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Review article: Applicability and effectiveness of structural measures for subsidence (risk) reduction in urban areas

Nicoletta Nappo[1,2] **and Mandy Korff**[1,2]

[1]Faculty of Civil Engineering and Geosciences, Technical University of Delft (TU Delft), Mekelweg 5, 2628 CD Delft, the Netherlands
[2]Deltares, Boussinesqweg 1, 2629 HV Delft, the Netherlands

Correspondence: Nicoletta Nappo (n.nappo@tudelft.nl, nicoletta.nappo@deltares.nl)

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Abstract. Managing subsidence and its impacts on cities in coastal and delta areas is a global challenge that requires comprehensive risk reduction policies, including both mitigation and prevention strategies. Urban areas often lack systematic methodologies for determining appropriate countermeasures. This paper proposes a twofold strategy for selecting subsidence reduction measures in urban areas – which refer to structural (i.e. technical) measures to prevent and mitigate subsidence and its physical consequences – based on their applicability and performance. The question-and-response (Q&R) system serves as a decision tree to identify suitable subsidence countermeasures based on their applicability to specific cases. Four indicators of effectiveness – i.e. reduction potential, operational reliability, negative impact, and service life – are then used to assess the performance of subsidence reduction measures. The proposed procedure was applied to 49 cases derived from a review of 52 scientific publications and additional expert sessions and surveys involving 5 academic scholars and 13 experts. Also, the method was applied to examples from Shanghai (China), Jakarta (Indonesia), and the San Joaquin Valley (USA, California). The strategies proposed in this paper proved suitable for an initial screening of subsidence reduction measures applicable in different urban areas, after which a site-specific assessment can follow. Furthermore, this study shows the need to collect and share experiences in evaluating the performance of subsidence reduction measures more systematically and gives a first framework to do so.

1 Introduction

Mexico City (Mexico), Jakarta (Indonesia), Bangkok (Thailand), Venice (Italy), New Orleans (USA, Louisiana), Lagos (Nigeria), Hokkaido (Japan), Shanghai (China), and Gouda (Netherlands) are examples of cities affected by subsidence (Bagheri-Gavkosh et al., 2021; Bucx et al., 2015; Davydzenka et al., 2023; Dinar et al., 2021; Erkens et al., 2015; Herrera-García et al., 2021; Hutabarat and Ilyas, 2017; Pedretti et al., 2024; Poland, 1984). The sinking rates in these cities span a few millimetres (for example in Gouda) to tens of centimetres (for example in Jakarta), causing socio-economic distress and environmental and structural damage (Erkens et al., 2015). The drivers of subsidence are generally distinguished as being natural or anthropogenic, although their combination is often the cause of negative impacts in cities (Galloway and Burbey, 2011). Natural causes typically include consolidation of compressible soils, shrinking and swelling of cohesive soils, decomposition of organic soils, groundwater discharge, and karst and tectonic processes (Gambolati and Teatini, 2021; Poland, 1984). Groundwater withdrawal, gas or oil extraction, mining, underground excavations, and urban sprawl and construction loading are anthropogenic factors causing or exacerbating subsidence processes (Gambolati and Teatini, 2021; Poland, 1984). Moreover, the combination of subsidence with sea-level rise and climate change increases the exposure of cities to additional risks, such as flooding (Herrera-García et al., 2021).

Unlike other geological or geophysical hazards with immediate disastrous impacts (e.g. earthquakes, landslides), subsidence is a relatively slow process with moderate intensity that can take decades to turn into a disaster (UNDRR,

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2024). For this reason, subsidence is often unnoticed and not acknowledged as a disaster, and its physical, socio-economic, and environmental impacts in urban areas are not perceived as a potential catastrophe (Bucx et al., 2015; Erkens et al., 2015; Kok and Costa, 2021). Nevertheless, small- to large-scale subsidence can cause costly short- to long-term negative effects to cities that deserve proper (risk) management and reduction policies (Herrera-García et al., 2021). Several authors (Bucx et al., 2015; Department of Regional NSW, 2023; Erkens and Stouthamer, 2020; Jin et al., 2024; Kok and Costa, 2021; Peduto et al., 2015; Piper, 2021; United Nations, 2015) proposed frameworks for subsidence (risk) management, outlining four primary steps.

1. *Problem analysis*. This involves data collection and analysis, determination of subsidence causes, damage assessment, and (inverse) predictive modelling.

2. *Planning*. This step encompasses scenario construction, vulnerability and risk assessment, cost–benefit analysis, forecasting, decision support systems, proposing innovative (alternative) solutions, exchanging knowledge and best practices, and selection of mitigation and prevention measures.

3. *Implementation*. This involves installing monitoring systems, starting pilot projects, and implementing mitigation and prevention measures.

4. *Evaluation*. The final step is dedicated to the assessment of the management cycle and outlook.

Most of the research activities reported in the literature (63 %) focus on measuring and monitoring subsidence in urban areas using ground-based (e.g. levelling, GPS, extensometers) and remote sensing techniques (such as interferometric synthetic aperture radar (InSAR) and lidar; e.g. Ezquerro et al., 2020; Herrera et al., 2010; Ikuemonisan et al., 2021; López-Quiroz et al., 2009; Nappo et al., 2021; Peduto et al., 2019), while 30 % report on modelling and forecasting and only 7 % provide examples of cities where mitigation and prevention measures are applied (Scopus, 2024).

Technical interventions are commonly employed to protect major cities from subsidence; however, a systematic and objective method for selecting suitable solutions has not yet been established. Additionally, because of the diversity of mitigation and prevention methods, subsidence characteristics, and impacted (infra)structures and societies, evaluating the short- and long-term performance of subsidence countermeasures remains challenging. From this perspective, this paper aims at bridging this gap by proposing a twofold strategy to select mitigation and prevention measures based on their applicability and performance. First, a question-and-response (Q&R) system is proposed to identify suitable subsidence mitigation and prevention measures tailored to the specific requirements of each case. Then, by leveraging methods used to assess the effectiveness of mitigation measures against earthquakes, snow avalanches, landslides, and floods (Bründl et al., 2016; Hudson et al., 2014; Januriyadi et al., 2020; Margreth and Romang, 2010), this paper introduces four indicators to evaluate the effectiveness of selected subsidence countermeasures. This paper focuses on structural (i.e. technical) measures to counteract subsidence risk in urban areas, addressing both ground settlements and the resulting physical consequences (i.e. damage) to structures. With few adjustments, the proposed methodology could be adapted for non-structural (i.e. non-technical) measures, socio-economic and environmental effects, or subsidence countermeasures in rural areas; this however is not the aim of this paper.

Following this Introduction, the paper is structured as follows: Sect. 2 recalls the definitions of reduction, mitigation, prevention, and adaptation used in this study; Sect. 3 presents the collected data; Sect. 4 introduces the Q&R system and the indicators of effectiveness; Sect. 5 applies the methodology to selected cases and analyses the obtained results; and Sects. 6 and 7, respectively, discuss and conclude this paper. A brief description of measures to counteract subsidence and its physical consequences in urban areas is provided in Appendix A.

2 Definitions

The definitions of terms given hereafter are based on the United Nations Multilingual Terminology Database (UNTERM, 2024) and the Sendai Framework Terminology on Disaster Risk Reduction (UNDRR, 2024). These definitions strictly refer to subsidence risk management; therefore, some of them may differ in other contexts, such as in climate change policies and civil structural engineering.

- *Reduction*. These are strategies to decrease or remove the risk of subsidence by acting on the predisposing factors, magnitude, intensity, or frequency of subsidence or on the vulnerability and exposure of urban areas affected by it. Subsidence reduction measures encompass both mitigation and prevention measures.

- *Mitigation*. These are structural and non-structural measures taken to minimize subsidence and its adverse impacts (e.g. damage) that cannot be entirely prevented. In urban areas, mitigation examples include repairing cracks in buildings following ground settlements or re-injecting fluids into aquifers after extraction.

- *Prevention*. These are structural and non-structural measures taken to entirely avoid subsidence and its adverse impacts (e.g. damage) and to avert cascading effects such as sinkholes or increased flood risk. In urban areas, prevention examples include using deep foundations for buildings in soft soils or enhancing soil strength before construction.

- *Adaptation*. This involves adjusting to the adverse impacts of subsidence or its evolving conditions that cannot be avoided or modified. This term is mainly used in the field of climate change. For subsidence in urban areas, it refers to non-structural measures.

- *Structural and non-structural measures*. This is a set of technical interventions and non-technical strategies employed to cope with new or existing subsidence and its (potential) disastrous consequences. Structural interventions involve hazard-resistant physical structures and engineering techniques to withstand the physical impacts of subsidence. Non-structural measures include laws, regulations, alternative urban planning, public awareness initiatives, and environmental and social policies. The term “structural and non-structural measures” in subsidence risk management differs from its usage in civil and structural engineering.

Other terms such as “remedial”, “reparative”, “precautionary”, “protective”, or “compensatory” measures to “control or arrest” subsidence and its physical consequences can be found in the literature (Nutalaya et al., 1996; Poland, 1984; Singh and Dhar, 1997; Stouthamer et al., 2020; Zektser et al., 2005), referring to what here is defined as “mitigation” and “prevention” measures.

It should be noted that, in this paper, the terms “subsidence countermeasures” and “subsidence reduction measures” are used interchangeably. Both terms refer to mitigation and prevention measures employed in urban areas to contrast subsidence and its physical consequences on (infra)structures.

3 Data collection

Scientific papers and technical articles were retrieved from publication databases and search engines (e.g. Google Scholar, Scopus). A set of 52 publications was selected for the purpose of this study because they describe cases where structural measures are used for contrasting subsidence and damage to structures in urban areas (Table 1). Additionally, two expert sessions and surveys were organized by the authors to gather experiences from 5 academic scholars and 13 experts on subsidence mitigation and prevention.

Table 1 lists the selected publications and the cases discussed during the expert sessions and surveys, detailing the location, cause of subsidence, average settlement rate, geology, and subsidence countermeasures for each case study.

A more detailed description of the subsidence countermeasures mentioned in Table 1 is provided in Appendix A.

4 Method to select subsidence reduction measures

This section describes the two-step approach proposed in this paper to select subsidence reduction measures in urban areas based on their applicability and estimated effectiveness. The applicability of subsidence countermeasures is determined via the question-and-response (Q&R) system. Then, four indicators are used to evaluate the performance of subsidence reduction measures in terms of effectiveness.

4.1 Applicability: the question-and-response (Q&R) system

Besides an initial distinction between structural and non-structural, subsidence reduction measures can be categorized as outlined in Table 2. These categories derive from a set of questions and responses selected by the authors together with the academic scholars and experts consulted for this study, and they reflect the key requirements influencing the selection of subsidence countermeasures in urban areas. By answering these questions, the applicability of each subsidence countermeasure to specific cases can be assessed. The Q&R system provides stakeholders and decision-makers with a tool to rapidly identify (a set of) suitable subsidence reduction measures that meet the specific requirements of each case.

Depending on the application, location, and available information, additional sub-categories (e.g. type of soil/rock, direct and indirect impacts, involved costs) can be added to the system, thus reaching a further level of detail. However, to facilitate a broader comparison among different applications, this paper does not include any sub-category. This decision is based on the review of worldwide case studies, where the inclusion of sub-categories would hinder the comparability of diverse applications.

4.2 Indicators of effectiveness

Once (a set of) suitable subsidence countermeasures are identified for a specific case, their effectiveness can be evaluated using four indicators: reduction potential, operational reliability, negative impact, and service life. A subsidence reduction measure is effective when it performs well across all the indicators and it contributes to reducing the (risk of) subsidence and its physical consequences in urban areas.

- *Reduction potential (RP)*. How much can subsidence and its physical consequences be reduced? This indicator estimates the percentage of subsidence and damage reduction by comparing observations made before and after the implementation of a subsidence countermeasure. It is ranked as follows:
  - *high* – $\mathrm{RP} \geq 50\,\%$
  - *medium* – $10\,\% \leq \mathrm{RP} < 50\,\%$
  - *low* – $\mathrm{RP} < 10\,\%$.

- *Operational reliability (OR)*. Does the subsidence countermeasure perform as intended during its service life

Table 1. List of publications and cases discussed during expert sessions and surveys that, to the authors' knowledge, document instances where structural (i.e. technical) measures have been employed to contrast subsidence and damage to structures in urban areas.

Reference	Location (country, city)	Cause of subsidence	Average rate of subsidence	Geology	Subsidence reduction measures
Abidin et al. (2015)	Indonesia, Jakarta	Groundwater extraction, construction loading	3–10 $cm\,yr^{-1}$	Alluvial deposits	Aquifer recharge
Akbar et al. (2019)	Indonesia, Semarang	Groundwater extraction, construction loading	6–7 $cm\,yr^{-1}$, 14–19 $cm\,yr^{-1}$ in some areas	Alluvial deposits	Retention pond, elevation of linear infrastructures
Alferink and Cordóva (2017)	Netherlands, Groningen Province	Gas extraction, seismic activity	0.3–0.5 $cm\,yr^{-1}$	Sand, clay	Flexible connections to underground infrastructures
Al-Zabedy and Al-Kifae (2020)	Iraq	Karst erosion	–	Gypsum	Improved foundations, soil injections, dynamic compaction of soil
Andreas et al. (2018)	Indonesia, Jakarta	Groundwater extraction, construction loading	1–10 $cm\,yr^{-1}$, 20–26 $cm\,yr^{-1}$ in some areas	Sand, silt, clay	Building jacking, elevation of linear infrastructures, structure relocation
	Indonesia, Semarang	Groundwater extraction, construction loading	6–7 $cm\,yr^{-1}$, 14–19 $cm\,yr^{-1}$ in some areas	Alluvial deposits	Building jacking, elevation of linear infrastructures
Andriani et al. (2021)	Indonesia, Tanjung Api-Api	Soil compaction and oxidation, groundwater extraction	5 $cm\,yr^{-1}$	Peat, clay	Infiltration well, retention pond, accelerate soil consolidation, elevation of linear infrastructures, lightweight construction materials
Basak and Chowdhury (2021)	Netherlands, Maasbommel	Shrink and swell, groundwater extraction, construction loading	< 0.1 $cm\,yr^{-1}$	Clay	Floating and amphibious housing
	Bangladesh, Dhaka	Groundwater extraction	0.3–2 $cm\,yr^{-1}$	Gravel, sand, silt, clay	Floating and amphibious housing
Bell et al. (2002)	USA, Las Vegas, Nevada	Groundwater extraction	5–6 $cm\,yr^{-1}$	Silt, clay	Aquifer recharge, retention pond
Bergado et al. (1993)	Thailand, Bangkok	Groundwater extraction, soil compaction	10 $cm\,yr^{-1}$	Clay	Accelerate soil consolidation, mechanical soil mixing
Brighenti (1991)	Italy, Abano Terme	Groundwater extraction	6 $cm\,yr^{-1}$	Marly limestone	Injection well
Carreón-Freyre et al. (2010)	Mexico, Iztapalapa, Mexico City	Groundwater extraction, construction loading	12 $cm\,yr^{-1}$	Clay	Repairing cracks, elevation of linear infrastructures
Deakin (2005)	UK, Wiltshire	Shrink and swell	–	Clay	Improved foundations, repairing cracks
English et al. (2016, 2021)	USA, New Orleans, Louisiana	Soil compaction	1 $cm\,yr^{-1}$	Peat	Floating and amphibious housing

Table 1. Continued.

Reference	Location (country, city)	Cause of subsidence	Average rate of subsidence	Geology	Subsidence reduction measures
English et al. (2021)	Netherlands, Maasbommel	Shrink and swell, groundwater extraction, construction loading	< 0.1 cm yr^{-1}	Clay	Floating and amphibious housing
Galloway and Riley (1999)	USA, San Joaquin Valley, California	Groundwater extraction, soil compaction	2.7–22 cm yr^{-1}	Clay	Retention pond, injection well
Gambolati et al. (2005)	USA, Wilmington, California	Oil extraction	2.25 cm yr^{-1}	Sand, silt	Injection well
	Italy, Venice	Groundwater extraction, soil oxidation, construction loading	0.2 cm yr^{-1}	Alluvial deposits	Injection well
Gutiérrez and Cooper (2002)	Spain, Calatayud	Karst erosion	2 cm yr^{-1}	Gypsum	Flexible connections to underground infrastructures, improved foundations
Hamidi et al. (2011)	UAE, Abu Dhabi	Groundwater extraction	–	Silty sand	Dynamic compaction of soil
Han (2003)	China, Beijing	Groundwater extraction	5 cm yr^{-1}	Silty clay	Aquifer recharge, retention pond
	China, Luo River		–	Alluvial deposits	Aquifer recharge
	China, Qingdao		3 cm yr^{-1}	Alluvial deposits	Aquifer recharge
	China, Shanghai		6 cm yr^{-1}	Sand, clay	Injection well
	China, Tianjin		3 cm yr^{-1}	Alluvial deposits	Injection well
Huang et al. (2015)	China, Shanghai	Groundwater extraction, construction loading	6 cm yr^{-1}	Sand, clay	Injection well
Jha et al. (2009)	Japan, Kōchi Prefecture	Groundwater extraction	–	Silty sand, gravel	Aquifer recharge, retention pond, exfiltration sewer
Kohlnhofer (1995)	Norway	Soil compaction	–	Peat	Lightweight construction material
	USA, Pickford, Michigan	Soil compaction	–	Silty clay	Lightweight construction material
Kok and Hommes-Slag (2020)	Netherlands, Gouda	Organic soil oxidation, groundwater extraction, construction loading	0.3 cm yr^{-1}	Peat	Compartmentalization, elevation of linear infrastructures, improved foundations, lightweight construction materials
Li et al. (2021)	China, Shanghai, Nanpu Bridge	Groundwater extraction	5 cm yr^{-1}	Silt, sand	Injection well

Table 1. Continued.

Reference	Location (country, city)	Cause of subsidence	Average rate of subsidence	Geology	Subsidence reduction measures
Liang et al. (2015)	China, Ningbo Port	Soft soil compaction	$5\,cm\,yr^{-1}$	Clay, fly ash, silty sand	Dynamic compaction of soil
Lixin et al. (2022)	China, Tianjin	Groundwater extraction	$7\,cm\,yr^{-1}$	Alluvial deposits	Retention pond
Luo et al. (2019)	USA	Coal mining	–	–	Repairing cracks
McBean et al. (2019)	China, Beijing	Groundwater extraction	$5\,cm\,yr^{-1}$	Silty clay	Exfiltration sewer
Nutalaya et al. (1996)	Thailand, Bangkok	Construction loading, groundwater extraction	$10\,cm\,yr^{-1}$	Clay, sand	Aquifer recharge
Ovando-Shelley et al. (2013)	Mexico, Mexico City	Groundwater extraction	$7–10\,cm\,yr^{-1}$	Clay	Improved foundations
Pacheco-Martínez et al. (2013)	Mexico, Aguascalientes	Groundwater extraction, construction loading	$7.2\,cm\,yr^{-1}$	Sand, gravel with silt and clay	Aquifer recharge, demolition of unsafe buildings
Paukstys et al. (1999)	Lithuania, Biržai	Karst erosion	–	Gypsum	Flexible connections to underground infrastructures
	UK, Ripon	Karst erosion	–	Gypsum	Flexible connections to underground infrastructures
Phien-Wej et al. (1998)	Thailand, Bangkok	Groundwater extraction	$10\,cm\,yr^{-1}$	Sand, gravel, clay	Injection well
Poland (1984)	China, Shanghai	Groundwater extraction	$6\,cm\,yr^{-1}$	Sand, clay	Injection well
	UK, Cheshire	Salt mining	$3.38\,cm\,yr^{-1}$	Marl, sandstone	Elevation of linear infrastructures, improved foundations
	Japan, Tokyo	Groundwater extraction	$7.6\,cm\,yr^{-1}$, $24\,cm\,yr^{-1}$ in some areas	Alluvial deposits	Retention pond, aquifer recharge
	South Africa, Far West Rand, Johannesburg	Gold mining	$56\,cm\,yr^{-1}$	Dolomite, unconsolidated deposits	Injection well
	USA, Alabama	Mining, karst erosion	$49\,cm\,yr^{-1}$	Carbonate rocks	Elevation of linear infrastructures, accelerate soil consolidation
	USA, Santa Clara Valley, California	Groundwater extraction	$7.8\,cm\,yr^{-1}$	Alluvial deposits	Retention pond, aquifer recharge, permeable pavement
Pötz and Bleuzé (2009)	Netherlands, Maasbommel	Shrink and swell, groundwater extraction, construction loading	$< 0.1\,cm\,yr^{-1}$	Clay	Floating and amphibious housing

Table 1. Continued.

Reference	Location (country, city)	Cause of subsidence	Average rate of subsidence	Geology	Subsidence reduction measures
Pramono (2021)	Indonesia, Semarang	Groundwater extraction, construction loading	6-13 $cm\ yr^{-1}$	Alluvial deposits	Retention pond
	Indonesia, Jakarta	Groundwater extraction, construction loading	11–13 $cm\ yr^{-1}$	Sand, silt, clay	Retention pond, exfiltration sewer
Ritzema (2008)	Netherlands, Maasbommel	Shrink and swell, groundwater extraction, construction loading	$< 0.1\ cm\ yr^{-1}$	Clay	Accelerate soil consolidation, flexible connections to underground infrastructures, floating and amphibious housing, improved foundations, lightweight construction materials
Saputra et al. (2017, 2019)	Indonesia, Jakarta	Groundwater extraction, construction loading	1–15 $cm\ yr^{-1}$, 25–28 $cm\ yr^{-1}$ in some areas	Sand, silt, clay	Building jacking, infiltration well
	Indonesia, Semarang	Groundwater extraction, construction loading	8–13.5 $cm\ yr^{-1}$	Alluvial deposits	Building jacking, lightweight construction materials
Shen et al. (2019)	Taiwan, district of Lukang	Liquefaction	–	Sand	Dynamic compaction of soil
Shi et al. (2016)	China, Shanghai	Groundwater extraction	6 $cm\ yr^{-1}$	Sand, clay	Injection well
Sneed and Brandt (2020)	USA, Coachella Valley, California	Groundwater extraction	10 $cm\ yr^{-1}$	Gravel, sand, silt, clay	Aquifer recharge, retention pond
Szucs et al. (2009)	Hungary, Debrecen	Groundwater extraction	0.8 $cm\ yr^{-1}$	Sand	Aquifer recharge, retention pond, infiltration well
Tang et al. (2022)	China, Taiyuan basin	Groundwater extraction	8 $cm\ yr^{-1}$	Soft soil, sand	Injection well
Testa (1991)	USA, Wilmington area, Los Angeles, California	Oil and groundwater extraction	36–45 $cm\ yr^{-1}$	Sand, gravel alternated with silt and clay	Injection well
Ting et al. (2020)	Taiwan, Pingtung Plain	Groundwater extraction	1.6 $cm\ yr^{-1}$	Alluvial deposits	Aquifer recharge, retention pond
Wu et al. (2020)	China, Shanghai	Groundwater extraction	6 $cm\ yr^{-1}$	Sand, clay	Injections well
Xuan et al. (2015)	China, Anhui Province	Coal mining	10 $cm\ yr^{-1}$	Silt	Soil injections
Yang et al. (2020)	China, Shanghai	Groundwater extraction, construction loading	6 $cm\ yr^{-1}$	Sand, clay	Injection well
Ye et al. (2016)	China, Shanghai	Groundwater extraction	6 $cm\ yr^{-1}$	Sand, clay	Injection well

Table 1. Continued.

Reference	Location (country, city)	Cause of subsidence	Average rate of subsidence	Geology	Subsidence reduction measures
Zektser et al. (2005)	USA, San Francisco, California	Groundwater extraction	0.2 cm yr^{-1}	Alluvial deposits	Retention pond
	USA, Redwood Creek, California	Groundwater extraction	–	Alluvial deposits	Retention pond
Expert sessions and survey	Netherlands, Amsterdam	Soil compaction, shrink and swell, building loading	0.1–0.3 cm yr^{-1}	Clay, sand	Accelerate soil consolidation, injection well
	Netherlands, Rotterdam	Soil compaction, groundwater extraction, construction loading	0.2–0.3 cm yr^{-1}	Clay, sand	Infiltration well, exfiltration sewer
	Netherlands, Woerden	Soil compaction and oxidation, shrink and swell, construction loading, groundwater extraction	0.1–0.4 cm yr^{-1}	Clay, peat, sand	Floating and amphibious housing, improved foundations, lightweight construction materials
	USA, Houston, Texas	Groundwater extraction	0.5–2 cm yr^{-1}	Clay, sand	Aquifer recharge, retention pond
	USA, New Orleans, Louisiana	Groundwater extraction	0.6–0.8 cm yr^{-1}	Peat, clay	Retention pond, exfiltration sewer, building jacking, improved foundations

without failure? This indicator reflects the functionality of the subsidence reduction measure. If the system reaches or exceeds its limit state (i.e. the system fails), the subsidence countermeasure loses its effectiveness and may require (major) restoration or replacement to re-establish its functionality. This indicator can be classified as follows:

  - *good* – no interventions are needed
  - *fair* – minor interventions are needed
  - *bad* – major interventions are needed.

- *Negative impact (NI)*. Does the subsidence countermeasure have negative side effects? This indicator evaluates whether a subsidence reduction measure causes any detrimental effects (e.g. water pollution, pore clogging, increase in subsidence, (increased) damage to adjacent structures) to the surrounding natural and built environment. It can be classified as follows:

  - *minimal* – no or minimal negative impacts are observed
  - *significant* – notable negative impacts are observed.

- *Service life (SL)*. What is the (expected) service life of the subsidence countermeasure? This indicator reflects the expected duration for which a subsidence reduction measure is able to contrast subsidence and its physical consequences. It can be classified as follows:

  - *long* – SL $>$ 50 years
  - *medium* – 20 $<$ SL $<$ 50 years
  - *short* – SL $<$ 20 years.

The effectiveness of subsidence countermeasures is evaluated by assigning equal weight to all indicators of effectiveness, treating them as equally important. The qualitative values of each indicator are scored on a scale from 1 to 3, where the lowest category (i.e. low RP, bad OR, significant NI, and short SL) receives a score of 1 and the highest category (i.e. high RP, good OR, minimum NI, and long SL) receives a score of 3. The overall effectiveness of subsidence reduction measures is determined by averaging the scores across all indicators. This approach ensures a balanced evaluation of all criteria and facilitates the prioritization of subsidence countermeasures.

5 Application of the proposed approach

This paper analysed 49 cases distributed across 18 countries, as shown in Fig. 1. The United States of America (USA),

Table 2. Question-and-response (Q&R) system serving as a decision tree to identify suitable subsidence reduction measures based on their applicability.

Question	Response	Category
What is the primary cause of subsidence in the area?	Consolidation of compressible soil, shrinking and swelling of cohesive soils, decomposition of organic soils, groundwater discharge, karst and tectonic processes	Natural subsidence
	Fluid extraction, mining, underground excavations, urban sprawl and construction loading	Anthropogenic subsidence
What is the predominant geology of the area?	Peat, silt, clay, sand, gravel	Soils
	Limestone, gypsum, etc.	Rocks
What is the primary objective of the intervention?	Avoid (new or additional) subsidence and its adverse impacts	Prevention
	Reduce subsidence and its adverse impacts	Mitigation
What needs to be prevented or mitigated?	Subsidence	Hazard
	Damage to structures	Vulnerability and exposure
What is the (potential) scale of application of the subsidence countermeasure?	$< 0.1\,km^2$	Micro scale
	$0.1–1\,km^2$	Small scale
	$1–10\,km^2$	Medium scale
	$10–1000\,km^2$	Large scale
	$> 1000\,km^2$	Regional scale
What type of urban area is involved?	Existing area	Rehabilitation
	Expansion area	New development
Where is the subsidence countermeasure to be applied?	Roads, streets, squares, parks, schools, parking, etc.	Public space
	Houses, monuments, back gardens, shops, etc.	Private space
What type of intervention is being considered?	Physical structures	Structural measure
	Laws, regulations, spatial planning	Non-structural measure

China, and the Netherlands are the countries with the highest number of locations where applications of subsidence countermeasures have been reported. It is worth underlining that the number of cities known to be affected by subsidence differs from the cases investigated here (see for example Davydzenka et al., 2023; Pedretti et al., 2023).

Figure 2 shows that 35 (71 %) of the 49 investigated cases identify anthropogenic activities as the primary cause of subsidence, while the remaining 14 (29 %) are attributed to natural causes. Additionally, 16 (32 %) of the 49 cases have a secondary cause of subsidence, with 9 (18 %) of them being anthropogenic and 7 (14 %) being natural. In 9 (18 %) of the 49 cases, subsidence is attributed to more than two causes. Groundwater extraction is the most common primary and secondary cause of subsidence, whereas construction loading and soil compaction are mostly identified as a secondary or tertiary cause.

The analysis of the scientific literature, expert sessions, and surveys reveals that 41 (84 %) of the investigated cases are characterized by a geology predominantly composed of soils, while the remaining 8 (16 %) are characterized by geology primarily composed of rocks (Fig. 3). Among the soil types, clay and sand are the most frequent, representing 13 (26 %) and 12 (23 %) of the cases, respectively. A single dominant lithology is observed in 30 (61 %) of the 49 cases, whereas the remaining 19 (39 %) exhibit a more complex geological structure with multiple lithologies.

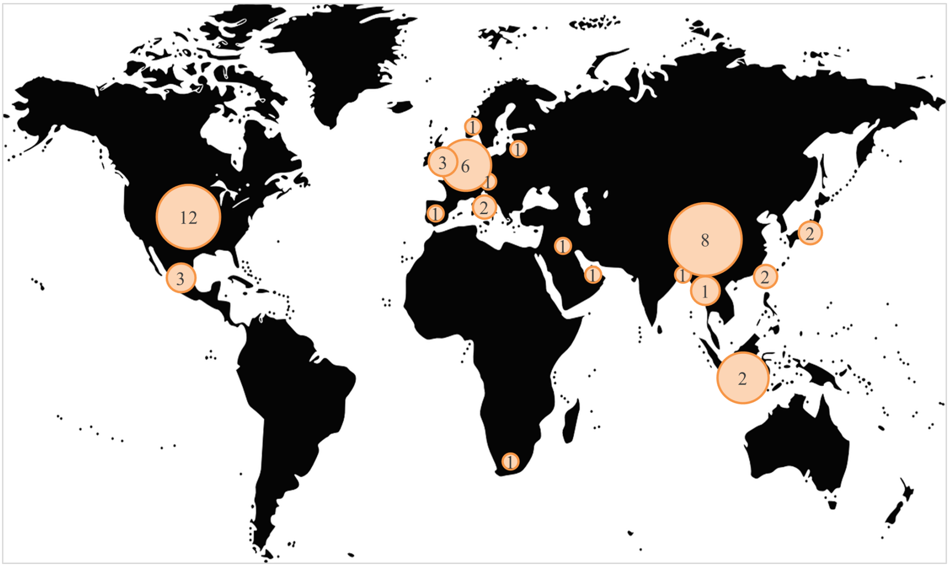

Figure 1. World map showing the number of cases investigated per country. The size of the bubbles is proportional to the number of scientific papers considered in this study.

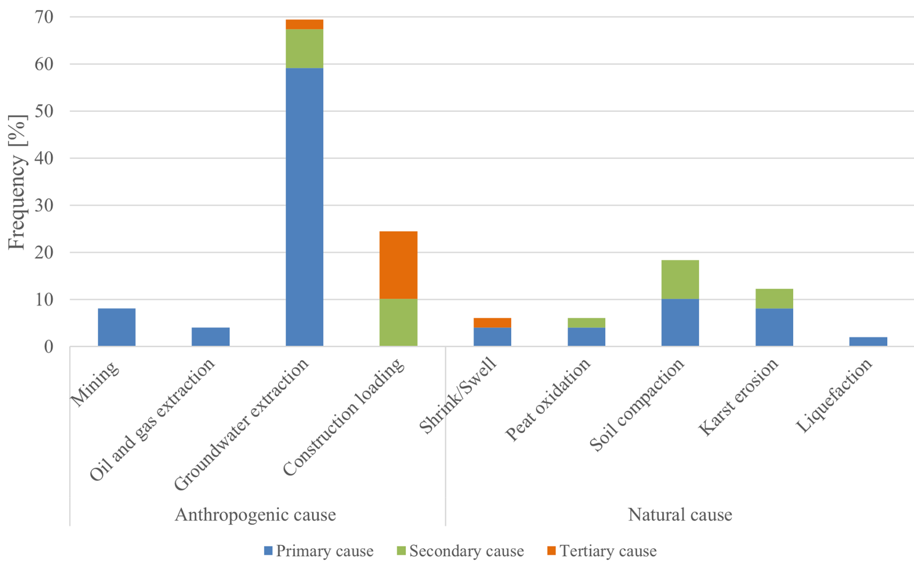

Figure 2. Frequency of the (anthropogenic and natural) causes of subsidence in the investigated case studies.

As for the subsidence reduction measures adopted in the investigated cases, Fig. 4 shows that in 25 cases (51 %) the interventions are related to (ground)water management, followed by construction improvements in 19 cases (39 %) and soil improvements in 5 cases (10 %). The most frequently employed measures are "retention pond" (8 cases) and "aquifer recharge" (7 cases).

Moreover, only 23 (47 %) of the cases employ a single subsidence countermeasure; instead, 26 (53 %) use a combination of measures (see also Table 1). Figure 5 shows a network graph where each node represents a subsidence countermeasure and each link between two nodes indicates at least one case in which the two measures were used together. The subsidence countermeasure with the highest number of connections (11 links) is "improved foundations". Notably, "mechanical soil mixing" was used exclusively in combination with "accelerate soil consolidation".

5.1 Applicability of subsidence reduction measures

The question-and-response (Q&R) system introduced in Sect. 4.1 was applied to evaluate the applicability of the subsidence reduction measures employed in the 49 investigated case studies (see Table B1 in Appendix B). Figure 6

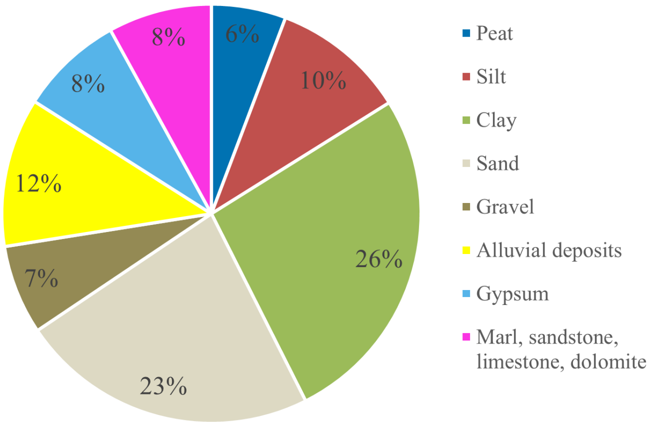

Figure 3. Distribution of geological types of the investigated case studies.

illustrates the results per subsidence countermeasure derived from the literature review, expert sessions, and surveys. This figure can be used to identify suitable subsidence reduction measures for a specific case by disregarding those that do not meet the requirements, which can be done by checking the categories in the columns. Alternatively, the graph can be used to evaluate the applicability of existing subsidence countermeasures by reading it horizontally along the rows. A square marker indicates that a subsidence reduction measure belongs to a specific category or that a category includes a particular measure. When a subsidence reduction measure does not belong to a category, no markers are shown.

5.2 Effectiveness of subsidence reduction measures

The four indicators presented in Sect. 4.2 – reduction potential (RP), operational reliability (OR), negative impact (NI), and service life (SL) – were applied to evaluate the effectiveness of the subsidence reduction measures adopted in the 49 investigated case studies (see Table B1 in Appendix B). Table 3 summarizes the results per subsidence countermeasure based on the outcomes of the literature review, two expert sessions, and surveys involving a total of 18 participants. The mode is used as a metric to assign a single value to each indicator of effectiveness for the subsidence countermeasures. In cases of equally frequent results, expert judgement is preferred if available; otherwise, the highest value is assigned. It is important to note that for some subsidence reduction measures some indicators are missing due to insufficient information in the consulted sources (see Table B1 in Appendix B). When no data are available, no value is assigned to the corresponding indicator of effectiveness. This limitation should be taken into account when using Table 3, as it may influence the prioritization and selection of subsidence countermeasures.

5.3 Selection of subsidence countermeasures based on applicability and effectiveness

This section demonstrates the application of the proposed procedure to three well-documented case studies to simulate its use in real-life scenarios.

5.3.1 Shanghai (China)

First reports of subsidence in Shanghai (China) due to groundwater extraction date back to 1921, with an average rate of 2.6 cm yr^{-1} (Erkens and Stouthamer, 2020; Yang et al., 2020; Ye et al., 2016). The extraction of groundwater for both domestic and industrial use peaked in the 1950s, accelerating subsidence up to 17 cm yr^{-1} (Gambolati and Teatini, 2021). To contrast the spread of subsidence, restrictions on groundwater extraction were established in the 1960s (Han, 2003; Huang et al., 2015; Shi et al., 2016; Wu et al., 2020). During the same period, a network of extensometers, benchmarks, and groundwater observation wells was installed to monitor subsidence (Erkens and Stouthamer, 2020; Ye et al., 2016).

In this context, subsidence countermeasures are necessary to mitigate subsidence in the predominantly clayey urban and peri-urban areas of Shanghai, which extend for more than 90 000 km^2 (Ye et al., 2016). Based on their applicability (see Sect. 5.1), three options are suitable: aquifer recharge (surface and trenches), injection well, and retention pond. Considering their effectiveness (see Sect. 5.2), the two subsidence countermeasures to be preferred are aquifer recharge (surface and trenches) and injection well.

The literature indicates that aquifer recharge from the surface was considered unfeasible due to higher costs (Shi et al., 2016). Instead, injection wells were preferred for recharging deep aquifers given the topography and land use of the city (Han, 2003; Huang et al., 2015; Shi et al., 2016; Wu et al., 2020). Nowadays, the monitoring network closely controls the rate of subsidence in Shanghai, maintaining it below 0.6 cm yr^{-1} (Yang et al., 2020). If subsidence exceeds 0.6 cm yr^{-1}, the amount of injected water is adjusted and additional countermeasures are implemented as necessary (Erkens and Stouthamer, 2020). The quality of the injected water is also closely monitored to minimize pollution and prevent the clogging of pores (Shi et al., 2016).

It can be concluded that the subsidence countermeasure employed in Shanghai in real life aligns with the results of the proposed approach. The final selection of injection wells over aquifer recharge from the surface primarily depends on cost considerations and more site-specific evaluations that are not part of the current approach.

5.3.2 Jakarta (Indonesia)

Subsidence was first observed in Jakarta (Indonesia) during Dutch colonization in 1925–1926, although little is known

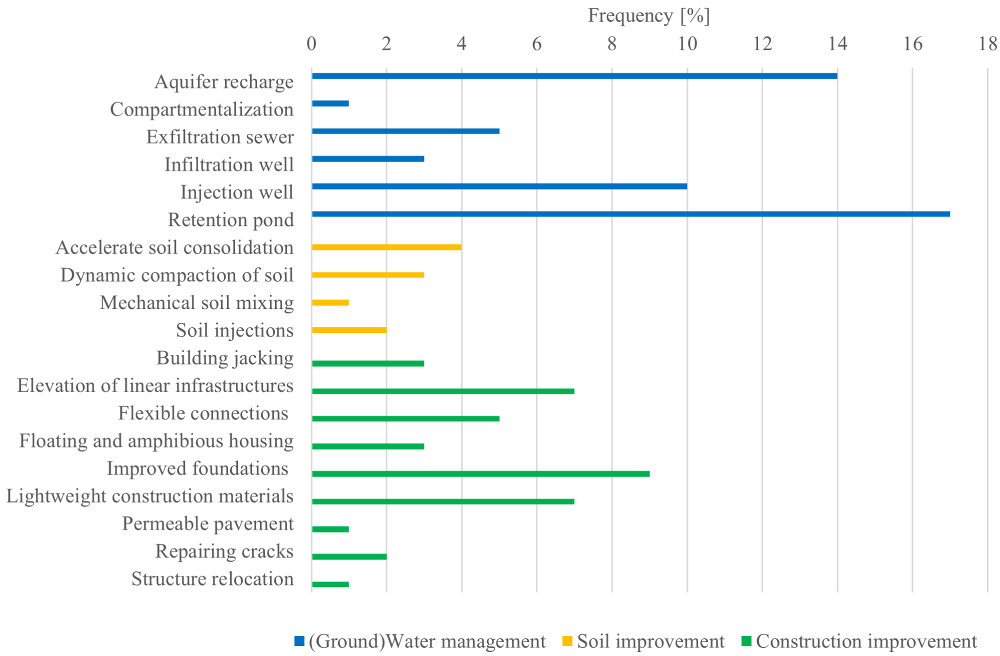

Figure 4. Frequency distribution of the subsidence reduction measures in the investigated cases.

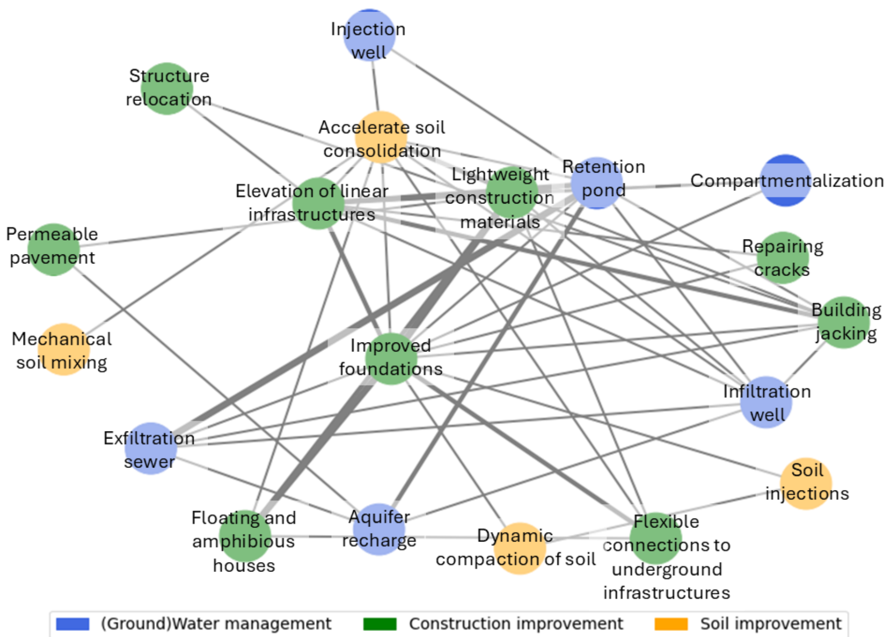

Figure 5. Network graph illustrating the connections among subsidence reduction measures used in the investigated cases. Each node represents a distinct countermeasure, while the connections between nodes indicate that two corresponding measures were implemented together in at least one of the investigated cases. The connection weight represents the number of times a connection is present in the case studies.

about the sinking rates measured at the time (Abidin et al., 2005). In Jakarta, subsidence was slow to be acknowledged as a potential disaster. Investigations were discontinued until 1978, when the impacts of subsidence became evident as cracking of (infra)structures, malfunctioning drainage systems, increased seawater intrusion, and expansion of the flood-prone area (Abidin et al., 2011; Andreas et al., 2018; Erkens and Stouthamer, 2020). Additionally, the excessive extraction of groundwater caused the water table to drop significantly, limiting access to clean potable water (Abidin et

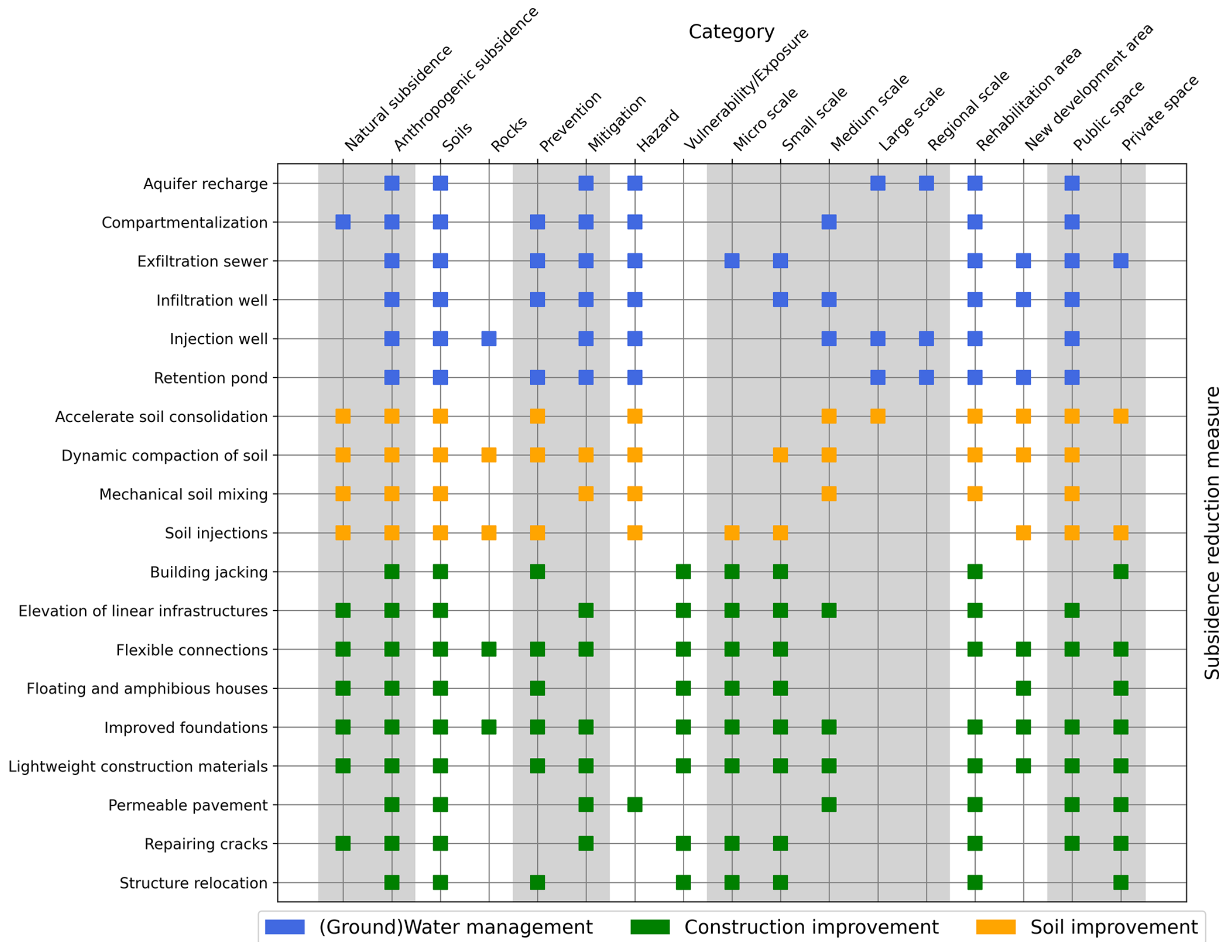

Figure 6. Subsidence reduction measures categorized according to the question-and-response (Q&R) system. The squares indicate the association between a measure and a category. The vertical grey shades highlight different groups of categories. Refer to Table B1 in Appendix B for a detailed version.

al., 2011; Andreas et al., 2018). The first levelling measurements indicated an average subsidence rate of 6 cm yr^{-1} between 1991 and 1997, with peaks of 25 cm yr^{-1} in some locations (Abidin et al., 2005, 2011). Over this 6-year period, cumulative subsidence reached up to 160 cm, particularly in the coastal areas (Abidin et al., 2005, 2011). Continuous groundwater extraction, extensive urbanization, and the presence of relatively young alluvial soils have since increased subsidence rates, with a current velocity of 11–12 cm yr^{-1} in the most affected areas of Jakarta (Abidin et al., 2015). Only after a severe flood in 2007 that submerged 40 % of the city did local authorities and governments recognize the severity of the problem and begin seeking solutions to mitigate and prevent subsidence and damage to structures (Bucx et al., 2015; Erkens et al., 2015).

In this context, a wider range of subsidence countermeasures is applicable to mitigate and prevent (i) subsidence in the inhabited area of Jakarta, which spans approximately 660 km^2, and (ii) damage to (infra)structures at the neighbourhood level (Abidin et al., 2011). At a large scale, measures to mitigate subsidence include aquifer recharge (surface and trenches), injection well, and retention pond, while retention pond and accelerate soil consolidation are suitable to preventing subsidence (see Sect. 5.1). At a small scale, measures to mitigate damage to (infra)structures include elevation of linear infrastructures, flexible connections, improved foundations, lightweight construction materials, and the repairing of cracks, while building jacking, flexible connections, improved foundations, lightweight construction materials, and structure relocation are suitable to prevent damage (see Sect. 5.1). Based on their effectiveness (see Sect. 5.2), aquifer recharge (surface and trenches), accelerate soil consolidation, and injection well should be prioritized to contrast subsidence at a large scale. At a small scale, improved foundations, structure relocation, and elevation of linear infrastructures should be prioritized to reduce damage to (infra)structures.

Table 3. Performance of subsidence reduction measures assessed using four indicators of effectiveness: reduction potential, operational reliability, negative impact, and service life. This is a concise version of Table B1 in Appendix B.

Subsidence reduction measure	Indicator of effectiveness			
	Reduction potential	Operational reliability	Negative impact	Service life
(Ground)water management				
Aquifer recharge	High	Fair	Significant	Long
Compartmentalization	–	Good	Minimal	Long
Exfiltration sewer	High	Good	Significant	Medium
Infiltration well	High	Good	Significant	Medium
Injection well	Medium	Fair	Significant	Long
Retention pond	Medium	Fair	Significant	Medium
Soil improvement				
Accelerate soil consolidation	High	Good	Significant	Medium
Dynamic compaction of soil	High	–	Significant	Medium
Mechanical soil mixing	–	Good	Minimal	Long
Soil injections	Medium	Fair	–	Medium
Construction improvement				
Building jacking	High	Fair	Significant	Short
Elevation of linear infrastructures	High	Good	Minimal	Medium
Flexible connections	–	Fair	Minimal	Medium
Floating and amphibious houses	High	Fair	Minimal	Long
Improved foundations	High	Good	Minimal	Long
Lightweight construction materials	High	Fair	Minimal	Medium
Permeable pavement	–	Fair	Minimal	Long
Repairing cracks	High	Good	Minimal	Short
Structure relocation	High	Good	Significant	Long

According to the literature, regulations on groundwater extraction have been introduced to contrast subsidence in Jakarta; instead, building jacking and elevation of linear infrastructures with sand fill have been extensively adopted to prevent and mitigate damage to (infra)structures (Akbar et al., 2019; Andreas et al., 2018; Saputra et al., 2017, 2019). Additional countermeasures, such as aquifer recharge, injection wells, and exfiltration sewers, have been proposed in recent years to tackle the water crisis and mitigate subsidence but have not yet been implemented (Abidin et al., 2015; Akbar et al., 2019; Pramono, 2021). In parallel, retention ponds have been constructed to manage rainwater runoff and reduce flooding in the sub-district of Kebon Jeruk, and deep foundations are increasingly in use in new development areas to prevent damage. However, subsidence in Jakarta is so severe that local governments decided to relocate a consistent portion of the city (Herrera-García et al., 2021).

Compared to Shanghai, the case of Jakarta is more complex. Groundwater serves as the primary source of potable water, but its excessive extraction accelerates the natural subsidence of alluvial soils, rendering the city more vulnerable to flooding and seawater intrusion. These factors, in turn, compromise the availability and quality of freshwater. As a result, local governments are seeking solutions to address multiple interconnected issues: subsidence, flood risk, freshwater scarcity, and deteriorating water quality. This complexity requires a broader set of options, which extends beyond the scope of this study. Instead, the proposed approach focuses strictly on subsidence reduction and does not account for other related issues. Therefore, while retention ponds are not considered suitable for reducing subsidence in Jakarta within this framework, they may still be viable for addressing other challenges. Similarly, building jacking may be more effective in managing flood risk than contrasting damage to (infra)structures caused by subsidence in Jakarta. Nevertheless, the subsidence countermeasures employed in Jakarta overall align with the results of the proposed approach.

5.3.3 San Joaquin Valley (USA, California)

Subsidence in the San Joaquin Valley (USA, California) due to groundwater extraction for agriculture has been observed since the 1920s (Galloway and Riley, 1999). Continuous exploitation of deep confined aquifers and the consequent soil compaction caused an area larger than 10 000 km^2 to sink by an average of 31 cm between 1925 and 1970 (Galloway and

Riley, 1999). In some localized areas, subsidence reached up to 8.53 m during the same period. In the 1960s, an extensive monitoring network composed of 31 extensometers was implemented to measure soil compaction rates and determine the extent of subsidence (Poland, 1984; USGS, 2024). Since the 1970s, alternative surface water, such as the California Aqueduct and other canals, has been supplied, allowing for a gradual reduction in groundwater extraction. However, recurring droughts in 1976–1977, 1986–1992, 2007–2009, and 2012–2015 drastically reduced surface water availability, leading to a renewed increase in groundwater extraction and aquifer compaction (Galloway and Riley, 1999; USGS, 2024). Between 2006 and 2022, subsidence was estimated to have reached 13 km^3, with rates as high as 0.84 $km^3\,yr^{-1}$ during droughts and periods of intense groundwater extraction (USGS, 2024).

Based on their applicability (see Sect. 5.1), suitable measures to mitigate subsidence at the regional scale in this soil-dominant area, primarily composed of alluvial deposits, include aquifer recharge (surface and trenches), injection well, and retention pond. Considering their effectiveness (see Sect. 5.2), this selection can be narrowed down to aquifer recharge (surface and trenches) and injection well.

The Sustainable Groundwater Management Act (SGMA) – legislation passed in 2014 – represents a significant step towards sustainable water management in the San Joaquin Valley, aiming to contrast groundwater depletion, aquifer compaction, and the impacts of droughts (Lees et al., 2021). Recently, initiatives have been launched to replenish groundwater by recharging shallow aquifers through surface water percolation, thus helping to balance extraction with natural recharge rates (Lees et al., 2021). Among these initiatives, one key strategy is flood-managed aquifer recharge (Flood-MAR), which combines shallow and deep aquifer management with management of extreme weather events like floods and droughts to preserve agricultural land and minimize damage to infrastructure (Flood-MAR, 2024). Additionally, promoting sustainable water use practices in agriculture and urban areas has become a priority to minimize wastage (USGS, 2024).

Similarly to the previous cases, the subsidence countermeasure employed in the San Joaquin Valley aligns with the results of this study. In this case, aquifer recharge (surface and trenches) was preferred over injection wells because it can handle larger volumes of water (approximately 220×10^9 gallons (8.33×10^8 m^3) of water are needed annually), it can be integrated with natural systems (e.g. river and trenches), it does not need large infrastructural works, and it is more environmentally sustainable. This case further underlines the importance of conducting detailed assessments of the suitability of subsidence reduction measures to also address changing climates and promote sustainable solutions.

6 Discussion

In the previous section, a review of 49 cases distributed in 18 countries gathered from scientific papers, technical articles, expert sessions, and surveys was conducted to formulate a twofold strategy to select subsidence reduction measures in urban areas based on their applicability and performance. The proposed method consists of two steps: the question-and-response (Q&R) system for identifying measures tailored to the specific requirements of each case and the indicators of effectiveness for evaluating the performance of subsidence countermeasures.

The Q&R system proved useful for an initial screening of subsidence reduction measures. Seven questions were determined to categorize the subsidence countermeasures based on the area's geology, cause of subsidence, scale of application, objective of the intervention, and type of urban area. With this system, stakeholders and decision-makers can determine the applicability of measures to specific cases and focus on a more limited number of choices. Each subsidence reduction measure can satisfy the requirements of multiple categories, which can be combined to create tailored decision trees. The proposed Q&R system could be further refined by adding sub-categories accounting for construction and maintenance costs, hydrogeology, geotechnology, and structural engineering. Also, the current Q&R system disregards the indirect effects of subsidence (e.g. the increased risk of flooding or seawater intrusion). In a more comprehensive risk management framework, where subsidence is not the only threat, the Q&R system should be improved to account for multiple hazards and effects.

The indicators of effectiveness proposed in this paper (i.e. reduction potential, operational reliability, negative impact, and service life) allowed for an initial assessment of the performance of subsidence reduction measures. Using these indicators, stakeholders and decision-makers can rapidly assess the effectiveness of suitable subsidence reduction measures selected via the Q&R system. Further improvements to the proposed method may involve novel indicators, such as inclusiveness (what societal groups are targeted) and responsibility (allocation of risks in public–private partnerships). At this stage, the proposed procedure allows for a qualitative assessment of effectiveness based on the joint evaluation of each indicator's performance. The evaluation of performance in Table 3 needs further refinement by considering a broader and well-documented range of cases. Currently, the information available to structure the scoring is limited, as demonstrated in Table B1 in Appendix B. This affects the criteria used to assign scores, possibly leading to over- or underestimations of the effectiveness of certain subsidence countermeasures. This limitation should be taken into account when applying the indicators from Table 3, as it may influence the selection of subsidence reduction measures. The lack of comprehensive and consistent data further underlines the need to collect and share experiences for evaluating the performance of subsidence reduction measures to create a more systematic framework. Once a sufficient number of applications is available for each subsidence reduction measure, quantitative estimations and ranking will also be possible. Additionally, more research is needed to determine the acceptable or unacceptable thresholds for the indicators of effectiveness, also considering the positive or negative interaction of subsidence countermeasures with adjacent assets.

The cases of Shanghai (China), Jakarta (Indonesia), and the San Joaquin Valley (USA, California) demonstrate that the proposed two-step procedure to select subsidence countermeasures based on their applicability and effectiveness is promising. In both Shanghai and the San Joaquin Valley, where the primary goal was subsidence mitigation at a regional scale (i.e. $> 1000\,\text{km}^2$), the Q&R system identified three suitable options, which was narrowed down to two based on the indicators of effectiveness. In both cases, the two most effective countermeasures (i.e. aquifer recharge and injection well) matched the options considered or implemented in practice. The case of Shanghai underlines that, when subsidence countermeasures have similar levels of effectiveness, cost considerations often play a decisive role, especially at larger scales where costs can escalate significantly. In the San Joaquin Valley, the discriminating factors were primarily the volume of recharged water (estimated at approximately 220×10^9 gallons ($8.33 \times 10^8\,\text{m}^3$) annually) and the sustainability of subsidence countermeasures. Both examples emphasize the importance of site-specific considerations and multi-criteria assessments that weigh effectiveness alongside costs and sustainability. In Jakarta, 11 different options were identified by the system based on their applicability to mitigate or prevent subsidence at a large scale (i.e. 10–1000 km^2) and damage to (infra)structures at a small scale (i.e. 0.1–1 km^2). This broader set of options was then narrowed down to six based on their effectiveness. In this case, five subsidence countermeasures identified by the procedure matched those employed or proposed in practice. Two additional countermeasures (i.e. retention pond and building jacking) that were deemed ineffective by the proposed procedure to contrast subsidence or damage to (infra)structures were implemented in Jakarta. However, these countermeasures were used to manage increased flood risk rather than subsidence.

These findings demonstrate that, besides the necessary refinements to enhance the accuracy of the proposed method in selecting subsidence reduction measures, careful interpretation of the results is essential. This involves considering the wide variety of subsidence reduction measures, the underlying causes of subsidence, site-specific settings, potential negative or secondary effects, and the long-term sustainability of countermeasures. Environmental considerations encompass potential alterations of local ecosystems, changes to water quality, depletion of natural resources, and increased energy consumption with associated carbon emissions. For instance, creating artificial retention ponds may disrupt natural habitats, while recharging aquifers – whether through surface or deep injections – may affect water quality. Similarly, infrastructure-heavy solutions, such as injection wells, can contribute to greenhouse gas emissions, especially if they rely on non-renewable energy sources. Social impacts involve the displacement of communities due to relocation, leading to social stress and loss of community identity. Equity issues can also arise, as the increased costs or reduced availability of potable water disproportionately affect low-income populations. Other economic implications include rising property values, which can lead to gentrification and displacement of lower-income residents. Given these challenges, stakeholders and decision-makers should adopt a multidimensional approach to subsidence (risk) management that integrates technical considerations with environmental stewardship, social equity, and economic feasibility. Proactively addressing the indirect consequences of subsidence reduction measures can contribute to sustainable and resilient urban development. Additionally, in settings with compound hazards, such as Jakarta, broader contextual analyses are necessary to fully understand the applicability and effectiveness of specific countermeasures. For a thorough validation of the proposed method, a detailed evaluation of effectiveness via measurable parameters – such as water table levels, water infiltration rates, the volume of extracted or recharged water, soil compaction, surface rebound, settlement rates, and crack widths – is crucial. It is rather surprising how few cases are reported in the literature, with even fewer with a sufficient evaluation of effectiveness. The consistent use of the four indicators of effectiveness specifically derived for evaluating the subsidence countermeasures presented in this paper can serve as the basis and catalyst for this.

7 Conclusions

Subsidence is a relatively slow process with moderate intensity that is rarely perceived as an imminent disaster. However, its physical, socio-economic, and environmental impacts in urban areas require tailored reduction policies encompassing both mitigation and prevention strategies.

After defining key terminology (i.e. reduction, mitigation, prevention, adaptation, and structural and non-structural measures), this paper proposed a twofold strategy for selecting structural (i.e. technical) measures to contrast subsidence and its physical consequences in urban areas based on their applicability and effectiveness. The objective is to assist stakeholders and decision-makers in managing subsidence (risk) in urban areas, with particular attention to the planning and implementation phases of the subsidence risk frameworks.

Despite the preliminary nature of this work, the proposed methods for selecting subsidence reduction measures and evaluating their effectiveness constitute a novelty in the scientific literature on subsidence studies and mitigation/prevention strategies as no framework currently exists to assess applicable and effective measures. Refinements and further validation are needed to integrate the procedure into current subsidence management practices in urban areas, with specific attention paid to the local hydrogeological, geotechnical, structural, environmental, and social settings where countermeasures are needed. Therefore, at its current stage, the methodology proposed in this paper should be considered a preliminary tool for stakeholders and decision-makers to identify a set of suitable solutions, which should be further discussed with local experts. Moreover, with appropriate adjustments, the presented methodologies could also be applied for selecting and evaluating the performance of non-structural (i.e. non-technical) measures, subsidence reduction measures in rural areas, and secondary subsidence effects.

Appendix A: Description of subsidence reduction measures

Table A1 provides a brief description and alternative names of structural (i.e. technical) measures considered in this paper to prevent and mitigate (i.e. reduce) subsidence and its physical consequences in urban areas. The countermeasures in Table A1 are organized into (ground)water management, soil interventions, and construction interventions.

Table A1. Structural (i.e. technical) measures to reduce subsidence and its physical consequences in urban areas.

Subsidence reduction measure	Alternative names	Description
(Ground)water management		
Aquifer recharge (surface spreading and trenches)	Planned recharge, induced recharge, artificial recharge	Water is spread or impounded on the ground surface so that it infiltrates through permeable soils (sand or gravel) into an unconfined aquifer. Trenches can also be used to collect runoff water and infiltrate it into the soil.
Compartmentalization		Large polder areas are divided into smaller portions by vertical waterproof barriers, typically made of retaining walls or clay walls. This creates a hydraulic barrier in the subsurface between compartments to maintain a stable groundwater level in each compartment.
Exfiltration sewer	Exfiltration trench, perforated pipe, clean water collector, exfiltration pipe	Perforated pipes (usually in PVC or vinyl) redistribute excessive surface or runoff water into the soil while being conveyed. If the groundwater level around the perforated pipe is higher than the water table inside the pipe, then the water conveys as in a conventional sewer. Downpipes from rooftops can be directed to the exfiltration sewer instead of wastewater sewers. The exfiltration sewers can be connected to retention ponds and infiltration wells, and, if the water needs to be moved from a lower to higher altitude, a mechanical water pump can facilitate the circulation of water.
Injection well	Recharge well, artificial fluid injection, deep wells	Deep confined aquifers are re-pressurized by injecting fluids through wells into porous geologic formations (sand, gravel, or clay). The injection pipe is usually placed in a fibreglass-reinforced plastic casing. The well is finished with cement grouting, sand, well screen, and gravel pack.
Infiltration well	Biopore hole	Excessive surface water is collected into a perforated plastic pipe of typically 10 cm in diameter during rainfall events, and it is redistributed into compacted soils with a poor infiltration rate. The infiltration wells can be also connected to sewer exfiltration systems, and they can be filled with organic waste to improve soil fertilization.
Retention pond	Retention basin, catchment area/basin, wet/storm pond, rainwater harvesting, water banking	This is a permanent catchment area suitable for urban areas to provide additional water storage capacity and attenuate surface runoff during rainfall events. By placing coarse draining material at the bottom (bed) of the pond, water can filtrate in the surrounding soil, keeping the desired groundwater level.
Soil improvement		
Accelerate soil consolidation		Vertical drains, sand pipes, and trenches are placed up to a depth of 35 m to quickly dissipate excessive pore water from soft or organic soils, thus accelerating their consolidation. Additional loads can be applied to the soil by lowering the atmospheric pressure inside the drains and therefore applying vacuum pressure. This method is usually used to prepare the soil before the construction of (infra)structures.
Dynamic compaction of soil		A heavy steel weight is repeatedly dropped on the ground surface to generate vibrations that, once transmitted to the subsurface, improve and densify soils and filling materials. It is mainly used to treat soils beneath foundations before the construction of (infra)structures. Therefore, the steel weight is dropped in selected locations forming a regular grid pattern.
Mechanical soil mixing	Deep soil mixing	Natural soil is mixed with cement or compound binders to improve its mechanical and physical properties. The mechanical binders can be operated in either wet or dry conditions, depending on the typology of soil and the improved characteristics to be achieved.

Table A1. Continued.

Subsidence reduction measure	Alternative names	Description
Soil injections	Void filling, subgrade stabilization	Additives are injected into the subsurface through one or more pipes installed vertically into the ground, thus improving the strength, load-bearing capacity, and stability of soft soils. Natural materials such as sand, fly ash, or rock powder are mostly used for soft soils. Crushed waste concrete, tyre crumb rubber, hydrated lime, resins, and polymers have been tested successfully in clay soils. Jet grouting of Portland cement or chemical grouts and foams are mostly used when cavities form in the ground.
Construction improvement		
Building jacking	Construction lift, house raising or lifting	A construction is lifted above its existing foundation to (re-)build a new one at a higher or similar level.
Elevation of linear infrastructures	Sand fill	The surface area of infrastructures such as roads and railways is lifted by placing an additional layer of material (typically sand and/or road material) on top of existing subsiding layers. In the case of bridges, also new (deep) foundations are usually built to elevate the bridge shoulders.
Flexible connections to underground infrastructures	Flexible joints	Thermoplastic composite materials or flexible connections are used to join two components of (underground) infrastructures, such as pipelines, thus permitting relative movements and providing them with major flexibility.
Floating and amphibious houses		Houses can be built on a waterbody and be designed with a floating system at their base to allow for them to float on water.
Improved foundations	Strengthening, replacement, repair, restoration, or improvement of foundations	Several methods allow for repairing, restoring, improving, or replacing (building) foundations to re-establish their structural capacity. – *Slab jacking, also called concrete lifting, slab levelling, or mud jacking*. It is a reparation method used to re-level uneven or sinking concrete slabs. Small holes are drilled into the concrete slab, and a strong cementing mixture is injected under the slab to align it back to its original position. The cement mixture, polymer resin, sand, gravel, ash, and polyurethane foam can be used as a base material. – *Underpinning, also called piering*. A system of vertical anchors is installed below an existing foundation to reach deeper soil layers with better geomechanical properties. This method can be used either to strengthen an existing foundation or to improve the soil before placing a new foundation system. Different techniques can be adopted to achieve this. *(a) Mass concrete underpinning*. The soil around an existing foundation is excavated through controlled stages (or pins), and, when a new suitable foundation soil layer is reached, the excavation is filled with concrete. *(b) Cantilever needle beam underpinning*. The area surrounding the foundation is excavated, and a cantilever needle beam is placed through a hole cut in the existing foundation wall. The beam is supported by micropiles, which are placed before excavation. *(c) Pier and beam underpinning*. Helical or push piers made of galvanized or epoxy-coated steel are drilled below the foundation until reaching a suitable depth where concrete bases are placed. (d) *Micropiling underpinning*. Micropiles are driven below the existing foundation with a certain inclination. Earth is excavated to the top of the pile so that the earth between the foundation and the pile can be replaced with concrete. *(e) Pile underpinning*. Piles are driven in the proximity of a foundation wall. Then, a needle beam is placed through the foundation wall and connected to the adjacent piles. – *Installation of (additional) piles*. It consists of placing (additional) piles or micropiles below an existing (shallow) foundation to redistribute the loading.

Table A1. Continued.

Subsidence reduction measure	Alternative names	Description
		– *Reduction in bacterial decay in wooden piles*. Wooden piles area treated with special coatings to preserve them from unforeseen anaerobic conditions and degradation. – *Reduction in negative adhesion/friction around piles*. When piles pass through cohesive soils, they can experience negative adhesion due to downwards shear drag movements. This can be reduced by using anti-friction coatings around the piles, by improving the soil characteristics with injections, or by using slender pile sections (e.g. H pile or precast pile) with a smaller pile area. – *Reinforced geotextiles*. Geotextiles can be placed on top of a system of piles to improve their bearing capacity. This technique is used often to reinforce the foundations of roads and railways.
Lightweight construction materials		Lightweight aggregates can be added to the cement to reduce the construction load. Pumice, scoria, volcanic cinders, tuff, diatomite, heating clay, shale, slate, diatomaceous shale, perlite, obsidian, and vermiculite can be used as lightweight aggregates. For road construction, cellular geosynthetics (geofoams and geocombs), the block-moulded expanded polystyrene (EPS), and recycled plastic can be used.
Permeable pavement	Permeable paving or porous asphalt	A porous paving surface is made of permeable pavers (in concrete or polymer), concrete, or asphalt that allow for surface or rainwater to pass through or around them and be slowly infiltrated into the soil. This pavement allows for reducing the runoff volume and peak rates of water discharge, and it is mostly used for parking lots, sidewalks, or low-traffic roads.
Repairing cracks		Different foam- and resin-based materials are used to repair cracks that appear on building facades or road pavements. Additional filling materials are fibre cement, epoxy resin, non-shrink grouts, hot rubber, and polymer asphalt.
Structure relocation		Buildings are physically moved from their original location to another. This can be done by disassembling and reassembling the construction or by transporting it whole to the new location. This method is used especially for monumental structures.

Appendix B: Applicability and effectiveness

Table B1 reports the assessment of applicability (see Sect. 4.1) and effectiveness (see Sect. 4.2) of the subsidence reduction measures adopted in the 49 cases investigated in this paper.

Table B1. Assessment of the applicability and effectiveness of subsidence reduction measures employed in the 49 investigated cases derived from the literature review, expert sessions, and surveys. The applicability results are from the question-and-response (Q&R) decision tree system. Effectiveness is evaluated using the indicators of reduction potential (RP), operational reliability (OR), negative impact (NI), and service life (SL). NA denotes information that is "not available".

Reference	Applicability					Indicator of effectiveness			
	Scale	Objective	Target	Urban area	Space	RP	OR	NI	SL
Aquifer recharge (surface spreading and trenches)									
Abidin et al. (2015)	Regional	Mitigation	Hazard	Rehabilitation	Public	NA	NA	NA	NA
Bell et al. (2002)	Large	Mitigation	Hazard	Rehabilitation	NA	High	Fair	Significant	Long
Han (2003)	Large, regional	Mitigation	Hazard	Rehabilitation	NA	NA	NA	NA	Long
Jha et al. (2009)	Large	Mitigation	Hazard	Rehabilitation	Public	Medium	NA	Significant	Long
Nutalaya et al. (1996)	Large	Mitigation	Hazard	Rehabilitation	Public	High	NA	Significant	Long
Pacheco-Martínez et al. (2013)	Regional	Mitigation	Hazard	Rehabilitation	Public	NA	Bad	Significant	Long
Poland (1984)	Regional	Mitigation	Hazard	Rehabilitation	NA	NA	NA	NA	NA
Sneed and Brandt (2020)	NA	Mitigation	Hazard	Rehabilitation	Public	NA	NA	NA	NA
Szucs et al. (2009)	NA	Mitigation	Hazard	Rehabilitation	Public	NA	NA	Significant	Long
Ting et al. (2020)	Regional	Mitigation	Hazard	Rehabilitation	Public	NA	Good	Minimal	Long
Expert sessions and survey	Regional	Mitigation	Hazard	Rehabilitation	Public	NA	Fair	NA	Long
Compartmentalization									
Kok and Hommes-Slag (2020)	Medium	Prevention, mitigation	Hazard	Rehabilitation	Public	NA	Good	Minimal	Long
Exfiltration sewer									
Jha et al. (2009)	Small	Mitigation	Hazard	Rehabilitation	Public	Medium	NA	Minimal	Medium
McBean et al. (2019)	Small	Mitigation	Hazard	Rehabilitation	NA	NA	NA	NA	Medium
Pramono (2021)	Micro	Mitigation	Hazard	Rehabilitation	Private	NA	NA	NA	NA
Expert sessions and survey	Small	Prevention, mitigation	Hazard	Rehabilitation, new development	Public	High	Good	Significant	Medium
Infiltration well									
Andriani et al. (2021)	Medium	Prevention, mitigation	Hazard	Rehabilitation	Public	NA	NA	NA	Medium
Saputra et al. (2017)	NA	Mitigation	Hazard	Rehabilitation	Public	NA	NA	NA	NA
Szucs et al. (2009)	NA	Mitigation	Hazard	Rehabilitation	Public	NA	NA	Significant	Medium
Expert sessions and survey	Small	Prevention, mitigation	Hazard	Rehabilitation, new development	Public	High	Good	Significant	Long

Table B1. Continued.

Reference	Applicability					Indicator of effectiveness			
	Scale	Objective	Target	Urban area	Space	RP	OR	NI	SL
Injection well									
Brighenti (1991)	NA	Mitigation	Hazard	NA	NA	NA	NA	Significant	Short
Galloway and Riley (1999)	Regional	Mitigation	Hazard	Rehabilitation	Public	NA	NA	Significant	Long
Gambolati et al. (2005)	Regional	Mitigation	Hazard	Rehabilitation	Public	Medium	NA	Minimal	Short
Han (2003)	Regional	Mitigation	Hazard	Rehabilitation	NA	NA	NA	NA	Long
Huang et al. (2015)	Medium	Mitigation	Hazard	Rehabilitation	Public	NA	NA	Minimal	Long
Li et al. (2021)	Regional	Mitigation	Hazard	Rehabilitation	NA	NA	NA	Significant	Long
Phien-Wej et al. (1998)	Medium, large	Mitigation	Hazard	Rehabilitation	Public	NA	NA	Significant	Short
Poland (1984)	Regional	Mitigation	Hazard	Rehabilitation	NA	NA	NA	Significant	Long
Shi et al. (2016)	Regional	Mitigation	Hazard	Rehabilitation	Public	NA	Fair	Significant	Long
Tang et al. (2022)	Regional	Mitigation	Hazard	Rehabilitation	Public	NA	NA	Minimal	Long
Testa (1991)	NA	Mitigation	Hazard	NA	NA	Low	NA	NA	NA
Wu et al. (2020)	Regional	Mitigation	Hazard	Rehabilitation	Public	NA	NA	Minimal	Short
Yang et al. (2020)	NA	Mitigation	Hazard	Rehabilitation	Public	NA	Good	Minimal	Long
Ye et al. (2016)	Regional	Mitigation	Hazard	Rehabilitation	NA	NA	NA	Minimal	Long
Expert sessions and survey	Medium	Mitigation	Hazard	Rehabilitation	Public	Medium	Fair	Significant	Short
Retention pond									
Akbar et al. (2019)	Large	Mitigation	Hazard	Rehabilitation	Public	NA	NA	NA	NA
Andriani et al. (2021)	Large	Mitigation	Hazard	Rehabilitation	Public	NA	NA	NA	Medium
Bell et al. (2002)	Large	Mitigation	Hazard	Rehabilitation	NA	High	Fair	Significant	Medium
Galloway and Riley (1999)	Large, regional	Mitigation	Hazard	Rehabilitation	Public	NA	NA	Significant	Medium
Han (2003)	Regional	Mitigation	Hazard	Rehabilitation	NA	NA	NA	NA	Medium
Jha et al. (2009)	Large	Mitigation	Hazard	Rehabilitation	Public	Medium	–	Significant	Medium
Lixin et al. (2022)	Regional	Prevention, mitigation	Hazard	Rehabilitation	Public	NA	NA	NA	NA
Poland (1984)	Regional	Mitigation	Hazard	Rehabilitation	NA	NA	NA	NA	Medium
Pramono (2021)	Regional	Mitigation	Hazard	Rehabilitation	Public	NA	NA	NA	NA
Sneed and Brandt (2020)	NA	Mitigation	Hazard	Rehabilitation	Public	NA	NA	NA	NA
Szucs et al. (2009)	NA	Mitigation	Hazard	Rehabilitation	Public	NA	NA	Significant	Medium
Ting et al. (2020)	Regional	Mitigation	Hazard	Rehabilitation	Public	NA	Good	Minimal	Medium

Table B1. Continued.

Reference	Applicability					Indicator of effectiveness			
	Scale	Objective	Target	Urban area	Space	RP	OR	NI	SL
Zektser et al. (2005)	NA	Mitigation	Hazard	Rehabilitation	NA	NA	NA	NA	Medium
Expert sessions and survey	Large	Prevention, mitigation	Hazard	Rehabilitation, new development	Public	Medium	Fair	Significant	Medium
Accelerate soil consolidation									
Andriani et al. (2021)	Large	Prevention	Hazard	Rehabilitation, new development	Public, private	NA	NA	NA	Medium
Bergado et al. (1993)	Medium	NA	Hazard	NA	NA	NA	NA	NA	Long
Poland (1984)	NA	Prevention	Hazard	Rehabilitation	NA	NA	Good	NA	Long
Ritzema (2008)	Medium	Prevention	Hazard	New development	Public, private	NA	NA	NA	NA
Expert sessions and survey	Medium	Prevention	Hazard	New development	Public, private	High	Good	Significant	Medium
Dynamic compaction of soil									
Al-Zabedy and Al-Kifae (2020)	Medium	Prevention	Hazard	New development	NA	High	NA	NA	Medium
Hamidi et al. (2011)	Small, medium	Prevention	Hazard	New development	Public	NA	NA	Significant	Medium
Liang et al. (2015)	Small	Mitigation	Hazard	Rehabilitation	Public	NA	NA	Significant	Medium
Shen et al. (2019)	Medium	Mitigation	Hazard	Rehabilitation	NA	NA	NA	NA	Medium
Mechanical soil mixing									
Bergado et al. (1993)	Medium	Mitigation	Hazard	Rehabilitation	Public	NA	Good	Minimal	Long
Soil injections									
Al-Zabedy and Al-Kifae (2020)	Small	Prevention	Hazard	New development	Public, private	Medium	NA	NA	Medium
Xuan et al. (2015)	Micro	Prevention	Hazard	New development	Public, private	NA	Fair	NA	Short
Building jacking									
Andreas et al. (2018)	Small	Prevention	Vulnerability and exposure	Rehabilitation	Private	NA	NA	NA	NA
Saputra et al. (2017)	NA	Prevention	Vulnerability and exposure	Rehabilitation	Private	NA	NA	NA	NA
Expert sessions and survey	Micro, small	Prevention	Vulnerability and exposure	Rehabilitation	Private	High	Fair	Significant	Short
Elevation of linear infrastructures									
Akbar et al. (2019)	Medium	Mitigation	Vulnerability and exposure	Rehabilitation	Public	NA	NA	NA	NA

Table B1. Continued.

Reference	Applicability					Indicator of effectiveness			
	Scale	Objective	Target	Urban area	Space	RP	OR	NI	SL
Andreas et al. (2018)	Micro, small, medium	Mitigation	Vulnerability and exposure	Rehabilitation	Public	NA	NA	NA	NA
Andriani et al. (2021)	Medium	Mitigation	Vulnerability and exposure	Rehabilitation	Public	NA	NA	NA	Medium
Carreón-Freyre et al. (2010)	Small, medium	Mitigation	Vulnerability and exposure	Rehabilitation	Public	High	Good	Minimal	Medium
Kok and Hommes-Slag (2020)	Medium	Mitigation	Vulnerability and exposure	Rehabilitation	Public	NA	NA	NA	NA
Poland (1984)	Medium	Mitigation	Vulnerability and exposure	Rehabilitation	NA	NA	NA	NA	Long
Flexible connections to underground infrastructures									
Alferink and Cordóva (2017)	Micro, small	Prevention	Vulnerability and exposure	Rehabilitation, new development	NA	NA	Fair	Minimal	Medium
Gutiérrez and Cooper (2002)	Micro	Prevention, mitigation	Vulnerability and exposure	Rehabilitation, new development	NA	NA	NA	NA	NA
Paukstys et al. (1999)	Small	Prevention	Vulnerability and exposure	New development	NA	NA	NA	NA	NA
Ritzema (2008)	Small	Prevention, mitigation	Vulnerability and exposure	Rehabilitation, new development	Public, private	NA	NA	NA	NA
Floating and amphibious housing									
Basak and Chowdhury (2021)	Small	Prevention	Vulnerability and exposure	New development	Private	NA	NA	Minimal	Long
English et al. (2016)	Small	Prevention	Vulnerability and exposure	New development	Private	NA	NA	Minimal	Long
Pötz and Bleuzé (2009)	Small	NA	NA	NA	NA	NA	NA	NA	Long
Ritzema (2008)	Small	Prevention	Vulnerability and exposure	New development	Private	NA	NA	NA	NA
Expert sessions and survey	Micro, small	Prevention	Vulnerability and exposure	New development	Private	High	Fair	Minimal	Long
Improved foundations									
Al-Zabedy and Al-Kifae (2020)	Medium	Prevention	Vulnerability and exposure	New development	NA	Medium	NA	NA	Long
Deakin (2005)	Micro, small	Mitigation	Vulnerability and exposure	Rehabilitation	Private	NA	NA	NA	Short
Gutiérrez and Cooper (2002)	Micro, small	Prevention, mitigation	Vulnerability and exposure	Rehabilitation, new development	NA	NA	NA	NA	NA

Table B1. Continued.

Reference	Applicability					Indicator of effectiveness			
	Scale	Objective	Target	Urban area	Space	RP	OR	NI	SL
Kok and Hommes-Slag (2020)	Medium	Prevention, mitigation	Vulnerability and exposure	Rehabilitation	Private	NA	NA	Minimal	Long
Ovando-Shelley et al. (2013)	NA	Prevention, mitigation	Vulnerability and exposure	Rehabilitation	Public, private	NA	Good	Minimal	Long
Poland (1984)	Medium	Mitigation	Vulnerability and exposure	Rehabilitation	NA	NA	NA	NA	Long
Ritzema (2008)	Medium	Prevention, mitigation	Vulnerability and exposure	Rehabilitation, new development	Public, private	NA	NA	NA	NA
Expert sessions and survey	Small, medium	Prevention, mitigation	Vulnerability and exposure	Rehabilitation	Private	High	Good	Minimal	Long
Lightweight construction materials									
Andriani et al. (2021)	Small	Mitigation	Vulnerability and exposure	Rehabilitation, new development	Public, private	NA	NA	NA	Medium
Kohlnhofer (1995)	NA	Prevention	Vulnerability and exposure	New development	Public	NA	NA	Minimal	Long
Kok and Hommes-Slag (2020)	Medium	Mitigation	Vulnerability and exposure	Rehabilitation	Public, private	NA	NA	NA	NA
Ritzema (2008)	Medium	Prevention	Vulnerability and exposure	New development	Public, private	NA	NA	NA	NA
Saputra et al. (2017)	NA	Prevention, mitigation	Vulnerability and exposure	Rehabilitation	NA	NA	NA	NA	NA
Expert sessions and survey	Micro, small	Prevention, mitigation	Vulnerability and exposure	Rehabilitation, new development	Public, private	High	Fair	Minimal	Medium
Permeable pavement									
Poland (1984)	Medium	Mitigation	Hazard	Rehabilitation	Public, private	NA	Fair	Minimal	Long
Repairing cracks									
Carreón-Freyre et al. (2010)	Micro	Mitigation	Vulnerability and exposure	Rehabilitation	Public	High	Good	Minimal	Medium
Deakin (2005)	Micro, small	Mitigation	Vulnerability and exposure	Rehabilitation	Private	NA	NA	NA	Short
Luo et al. (2019)	Micro	Mitigation	Vulnerability and exposure	Rehabilitation	Public	NA	NA	NA	Short
Structure relocation									
Andreas et al. (2018)	Micro, small	Prevention	Vulnerability and exposure	Rehabilitation	Private	High	Good	Significant	Long

Data availability. The data used in this study were compiled from sources including publicly available literature, surveys, and expert sessions. While the literature is accessible to most readers, the aggregated dataset generated for this study is not publicly available.

Author contributions. NN and MK conceptualized the research. NN collected and analysed the data, designed the methodology, and prepared the draft and edited version of the manuscript. MK reviewed the manuscript and supervised the activities involved in the research.

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