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Introductory Chapter: Infrastructure Management, Construction, Structure and Industry 4.0

Samad M.E. Sepasgozar, Sara Shirowzhan and Faham Tahmasebinia

1. Introduction

Infrastructure has large capacity to enhance the efficiency of cities and the productivity of the national economy. It has a wide range of benefits from different perspectives including social, economy and environment in both short and long terms. The main objectives of an infrastructure are to improve national, interregional and international network and connectivity for people, business and trades. Infrastructure development is one of the most important functions of governments all around the world since it has a great impact of the national economy.

This book presents some concepts and practices around the theme of critical infrastructure. The following sections introduce (i) the concept of critical infrastructure management, (ii) structural design for concrete elements of infrastructure, and (iii) Industry 4.0 and digital data, which may be used for infrastructure management including mapping and monitoring technologies.

2. Definitions and concepts

Many countries are planning to invest on infrastructure projects. For example, the Australian government planned to invest over $75 billion for developing transportation network including tunnelling, roadways and railworks across the country in a period of 10 years.

Infrastructure generally refers to any foundation, system or basic physical for social development. It can be a basic structure, system or service such as highways, streets, roads, bridges, mass transit infrastructures (e.g. airports), dam, reservoirs, water supply and resources, waste and waste water infrastructure, hydroelectric plants, massive irrigation systems, telecommunications facilities, power generation and transmission and hazardous waste removal and storages. This type of infrastructure is synonymous to economic infrastructure. Social infrastructure includes cultural, educational and healthcare facilities.

The ninth goal of the Sustainable Development Goals introduced by the United Nations Development Programme refers to 'industry, innovation and infrastructure'. Innovation refers to the use of any new creative idea, technology, system, process, practice, material artefact or a nontrivial change and improvements that bring about valuable and meaningful change with benefit to stakeholders [1, 2].

Term and concept	Purpose and definition
Sustainable infrastructure	Gives access to energy, improves connectivity and mobility, increases the community benefits and balances social, economic and environmental needs. It also includes rehabilitation and reuse of current infrastructure
Smart city [3]	A modern high-tech city that uses intelligent and communication technologies to connect citizens, information and governance and manage resources, economy and city elements. Its purpose is to provide a sustainable, green, efficient and innovative environment and to increase mobility and the human life quality
Smart infrastructure (structural health monitoring)	Utilisation of new information and communication systems including connected sensors (Internet of Things) to monitor and manage infrastructure in a real-time manner. The sensors help to minimise disruption, costs and down time and maximise capacity, operational efficiency, effectiveness and sustainability
Critical infrastructure	Refers to assets, facilities, systems and processes required for a society to function. This may include heating facilities (e.g. natural gas, fuel), food production and distribution networks, water supply (water, sewage), hospitals, transportation systems (railway network, airports, harbours, fuel supply), electricity generation and distribution systems, telecommunication networks Critical infrastructure risks: risk = *threat × vulnerability × consequence*
Critical urban infrastructure	Refers to facilities and network systems at the urban scale such as water, sewerage, power lines, gas and telecommunications
Critical infrastructure sectors	A total of 16 sectors identified by Presidential Policy Directive 21 (PPD-21) are [4] transportation systems, water and wastewater systems, information technology, materials and waste, government facilities, healthcare and public health, financial services, food and agriculture, energy, emergency services, dams, defence industrial base, communication, critical manufacturing, commercial facilities and chemical sectors
Critical infrastructure resilience (CIR)	Refers to the ability of the city or country to anticipate, prevent and protect with a coordinated plan for the network, responsive and timely recovery actions, while circumvent threats provide minimum level of services

Table 1.
Definitions of basic terms and concepts.

It also mentions that economic growth highly depends on the investment on infrastructure and innovation. There are several terms and concepts related to infrastructure, which will be introduced in **Table 1**.

Australian investment plan is an example of infrastructure investment plans, which are committed in developing transport infrastructures over a decade. The investment plan presents a positive reform and roadmap for a period of 15 years for this country. The main objectives of the investment plan are to improve

Figure 1.
Woolgoolga to Ballina in October 2018 (project ID: INF12): (a) bridge over Clarence River and (b) bridge over Richmond River. (courtesy: www.pacifichighway.nsw.gov.au).

| Project ID	Infrastructure project	Short description
INF01	WestConnex (including different stages)	33-km-long underground motorway including 19 km of new tunnels, widening 7.5 km of the existing M4, estimated project cost $10–$45 billion including land acquisitions and network extensions
INF02	M4 Western	46-km-long dual carriageway motorway
INF03	NorthConnex	9-km-long dual road tunnels, linking the M1 and M2 Motorways, estimated project cost $3 billion
INF04	The Northern Road upgrade	35-km-long, upgrades four to eight lanes in the Northern Road, estimated project cost $1.6 billion
INF05	M12 Motorway	A new east-west motorway in Sydney, major access route to the Western Sydney Airport, estimated project cost $1.2 billion (duration, 2020–2025)
INF06	Bringelly Road	10 km upgrading Bringelly Road from two lanes to a six-lane divided road, estimated project cost $509 million (duration, 2015–2020)
INF07	CityLink-Tullamarine widening project	Upgrading of the Tullamarine Freeway between the Melbourne Airport and Melrose Drive in Victoria state, estimated project cost $250 million (duration, 2016–2018)
INF08	Great Western Highway	Install concrete median barrier, install raised islands, safety upgrades at different locations of the Great Western Highway (NSW)
INF09	Bringelly Road upgrade	10-km-long, upgrades Bringelly Road from two lanes to a six-lane divided road, located near to Eastwood Road (NSW), $509 million (duration, 2015–2020)
INF10	Sydney Light Rail (including several projects or phases)	(i) CBD and South East Light Rail (12 km route including 19 stops) (ii) Inner West Light Rail (12.7 km route including 23 light rail stops, capacity to transport more than 9.7 million customers yearly) (iii) Newcastle Light Rail (iv) Light rail in Randwick
INF11	Badgerys Creek Airport	Sydney's second airport, estimated project cost $2.5 billion
INF12	Woolgoolga to Ballina (see **Figure 1**)	155-km-long, link in the Pacific Highway including 9 interchanges, 170 bridges and 350 connectivity structures
INF13	The new Northern Beaches Hospital	With 488 beds, 50 emergency bays, 14 operating theatres, 20 intensive care beds, 40 maternity beds

Note: Descriptions of the benefit of each project and any other specific project details can be obtained from websites of the Department of Infrastructure, Regional Development, New South Wales Government, New South Wales Roads and Maritime Services (RMS), and/or relevant city council, designers, consultants or contractors.

Table 2.
Selected infrastructure projects in a metropolitan.

connectivity of peopled and regions, interregional logistics, health, safety, security and effectivity to the national transport system. **Table 2** shows a list of examples of infrastructure projects to address these objectives.

3. Mechanism of prestressing

The structure of infrastructure can be a mix of different materials and elements [5]. This section focuses on one of the popular innovations which can be used in many different infrastructures. One of the most relevant concepts to structure is prestressing. Prestressing refers to the intentional creation of permanent stresses in an element of a structure, for the purpose of improving its strength and behaviour under various services and conditions [6]. Prestressed concrete is an engineering
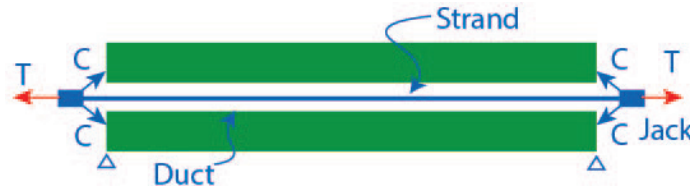
Figure 2.
A simplified illustration of the mechanism of prestressing.

innovation that improves many of the service and strength performance behaviours of reinforced concrete. This is a practical solution to the design of many engineering structures in a cost-effective manner. Prestressed concrete is a fastidious form of reinforced concrete. Prestressing engages the application of an initial compressive load to the structure to decrease internal tensile forces which may lead to controlling crack. The initial compressive load is imposed and sustained by highly tensioned steel reinforcement (tendons) reacting on the concrete. With eliminating cracking, a prestressed concrete section is significantly stiffer than the equal reinforced concrete section.

The tendons are cast within the concrete at first freely within ducts, which are grouted at a later stage to bond the tendons. Prior to grouting, the tendons are jacked to very high stresses. The jacking reactions are pressed against the ends of the concrete member and then transferred permanently to cast in end anchors. This is shown in a simplified form in **Figure 2**.

In practice the duct 'profile' will vary to suit the purpose of the member. The tendons are permanently 'prestressed' in tension; the concrete is permanently 'prestressed' in compression. High-tensile wire strands have $f_y \approx 1870$ MPa. Higher-strength concretes have $f_c' \approx 30$–50 MPa. Although strong in compression, concrete is weak in tension. **Table 3** presents the basic concepts in prestressed concrete structures.

The poor performance of the concrete in tension gave rise to the concept of 'prestressing' the concrete in order to overcome bending tensions and cracking produced under load, thereby retaining elastic behaviour. Early attempts at prestressing failed because of the shrinkage and creep strains in the concrete. For example, early reinforcing bars had yield stresses ≈ 200 MPa and could be pretensioned to a stress of order 120–150 MPa. The subsequent strains are of order

$$\varepsilon = \sigma/E = 120/200{,}000 = 600 \times 10^{-6} \qquad (1)$$

where ε is the strain, σ is the stress and E is the module of elasticity.

The development of prestressed concrete is credited to Eugene Freyssinet of France [7], who in 1928 started using high-strength steel wires for prestressing. Such wires, with an ultimate strength as high as 1725 MPa and a yield point over 1240 MPa, are prestressed to about 1000 MPa. At this level of stress, the losses are a much smaller percentage of the prestress. For example, assuming a total creep and shrinkage strain of order 800×10^{-6}, this would result in a loss of prestress of order:

$$\sigma = (800 \times 10{-}6) \times (2 \times 105) = 160 \text{ MPa} \qquad (2)$$

Hence, the residual prestress =1000–160 = 840 MPa or 84% of the original level. Practical development of prestressed concrete was made possible by further development of high-strength concrete and high-tensile wire strands through the twentieth century [8–11]. It was also necessary to develop reliable and economical

Element	Description
Strand	An element in which a number of high-tensile wires are woven together as a combined unit
Tendon	Generally defined as the wire, strand or bar (or any discrete group of wires, strands or bars) that is intended to be prestressed
Cable	Groups of tendons, collected together in a duct or anchorage
Prestressed	The prior stressing of both the concrete and the tendons prior to the service use of the element
Pretensioned	The tendons are tensioned (in a casting bed) prior to pouring of the concrete. The tendons are cut and bonded to the concrete after it attains strength. Used in precast construction
Post-tensioned	The tendons are laid in metal ducts in the concrete and tensioned after the concrete attains strength. This is the most commonly used system in buildings and other structures in Australia
Bonded tendons	Where the ducts which contain the tendons are filled with cement grout after the tendons are stressed—this effectively bonds them to the concrete like reinforcing steel. Tendons can subsequently develop further stresses under bending actions due to strain compatibility, enabling the full strength of the bonded tendons to be realised at ultimate strength
Unbonded tendons	Where the tendons are not grouted but are greased for corrosion protection and contained within a plastic sheath. This method is not permitted under as 3600 except for slabs on the ground. Unbonded tendons can be used in specialised applications such as cable-stayed bridge cables, for example, allowing the monitoring and replacement of individual strands
Immediate losses	(a) Short-term elastic strain of the concrete (progressive stressing) (b) Anchor wedge draw-in (c) Friction loss along the length of the ducts
Time-dependant losses	(a) Long-term creep and shrinkage strain of the concrete (b) Relaxation in the (seven wires twisted) strands

Table 3.
The basic concepts in the prestressed concrete structures including main elements of the structure.

methods of tensioning the strands and for the permanent end anchoring the strands to the concrete. Freyssinet [7] developed conical wedges for end anchorages and designed double acting jacks which tensioned the wires and then thrust the wedges into the anchor cones which held them. These early advances in prestressing were mainly European. Steel became the primary construction material in the USA, with the secondary use of structural concrete in buildings. However, the American engineer Lin [6] became a major contributor developing the load balancing theory during the 1950s. Australia, with a more developed concrete industry and low seismic activity, became a major advocate of prestressed concrete buildings (**Figure 3**).

Loss of prestress in the tendon force up to 40% or more of the jacking force can be experienced, depending upon the cable length, drapes, concrete shrinkage and so forth. This becomes important in relation to AS3600 [12]. It is necessary that a minimum amount of prestress remains in the strands, so that they may develop their full-strength capacity in strain compatibility with the concrete as it bends.

In addition to the longitudinal force P (or C) exerted on a prestressed member at the anchorages, transverse forces are also exerted on the concrete member wherever change of angle or curvature exists in the tendons. Other bending actions are also applied to the member where the member section changes due to
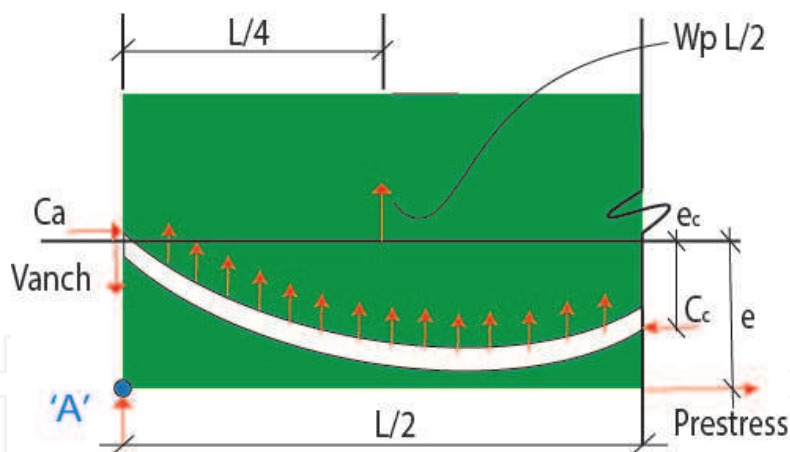
Figure 3.
A prestressed section for analysis.
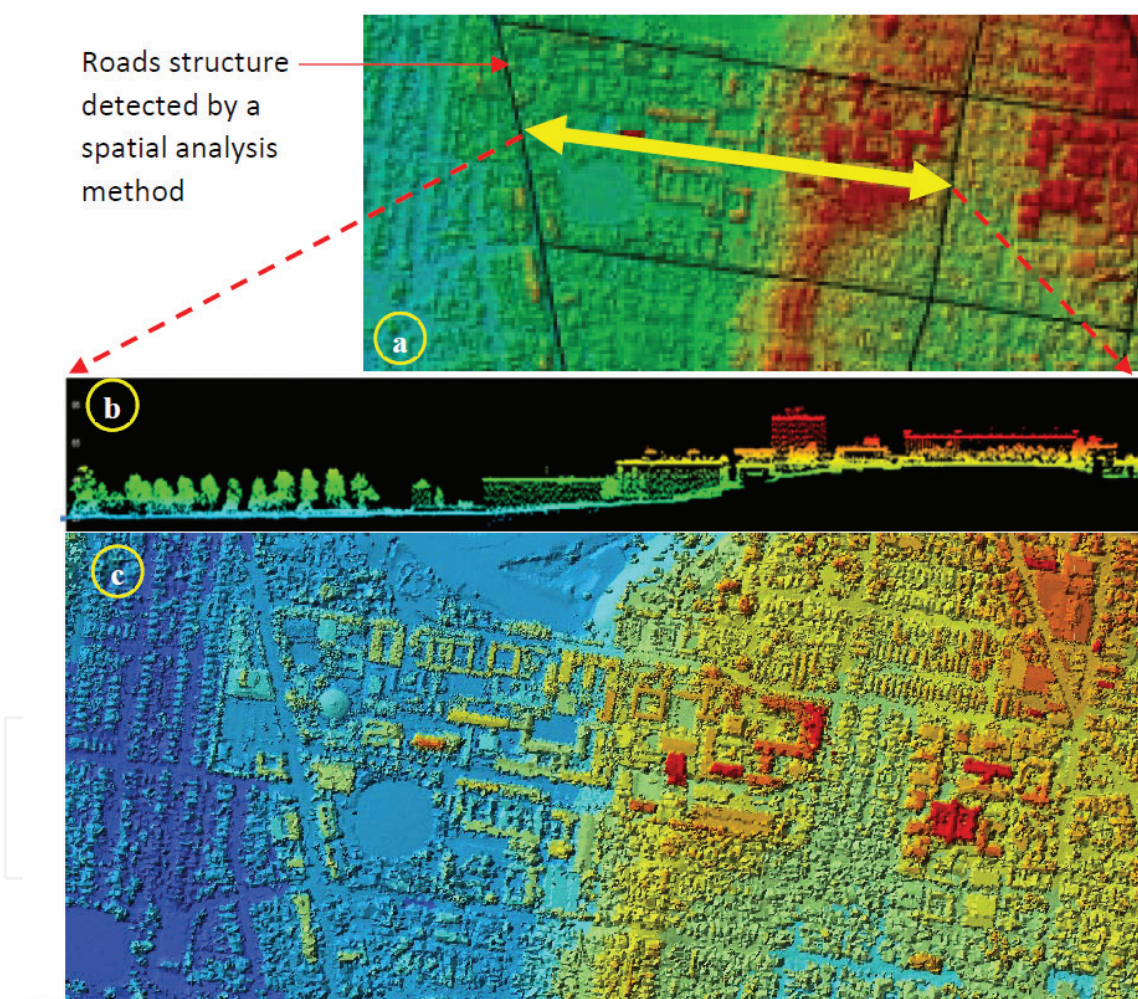
Figure 4.
Producing profile from an urban area to present building objects: (a) lidar data including road structure; (b) profile; (c) a selected lidar point cloud of Sydney areas produced by an UAV.

steps and so forth or P is applied eccentrically. For this analysis it is very helpful to remember that the concrete is a free body distinct from the tendon until the ducts are grouted, at which point they start to act together. This is then considered how the tendon imposes forces on the concrete free body at the anchorages and through its changes of direction. Consider the concrete in half of the beam as a free body, which has forces imposed on it from the tendon and the other half of the beam (**Figure 3**).

The forces on the concrete are:

- C_a and C_c in horizontal equilibrium

- $w_pL/2$ and V_{anch} in vertical equilibrium

Now determine e_c the eccentricity between the two C forces. Note that the P force in the tendon reacts against the concrete as C_a and there is no support reaction since there are no externally applied loads.

For moment equilibrium about **A**, and ignoring friction losses

$$C_c\ (= C_a = P) \times e_c\ = w_p L/2 \times L/4 = w_p L^2/8\ (= P \times e) \qquad (3)$$

Now consider the elastic stresses in the concrete:

$$P/A\ (pre - compression) \pm M/Z\ (uplift\ moment\ due\ to\ the\ cable) \qquad (4)$$

$$= P/A \pm P \times e \times y/I \qquad (5)$$

In order to designing prestressed concrete structures, a proper understanding of structural performance at all stages of loading is important. This can be essential where it is a comprehensive knowledge of the design criteria specified in the relevant design standard, such as the minimum requirements to fulfil both ultimate and serviceability requirements.

4. Industry 4.0 technologies and digital data

This section presents different technologies and techniques which can be used for monitoring the structure of urban areas and infrastructures. The new trend of automation and data transferring process is called Industry 4.0. The core component of Industry 4.0 is digital data. Industry 4.0 refers to different technology applications using Internet of Things (IoT), cyber-physical systems, artificial intelligence, machine learning, cloud computing, machine-to-machine and human-to-machine communication and real-time technologies. The concept of Industry 4.0 is adopted by the construction industry. The concept of Construction Industry 4.0 can give better connectivity among construction supply chain stakeholders and real-time access to construction operation, enhancing safety, productivity and the quality of construction. Utilisation of digital technologies such as 3D printing [13], airborne lidar [3, 14, 15], hand-held laser scanners [16, 17], building information modelling (BIM) [18], wireless sensors [19] and automation is changing the infrastructure management including construction and maintenance.

For example, **Figure 4** shows the temporal airborne lidar which can be used for analysing 3D urban changes. Airborne lidar provides valuable digital data which is useful for analysis of the spatial pattern of building height and the proximity analysis with the road's hierarchy.

Spatial data mining (SDM) methods have been used to investigate the unknown relationships between spatial and nonspatial attributes of data sets [20] that may not be apparent using more basic data analysis techniques. The need for knowledge discovery and spatial data mining 'to extract unknown and unexpected information from spatial data sets' was suggested by Mennis and Guo [21]. Two popular SDM methods being used in geographic information systems (GIS) and remote sensing

are spatial autocorrelation statistics [14, 21, 22] and nonparametric density estimation [23]. However, the potential of these SDM methods to explore urban height patterns using airborne lidar data has yet to be actively investigated. While a spatial autocorrelation statistic known as local Moran's I (LMI) is used to find the distribution pattern of building heights, the elevations of buildings were aggregated into large-sized cells using the mean elevation value of the included buildings [3, 22, 24].

Detection of the distribution pattern of clusters of relatively higher (CRH) buildings in a city with varying or heterogeneous heights is crucial for the spatial and temporal change analysis of vertical developments and for trend analysis of vertical urban compactness over time [15]. Detection of the CRH buildings in a city of heterogeneous heights is also essential for thermal urban modelling and urban heat island analyses because the level of heat produced by higher buildings is different from that by lower buildings [25].

Geostatistics is a useful technique for spatial analysis. It refers to statistics used to analyse spatial data and spatiotemporal data sets. Shirowzhan and Lim [22] utilised a spatial analysis procedure using temporal point clouds in advanced GIS. In this analysis a novel method examined ground elevation extraction in slant areas and building classifications. A relevant technique for measuring compactness in three-dimensional environment is Moran's I (MI) and G indices. Moran's I and G are global autocorrelation statistics, which computes the correlation between pairs of data points [14]. Autocorrelation can be calculated for a variable that changes over time, for linear spatial series and for two-dimensional spatial series. MI is an extended version of Pearson's product-moment correlation coefficient for a single variable [14]. Pearson's correlation between two variables x and y from n observations is defined as

$$\rho = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\left[\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2\right]^{1/2}} \tag{6}$$

where x and y are the mean values of x and y, respectively. For a univariate series, say x, MI will estimate the correlation between x_i and x_j.

For infrastructure monitoring, autocorrelation statistics can be applied to the variable describing the elevation of airborne lidar points in order to determine if x_i and x_j belong to the same class.

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