of adopting resilience strategies for infrastructure systems.

3.2. Application of resilience strategies for developing safe-to-fail infrastructure in the metro-Phoenix area (*question B*)

Idealized sorts for *question B* produce three discourses driven by practitioners' professional experience and their current role mitigating flooding risks with infrastructure development and management in the metro-Phoenix area. We define three idealized sorts for *question B* as *the adaptive infrastructure discourse*, *the transformative infrastructure discourse*, and *the efficient infrastructure discourse* (table 3, figure 3). These discourses feature viewpoints on applying resilience strategies for safe-to-fail infrastructure development in the metro-Phoenix area. We find that the primary contribution to the variety of viewpoints for this question is dependent on how practitioners perceive the most pressing flooding problem in the metro-Phoenix area and their decision boundary for dealing with flood problems. Participants said that their interpretation of resilience strategies had changed because they applied a specific decision context for this sorting which reflected their daily tasks in the organizations. Among 19 strategies, participants have a consensus across the three idealized sorts on statements like renewability/regrowth (#15, +1) as moderately relevant and redundancy/modularization (#14, 0) as neutral in developing safe-to-fail infrastructure for confronting flooding issues (table 1, figures 6–8). This consensus is attributed to the conventional features of flood management solutions currently in place in the region. It also demonstrates a common understanding that a 'safe-to-fail' approach underscores the safe performance of infrastructure by adding multiple components for backups to provide reliable services and/or enabling the effective recovery of infrastructure from a functional failure (Ahern 2011 and Möller and Hansson 2008).

3.2.1. The adaptive infrastructure discourse

This discourse is based on developing safe-to-fail infrastructure for flood management by focusing on localized flooding problems in the metro-Phoenix area (figure 6). This perspective aligns with the general perspective on resilience identified by *the realistic resilience discourse* in *question A*, but more focuses on seeking creative and unprecedented solutions for local flooding issues. Practitioners identified in this discourse suggest that creative solutions and knowledge are needed to prepare and design infrastructure for flooding caused by infrequent, but highly variable, precipitation occurrences in the area. While the participated engineers interpreted the strategy of adaptive planning & design innovation as a need for improved risk modeling and prediction, planners in the study interpreted it as a strategy for integrating future visions of how city might look like in project design

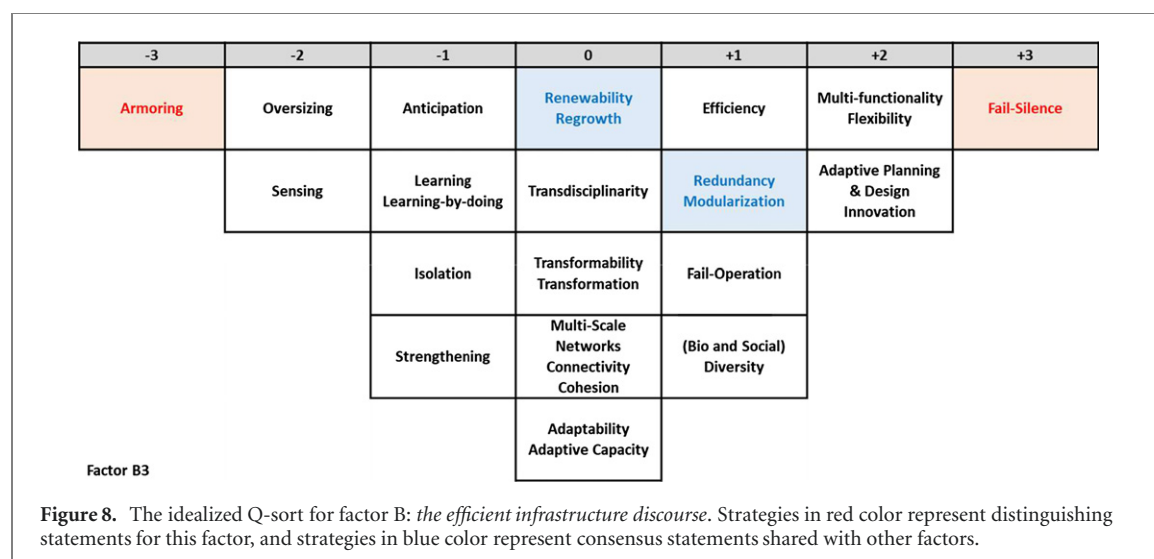


processes. As the impact of infrastructure failures from localized flooding does not often cause fatal damages, practitioners tend to put importance on transformational strategies like (bio and social) diversity (#5, +2) and multi-functionality/flexibility (#11, +1) (table 1, figure 6), which may require a pilot period to evaluate the solution performance before the actual implementations. Also, these strategies enable the system to adapt when flooding risk thresholds are compromised. Multiple respondents to this discourse describe their rationale for sorting strategies as associating safe-to-fail with characteristics of green infrastructure or best practices that provide the value of ecosystem services in risk reduction to localized flooding. This discourse also emphasizes the need for the repair and maintenance planning across a system's entire life span to support the safe-to-fail nature of the infrastructure with the increased system's adaptive capacity.

The adaptive infrastructure discourse finds armoring (#4, -2) and isolation (#9, -3) as unattractive and unfeasible to fund for rain-induced flood management. Also, since stormwater systems for flooding in urban areas are usually set up in accordance with other primary infrastructure (e.g., roads), it is not plausible to reduce system connectivity or add new components and functions to the existing systems. Similarly, multi-scale networks/connectivity/cohesion (#12, +2) is sorted as relevant in this discourse because connectivity is not only required by physical structures, but also among the various levels of infrastructure managing institutions.

3.2.2. The transformative infrastructure discourse

This discourse is based on developing safe-to-fail infrastructure with respect to large-scale flooding events and the rapid growth of population and urban developments in the metro-Phoenix area. Interestingly, all of the key stakeholders in this perspective are affiliated with the Flood Control District of Maricopa County. They established the decision context of regional flooding problem for their sorting and put importance on strategies that



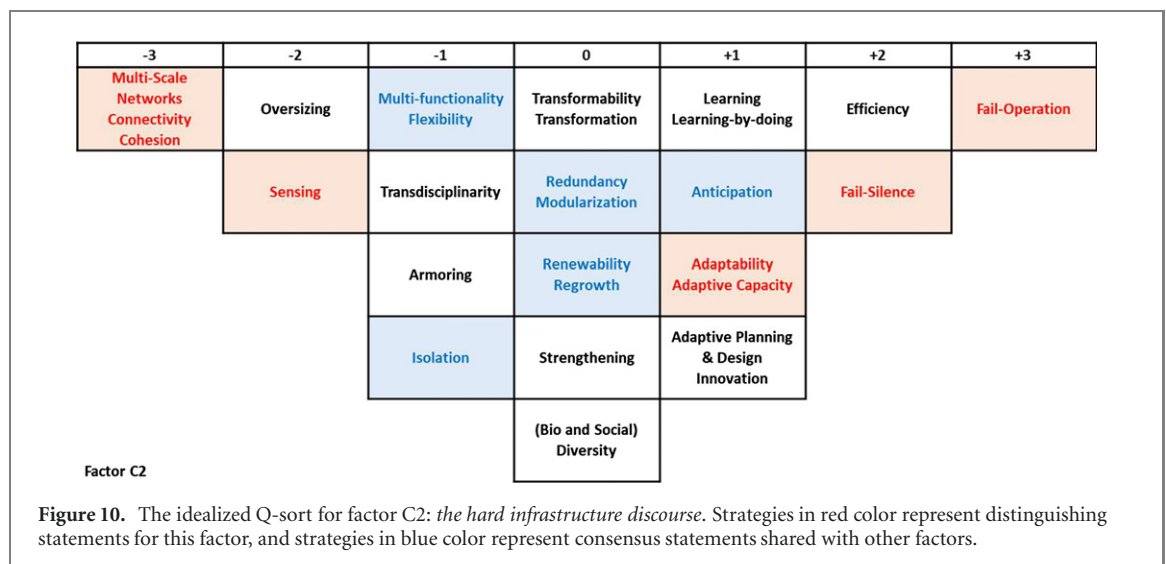
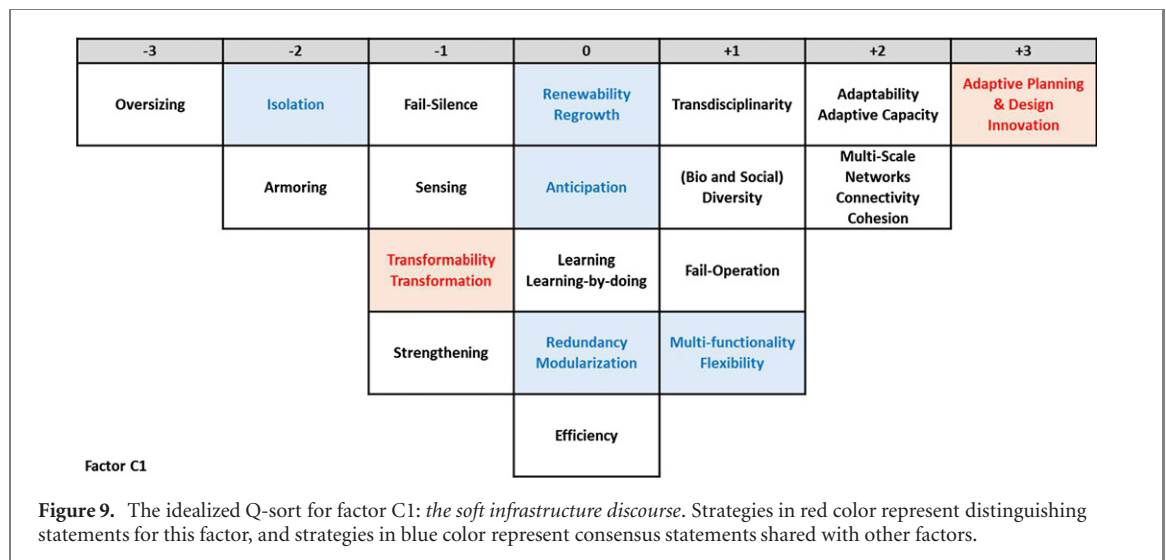
are ‘overarching.’ Considering population growth in the region, participants stressed the need for transformability/transformation (#19, +3) strategies to develop safe-to-fail infrastructure against heavy precipitation (e.g., 100 years return period) (table 1, figure 7). *The transformative infrastructure discourse* emphasizes a need to create an entirely new infrastructure system when existing structures are untenable, such as relocating residential areas away from the current flood hazard zone. The fail-operation (#7, +2) and fail-silence (#8, +1) strategies are also emphasized as infrastructure systems managing large-scale floods should be designed for minimizing the impact of failures and associated damages.

In this discourse, the strategy of oversizing (#13, 0) receives neutral relevance for safe-to-fail design by practitioners, despite it is usually a strategy associated with the fail-safe design in literature, because the current infrastructure design practices often require scaling up the system in order to address safety threshold for increased climate risk projections. Still, participants recognize that oversizing and/or strengthening the infrastructure system has minimal capability to control the failure consequences when risk thresholds are exceeded, and thus, a need for infrastructure design that manages the system failure. Interestingly, this discourse is distinct as multi-scale networks/connectivity/cohesion (#12, -1) is treated as less relevant for developing safe-to-fail infrastructure in the metro-Phoenix area when compared to other idealized sorts (i.e., *the adaptive infrastructure discourse* and *the efficient infrastructure discourse*). Large-scale flood infrastructure such as flood storage and open channel conveyance are built and managed by a single responsible institution and are managed under strict regulations. Thus, participants argue that structural gaps among institutions make them difficult to create or harness linkages between systems and managerial institutions in flood infrastructure operation and management.

3.2.3. The efficient infrastructure discourse

The efficient infrastructure discourse focuses on developing safe-to-fail infrastructure with respect to region-wide flooding problems and current financial constraints (figure 8). Viewpoints on safe-to-fail infrastructure in this discourse emphasize pragmatic solutions to mitigate flooding risks when, in the metro-Phoenix area, there is a little attention paid to flood management attributed to its desert climate. These practitioners state that there is currently limited funding to deal with flooding issues, especially since the semi-arid region of Phoenix experiences only infrequent flash floods. However, precipitation patterns are becoming unpredictable, making flood control a more complicated issue than it was in the past. Utilizing a multi-functionality/flexibility (#11, +2) strategy that adopts the design of systems or components with extensible functionality, capacity for reconfiguration, intertwining and combined functions, and time-shifted functions (table 1, figure 8) is highly valued to prepare for unpredictable, infrequent flooding on a limited budget by practitioners in the region. For example, creating green areas in existing vacant lots can promote multi-functionality by creating a place for recreation and social cohesion during dry seasons, while acting as a bioretention basin to accommodate rainfall during wet seasons. Notably, fail-silence (#8, +3) is emphasized in this discourse by highlighting the need to shut down infrastructure systems when multi-functional solutions do not work and avoid more intricate and problematic damages across various system functions (table 1, figure 8).

Since funding constraints are the highest concern of this discourse, armoring (#4, -3) and oversizing (#13, -2) are perceived as the least relevant strategies for safe-to-fail infrastructure development. Multiple respondents portray these strategies as expensive solutions for the limited improvement they offer in mitigating flood risk and system failure.



3.3. Considering failure consequences in the process of developing resilient infrastructure (*question C*)

Results of the factor analysis for *question C* construct two discourses based on idealized sorts (figures 9 and 10). We define two idealized sorts for *question C* as *the soft infrastructure discourse* and *the hard infrastructure discourse* (table 4, figure 4). Each considers infrastructure system failure consequences in the process of developing resilient infrastructure. These discourses are driven by participants' standpoint on failure consequences and emphasize either soft or hard infrastructure solutions. Soft infrastructure encompasses knowledge systems, humans, institutions, and policies such as communication among institutions, rules and regulations governing the various infrastructure systems, design specifications, the financing of systems, and the professionals who manage infrastructure. Hard infrastructure refers to physical systems that are built and engineered (Slota and Bowker 2007). The case example of Hurricane Harvey in Houston, Texas was used to form *question C*, which the failure of infrastructure systems and resulting consequences exemplified problems that can be solved both by soft and hard infrastructure. Issues we identified in this case include insufficient information on climatic conditions that exacerbate the damage caused by heavy rainfall, infrastructure systems built without considering pre-existing topographical characteristics of city, path-dependent infrastructure management practices, malfunctioning infrastructure, and a lack of funding for upgrading the infrastructure systems, among others.

There is a consensus across two resulting discourses on strategies like renewability/regrowth (#15, 0), redundancy/modularization (#14, 0), anticipation (#3, 0), multi-functionality/flexibility (#11, +1), and isolation (#9, -2). This consensus is attributed to the broad applicability of these strategies in both in soft and hard infrastructure solutions for #3, #11, #14, and #15 (table 1). Isolation (#9) is perceived as a less promising strategy for the Houston case, as bayous were identified by participants as ineffective for isolating flood retention basins from residential areas.

3.3.1. The soft infrastructure discourse

This discourse focuses on addressing failure consequences by enhancing soft infrastructure solutions in the infrastructure development process (figure 9). Practitioners highlighted in this discourse emphasize that the major problem in Harvey appeared to be a lack of planning and a poor understanding of what the actual flooding risks were. A practitioner working for a city government mentioned that flood risk mitigation should not be done by ‘putting all of your eggs in one basket by focusing on one particular solution or location’ as storm threats can occur in cascading ways. The study participants identified the actual risks as damages experienced by overflow from the bayous and waterways in nearby neighborhoods for the Houston case. While the physical infrastructure such as bayous and waterways were constructed and widened as the flood hazard zone expanded in prior to the occurrence of Hurricane Harvey, when the capacity of these structures was exceeded beyond the design thresholds, nearby neighborhoods were flooded without extended protection.

This discourse recognizes a stagnant flood mitigation strategy focused on built systems was ineffective for minimizing consequences in Houston and suggests increasing infrastructure resilience requires practitioners to come up with new solutions by promoting adaptive planning and design innovation (#2, +3). This is primarily achieved with soft infrastructure solutions that create greater recognition of climate risks with sufficient climate data and past experiences, e.g., by working with community members to inform about risks of living in flood hazard zones or by allocating funds to various attributes of infrastructure. This discourse considers transformability/transformation (#19, −1) as especially irrelevant for dealing with failure consequences, since changes in knowledge systems, institutions, regulations, and policy usually take a longer time to be implemented to lead to changes in physical systems.

3.3.2. The hard infrastructure discourse

The hard infrastructure discourse focuses on addressing failure consequences by remedying past failures and improving existing physical infrastructure solutions during the infrastructure development process (figure 10). Respondents in this discourse are mostly engineers and focus on how to better design and manage physical infrastructure systems to avoid catastrophic failure. They highlight fail-operation (#7, +3) and fail-silence (#8, +2) as the most relevant strategies in developing a hard infrastructure system that would not forfeit nearby neighborhoods nor other connected infrastructure systems by shutting down physical systems and maintaining their critical function despite component failures (table 1, figure 10).

Notably, this discourse considers multi-scale networks/connectivity/cohesion (#12, −3) and sensing (#16, −2) as less relevant than the other factor (compare with *the soft infrastructure discourse* in figure 9). Creating a more connected and interdependent system would inherently make the management of a system more difficult, especially in situations that require shutting down failing systems. Also, hard infrastructure is mostly built in accordance with design specifications and regulations to last for a long time with less flexibility; thus, improving the capacity to sense new stresses and incorporate new risk information in infrastructure design decisions is challenging. This discourse defined by practitioners is particularly contradictory from the view of researchers on safe-to-fail design from the infrastructure resilience literature, where strategies like fail-operation, fail-silence, and efficiency are considered far from promoting resilience in theory.

4. Conclusion

Various resilience perspectives drawn by practitioners on infrastructure systems show that resilience should rather be considered on a spectrum of system characteristics and design strategies. Literature on resilience has suggested various system characteristics (e.g., efficiency, redundancy, fail-operation, multi-functionality) or design strategies (e.g., adaptive planning, learning-by-doing, sensing, oversizing) as ways to enhance infrastructure adaptive capacity to be resilient while responding to changing environment and risks (Ahern *et al* 2014, Chester and Allenby 2019, Kim *et al* 2017, Park *et al* 2013, Rosenzweig *et al* 2019 and Underwood *et al* 2020). These studies have provided useful insights on what we need to consider in order to incorporate a fuzzy concept like resilience into infrastructure development, beyond design manuals and engineering criteria. Nevertheless, practitioners found terms describing resilience in the literature to be abstract, limited to specific systems, and therefore not generalizable. Moreover, a few applicable resilience characteristics or strategies for systems were largely focused on identifying a system resilience in a definitive way. Through this study, practitioners have interpreted all 19 resilience strategies extracted from the resilient infrastructure literature and ranked them as they apply to a particular situation. This illustrates how infrastructure systems can be developed and perform as being resilient to changes, as well as why some strategies are more useful than others depending on various decision contexts including geographical, meteorological, institutional, and technological conditions. Practitioners’ definitions of resilience for infrastructure

are truly subjective and have multiple facets, as they are subject to why, when, how, and which systems are being developed.

This study also confirms several benefits of using Q-methodology to engage with stakeholders in a decision-making process. Firstly, there is a limited number of practitioners in city, regional, and state governments who directly influence decisions for infrastructure development. Where R-methodology (e.g., surveys and questionnaires) usually requires a large sample size to uncover statistically meaningful results, Q-methodology requires fewer respondents (as low as 12) who are most associated with the topic. Also, Q-methodology shows the variety of perspectives among participants through the valuation of all statements presented, rather than R-methodology's focus on isolated statements. This facilitates incorporating multiple resilience strategies in infrastructure development by observing valuable expert knowledge held in a small number of key perspectives, instead of identifying resilience strategies that are popular (for unknown reasons) among many respondents. Secondly, Q-methodology can support safe-to-fail infrastructure development where a diversity of infrastructure failure consequences must be prioritized by decision-makers. Q-methodology is designed in a way that respondents must evaluate all the given statements in relation to each other and must make trade-offs in prioritizing one statement over the other. While this study uses Q-methodology to prioritize resilience strategies, it can also be used to prioritize various types of failure consequences and costs and benefits in development (Kim *et al* 2019). This may reveal how stakeholders consider both tangible and intangible costs experienced when infrastructure fails and provide a means to achieve safe-to-fail development.

By engaging with practitioners at state, regional, and municipal governments, this study demonstrates a structured way to assess how practitioners view resilience and its associated strategies as important means to develop infrastructure and tackle climate risks. More importantly, by using the Q-methodology, we can understand how they arrive at their conclusions. A certain definition of resilience does not neatly describe the importance or relevance of practical regimes nor there is a standalone perspective that fits in all contexts. From the diverse perspectives on resilience observed in this study, practitioners' interpretations of resilience add value to the literature by revealing why different resilience strategies may be preferred in different decision contexts. Practitioner perspectives further reveal that decision considerations such as intensity of the event, identified system vulnerability, and the extent of institutional, social, physical, and financial capacity to withstand infrastructure failure all affect infrastructure development and management decisions. They put different importance on various resilience strategies, even when considering the same city for the same weather risk (i.e., flooding). Further studies on using Q-methodology to engage with other stakeholders in the city, such as community members, may be useful to identify climate risks and infrastructural damages that are most detrimental on their lives. Multiple stakeholder's elicitation on how they prioritize various resilience strategies in order to minimize the overall impact of infrastructure functional loss and failure will provide useful information in upgrading infrastructure design criteria to retrofit the construction of flexible and agile infrastructure that have greater adaptive capacity to unforeseen future climate risks.

Ethical statement

This study was approved by the Arizona State University institutional review board [STUDY00007659] and was conducted in accordance with the principles embodied in the declaration of Helsinki and in accordance with local statutory requirements. All participants in this study gave written informed consent to participate in the study.

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Data availability statement

The data that support the findings of this study are available upon request from the authors.

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