



Review

Performance-Based Analysis in Civil Engineering: Overview of Applications

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Abstract: Traditional design approaches in civil engineering mainly focus on codes/guidelines related to building an infrastructure, while performance-based analysis (PBA), an emerging new reality around the world, focuses on the performance of the end product. Professional organizations, academicians, and the industry have made significant contributions in formulating PBA in various civil engineering fields, where practical guidelines and principles have been adopted in infrastructure analysis. This paper presents a critical review of PBA applications in three civil engineering fields: transportation, environmental, and structural engineering. The applications are grouped into a wide array of civil engineering areas, including highway transportation, pavement design and management, air transportation, water-structures design and operation, landfill design, building architectural design for evacuation, urban energy design, building earthquake-based design, building wind-based design, and bridge design and management. A total of 187 publications on PBA were reviewed and details on 122 application papers (from 23 countries/regions) are presented. The review consists of vertical and horizontal scans of PBA applications. In the vertical scan, the applications in each civil engineering area are summarized in tabular format that shows the system element modeled, analysis objective, performance criteria, analytical tool, and specifications/codes. The horizontal scan (discussion and lessons learned) addresses the following aspects of PBA: (1) the wide array of analytical tools used, (2) the broad functional and process-related areas, (3) the advantages, challenges, and opportunities, and (4) potential future applications. It is hoped that the state-of-the-art review presented in this paper will help researchers/practitioners quickly find useful information about PBA and promote its development in their respective fields.

Keywords: performance-based analysis; design; civil engineering; structural; transportation; environmental; review; applications; reliability; pushover analysis; simulation

1. Introduction

Many developed countries around the world are moving toward performance-based analysis (PBA) away from the traditional perspective design. The perspective approach focuses on the means to develop a design and simply involves applying codes/standards to design an engineering element. In fact, this approach assumes that the safety objectives are implicitly defined. On the other hand, PBA requires explicit definition of objectives and performance specifications, as shown in Figure 1. The design process primarily focuses on the objectives, related performance criteria, and development of innovative solutions to optimize the design [1,2]. Thus, PBA can be viewed as the practice of thinking and working in terms of the ends rather than the means. In this respect, the PBA concept used in this paper can be applied to any stage of a project, including planning, design, operation, and management.

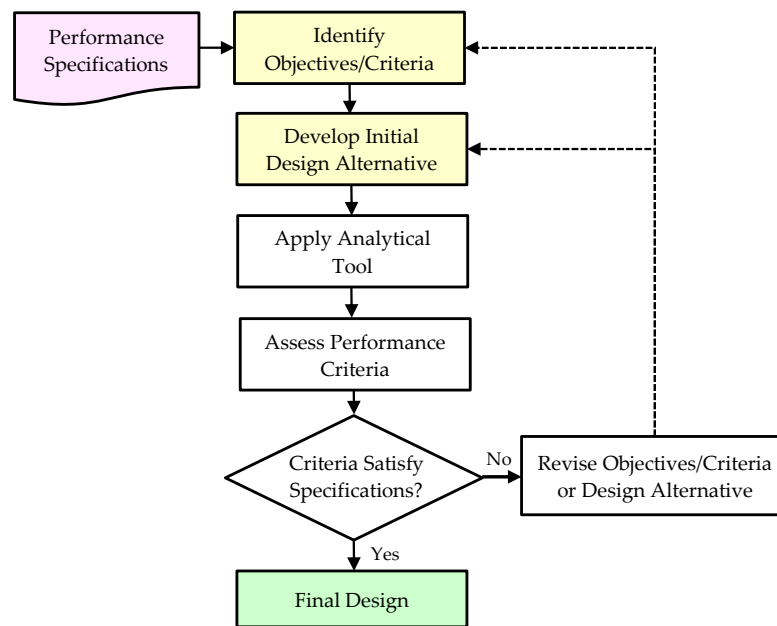


Figure 1. Typical performance-based analysis (PBA) process.

Performance-based design (PBD) formally began in 1994 after the Northridge earthquake in California when the Federal Emergency Management Agency (FEMA) sponsored Vision 2000: performance-based seismic engineering of buildings: interim recommendations, which was produced by the Structural Engineers Association of California [3]. What is interesting is that in most transportation and environmental engineering areas PBA is emerging and has not been fully developed. Thus, numerous great opportunities for research developments exist in these civil engineering fields. In fact, the progress of PBA in structural engineering has started to inspire professionals in other civil engineering fields to develop formal PBA processes. In structural engineering, the PBA process has been preceded for several decades by well-established reliability analyses, which form a key element of PBA. However, in transportation and environmental engineering, reliability analysis appears sporadically in some applications.

Traditionally, lab tests have been used to evaluate and diagnose the performance of proposed structures. However, lab tests are time-consuming and expensive as they require long hours of preparation, setup, data collection, and subsequent analysis [4,5]. Therefore, different analytical and computer-aided tools have been developed in civil engineering, where PBA has been a beneficiary. First, the latest PBA studies are no longer bound by a single objective. Modern infrastructure analysis has involved multiple objectives related to safety, cost, environmental, and other considerations. These have led to the implementation of multi-criteria optimization that balances all requirements in an efficient manner. For example, civil engineers place more concern on the deformation, displacement, and inter-storey drift when designing tall buildings, while the stakeholders focus more on operational budget and date of completion. Thus, the use of optimization tools can aid in balancing these needs to yield an optimal design scheme.

During the past two decades, passionate discussions and research efforts emerged in the civil engineering literature regarding PBA [2,6]. This can be attributed to improved sensor design (to support measurement/monitoring in different stages), algorithmic development (to perform mechanistic design), computer simulation (to foresee and evaluate infrastructure performance), and most importantly increased awareness of safety concerns [7]. The first three advances have further led to a wide array of new applications in all areas of civil engineering. Although the traditional design method mainly focuses on serviceability, the emergence of PBA adds a new vision to the design and

testing mechanism with respect to the desired safety level. This way, civil engineers can establish certain design guidelines and principles to assess potential risk of the proposed design.

This paper reviews a wide array of applications in different civil engineering fields with the aim of understanding the breadth and depth of PBA applications in different areas. A total of 187 publications in PBA were reviewed and details on 122 application papers (from 23 countries/regions) in three civil engineering fields are presented (see Table 1). North America countries, the United States (28%) and Canada (27%), take the lead in promoting and establishing specifications/codes for the use of PBA. Asian countries, including China (8%), Japan (6%), Iran (4%), and India (3%), also have emerging focus on this topic. Australia and European countries, such as France, Greece, and U.K., have comparatively less publications in the PBA areas. The civil engineering fields (areas) covered in the paper include transportation engineering (highway transportation, pavement design and management, and air transportation), environmental engineering (water-structures design and operation, landfill design, building architectural design for evacuation, and urban energy design), and structural engineering (building earthquake-based design, building wind-based design, and bridge design and management). The review consists of vertical and horizontal scans of PBA applications. In the vertical scan, the applications in each area are briefly discussed and summarized in tabular format that helps the reader to extract meaningful information efficiently. We also attempt to describe the recent applications and their main findings. Some earlier references were included in an attempt to present a complete perspective on PBA development. The horizontal scan (discussion and lessons learned) addresses the following aspects of PBA: (1) the wide array of analytical tools used, (2) the broad functional and process-related areas, (3) the advantages, challenges, and opportunities, and (4) potential future applications. As such, this paper should be valuable for researchers in identifying areas for future research and for practitioners in acquiring a perspective on key aspects of PBA.

Table 1. Summary of the number of applications reviewed in various civil engineering areas.

Civil Engineering Field	Area of Application	Number of Applications
Transportation Engineering (36)	• Highway transportation	15
	• Pavement design and management	17
	• Air transportation	4
Environmental Engineering (33)	• Water-structures design and operation	13
	• Landfill design	6
	• Building architectural design for evacuation	8
	• Urban energy design	6
Structural Engineering (53)	• Building earthquake-based design (traditional)	17
	• Building earthquake-based design (special)	18
	• Building wind-based design	8
	• Bridge design and management	10

The remainder of the paper is organized as follows. Sections 2–4 review representative applications of PBA in transportation, environmental, and structural engineering. For each civil engineering area, the characteristics of a variety of applications (arranged from the earliest to the most recent) are summarized in a table and sample applications are described in the text in some details. For each application, the table presents the system element modeled, analysis objective, performance criteria, analytical tool, specifications/codes, country/region of the first author, and corresponding reference. Section 5 presents an in-depth discussion and the lessons learned from the review of PBA applications presented in the paper so as to pave the way for future developments. The lessons learned include the wide variety of analytical tools used and potential future applications of PBA. The last Section 6 presents concluding remarks.

2. Transportation Engineering Applications

Performance-based analysis in transportation engineering has been applied to varying degrees in the areas of highway transportation, pavement design and management, and air transportation. Applications related to highway design are just emerging [8–10]. The performance-based (PB) approach in transportation engineering applications is implemented at the design, operation, and management stages. Some specifications and guidelines that include performance have been established in different transportation areas. Examples include the performance-based navigation (PBN) manual, published by the International Civil Aviation Organization [11], American Association of State Highway and Transportation Officials (AASHTO) design method and the mechanistic–empirical pavement design guide (MEPDG), published by AASHTO [12]. In addition, the U.S. National Cooperative Highway Research Program has published several PB documents in the area of highway geometric design [13], highway maintenance and operations management [14], and transportation planning [15].

2.1. Highway Transportation

The conventional approach in highway geometric design relies on adherence to criteria based mainly on empirical data that relate driver/vehicle performance to geometric characteristics (nominal safety). Acceptable performance is presumed to be produced through proper application of the technical guidance, but is nonetheless an indirect outcome of a process that produces physical design dimensions [16]. Recently, designers have begun to recognize that design should be based on actual performance, including crash experience (substantive safety), mobility, and cost. PB geometric design has been sporadically applied using such concepts as reliability analysis, value engineering, and context-based design. The concept has also been aided by several recent developments, most notably the Interactive Highway Safety Design Model [17], Highway Safety Manual [18], and Roadside Safety Analysis Program [19]. These developments provide designers with better analysis tools than the conventional approach. However, they generally focus on single performance measures for two reasons: (1) some performance measures are not well understood and have not been quantified yet and (2) a comprehensive methodology that simultaneously considers all relevant performance measures is lacking. Recognition of the importance of performance measures in real projects implies the need for more formal and comprehensive tools to aid broader implementation in practice. This need has been recently recognized by researchers and practitioners.

Various applications related to geometric design and traffic operations [20–34] are found in Table A1. The applications rely mostly on the geometric design guides by AASHTO [35] and the Transportation Association of Canada (TAC) [36]. As noted, most research has focused on a single performance measure of geometric design, namely sight distance (SD). Navin [20] was the first to introduce reliability into highway geometric design. He defined some rules to determine the margin of safety and reliability index for highway horizontal and vertical curves based on stopping, decision, and passing SDs. For railroad crossings, Easa [21] developed a multi-criteria model of SD using advanced first-order second-moment (AFOSM) method that considered two failure modes and their correlations. Two cases of SD were modeled as two parallel-components and with single-component systems. The method was validated using Monte Carlo (MC) simulation. Easa [22] used reliability analysis to determine the required SD at stop-control intersections for specified probability of non-compliance (P_{nc}).

El-Khoury and Hobeika [23] applied MC simulation to estimate the uncertainty level contained in passing sight distance (PSD) requirements on straight roadway segments. A reliability-based design method was developed to estimate the uncertainty of the three-dimensional (3D) SD boundaries on horizontal alignments that overlap with flat grades, crest curves, and sag curves [24]. For the horizontal alignment of two-lane rural highways, Easa and Mehmood [25] developed a substantive-safety approach based not only on minimum design guidelines, but also on actual collision experience. The model also considered physical obstructions in selecting optimal alignment. A general framework was introduced to determine a targeted value of design safety by calibrating the highway geometric design criteria that deal with the uncertainty associated with input parameters [26]. Ibrahim et al. [27] introduced a

reliability-based quantitative measure of probability of non-compliance and used it to develop a safety performance function for the relationship between design reliability and expected collision frequency. Probabilistic approaches were also developed for the freeway acceleration distance [28] and freeway speed-change lanes based on acceleration and gap acceptance behavior [29].

For roundabout operations, two optimization models were developed for roundabout design. One model [30] maximizes design consistency based on operating speeds of various movements, and the other [31] is a multi-criteria model that maximizes design consistency and minimizes delay. Another operation-based reliability model was developed by Easa and Cheng [32] using FOSM to estimate the required minimum green time for pedestrians at signalized intersections. The start-up time and walking speed were considered as random variables. A closed-form solution for the minimum supplied green interval is derived and a procedure for establishing walk and the flashing “do not walk” intervals is presented. The method was validated using MC simulation. Osama et al. [33] developed a reliability analysis framework based on FOSM and Importance Sampling to evaluate the risk of limited SD for permitted left-turn movements. Data for two signalized intersection approaches in the city of Surrey were used as case studies. Geometric and traffic video data were collected and analyzed using a computer vision tool to extract the relevant probability distributions.

2.2. Pavement Design and Management

Pavement applications have addressed both design and rehabilitation. Since asphalt pavements usually suffer from high distress due to massive traffic loads, particularly on primary highways and urban roads, surface rutting and distresses (e.g., cracks and potholes) unavoidably occur. Thus, civil engineers would seek an optimal design of pavement layers and subgrade so as to reduce the life-cycle cost of designed pavements. Various applications in this area [37–53] are summarized in Table A2.

Early research on reliability analysis focused on aggregate blending which is the first step in pavement mix design. Easa and Can [37] developed a stochastic optimization model to determine the optimum proportions of the blended aggregates (course, fine, and mineral filler), subject to specifications on percentage passing each sieve and blend properties. The model accounted for the uncertainty in the percentage passing the sieves and considered two performance criteria: cost and closeness to mid specifications. Subsequently, Easa et al. [38] applied AFOSM method for predicting thermal cracking of asphalt pavements. Two failure modes were considered: low-temperature cracking and thermal-fatigue cracking. The model accounted for the variability in the component design variables and the correlation between the two failure modes. The model results were verified using MC simulation.

Abaza and Abu-Eisheh [39] developed an optimal design approach by using a performance prediction model to construct flexible pavement curves that minimize life-cycle disutility and yield optimal terminal serviceability index. Later, Abaza [40] further proposed a PB model for overlay design of flexible pavements. Both studies followed the basic design equation for incremental analysis by AASHTO. Despite the development of prediction models, both lab testing and in-suit measurements were reported to properly assess physical pavement response. Lambert et al. [41] used four different materials for pavement subgrade design: mudstone, crushed concrete, site-won sandy gravel, and crushed rock. They performed both lab and field tests to assess the performance of granular materials in terms of composite stiffness and strength with respect to moisture content. The results showed that composite stiffness increases as moisture content decreases for sandy gravel.

Recently, studies in pavement design shifted from optimal design to empirical design, and then to mechanistic–empirical (M–E) design. McDonald and Madanat [42] presented an optimization model for minimizing life-cycle cost of construction and maintenance of flexible pavements using M–E design. Luo et al. [43] developed an approach based on first-order reliability method (FORM) for M–E pavement design considering fatigue and rutting failures. Kalita and Rajbongshi [44] conducted MC simulation to assess asphalt pavement performance considering traffic repetitions, fatigue life, and rutting life. Since pavement design performance is associated with large uncertainties,

the preceding M–E design approaches follow an iterative design process to assess pavement response following MEPDG [12].

The aggregate blending problem was re-visited by Kikuchi et al. [45], who developed an optimization model based on fuzzy optimization. The model selected the best mix of aggregates such that not only gradation and physical specifications were met, but also their desirability within each range was satisfied as much as possible. The model addressed the practitioner’s uncertainty about the limits of the specification ranges and the desire to achieve different objectives.

Despite the preceding research work, PBA of asphalt mixtures has been lacking. Recently, PBA was fully incorporated in the superior performing asphalt pavement (Superpave) asphalt mix design method, which is based on a multi-million joint US–Canada project (1988–1993). The method consists of five stages. For stage 1, the performance grading of asphalt binders has two numbers that refer to extreme high and low pavement temperatures at which the binder is expected to perform adequately. These extreme temperatures are defined based on reliability which is established using the means and standard deviations for design high and low-pavement temperatures [54]. The temperature data have been collected for thousands of sites in the United States and Canada. For stage 2, a stochastic optimization model was developed that includes the uncertainties of individual aggregate gradations, primary aggregate (PA) properties, and related specifications [46]. The model can directly determine three different trial blends. The constraints of the model include gradation control specifications, restricted-zone (RZ) limits, PA properties, and special and unity constraints. The uncertainty is formulated to ensure that the trial blends satisfy model constraints for a specified confidence level. A binary variable is used to allow designers to produce a blend that passes below, above, or through RZ.

For stage 3, the design involves evaluation of selected trial blends of the Superpave aggregate structure based on volumetric, compaction, and dust proportion requirements [47]. This research incorporates the uncertainties of all variables involved in the process and develops a revised procedure for comparing mixture properties with the PB criteria. The developed mathematical formulas of uncertainty were verified using MC simulation. Figure 2 shows the mathematical path for four asphalt mix properties (performance variables) involved in the PB evaluation process. The uncertainty of the performance variables is calculated based on the uncertainty of eight measured variables. However, there are 13 intermediate variables that also possess uncertainty and should be checked for reliability [47]. This figure helps the designer trace the uncertainty of the unreliable variables back to the measured properties so that their precisions may be revised. Some issues related to uncertainty analysis are discussed in Section 5.1.

For stage 4, a design method of asphalt mixtures that considered the uncertainties of the measured properties that propagate to the calculated performance variables was developed [48]. The FOSM method was used to establish acceptance sampling criteria that ensure that the performance variables were reliable. In addition, a procedure for determining optimum asphalt content that ensures that specifications were satisfied within the confidence intervals is presented. For stage 5, a new method for evaluating moisture susceptibility considering uncertainty was developed [49]. The method considers the uncertainties of the four measured properties (thickness and maximum load) of conditioned and unconditioned specimens in formulating the uncertainty of the tensile strength ratio (TSR). The probability distribution of TSR is established based on a normality assumption which is verified using MC simulation. A simple formula is developed for checking whether the TSR criterion is satisfied. The results show that the existing deterministic method overestimates the TSR value and could inaccurately lead to the conclusion that the mix satisfies the minimum criterion.

In pavement management, Zheng et al. [50] proposed a comprehensive pavement life-cycle sustainability assessment methodology that integrated three criteria: cost analysis, environmental assessment, and social assessment. A four-step structure was developed for the proposed methodology, including system definition, modeling, unifying, and interpretation. A multi-criteria decision-making model was developed to unify the three criteria and select the best pavement alternative. A case study in China was applied to illustrate the proposed methodology.

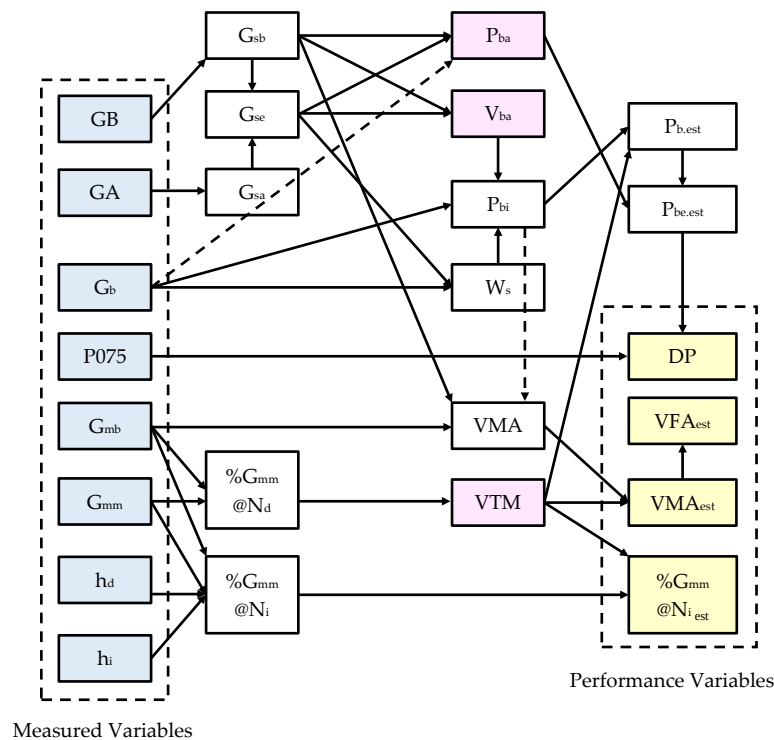


Figure 2. Mathematical paths of the variables involved in the performance evaluation of superior performing asphalt pavement (Superpave) design aggregate structure [47].

2.3. Air Transportation

Air transportation applications covered air navigation and airport terminal design. The concept of PBN for air transportation aims to design routes, especially during congested demand periods. The system includes two major components: area of navigation (RNAV) and required navigation performance (RNP). Regardless of its applications, PBN for air transportation mainly improves the efficiency of route operation (terminal or aircraft) and maintains the required safety level.

Various applications in this area [55–59] are summarized in Table A3. MacWilliams and Proter [55] demonstrated the use of relative position criterion (RPC) to project actual aircraft route within the qualification region, and deliver and sequence the aircrafts to runway by merging multiple flows into a single flow. Additional rules, such as altitude, heading, runway assignment, heavy indicator, and ground speed can also be considered. They claimed that an annual saving of USD \$1.2 to \$1.6 million can be achieved for the study airport while maintaining constant workload and ensuring safety. Thipphavong et al. [56] evaluated terminal sequencing and spacing (TSS) system for PBN arrivals using a case study in Phoenix Sky Harbor International Airport, United States. They used NASA air traffic control simulation facility (multi-aircraft control system) to evaluate the TSS system with different traffic volume scenarios. The experimental simulation showed that the TSS system achieved benefits with PBN-enabled operation and maintained a high throughput rate of 10% above the baseline demand level. In addition, the flight path prediction was improved and the self-reported controller workload was reduced. Timar et al. [57] assessed RNAV's standard instrument departure (SID) and standard terminal arrival (STAR) procedures under PBN. They used a generic sequencing model to capture SID/STAR inefficiency and mitigation mechanism using a case study in Northern California, United States. This study quantified the benefits of PBN and paved the way for the next generation air transportation system in the United States.

In addition to terminal route planning, applications of PBN can be found in the flight control system. Zhao et al. [58] and Zhao et al. [59] developed an estimation model to assess the lateral flight technical error (FTE), which is the distance between the estimated and pre-defined paths for

the automatic flight control system (AFCS). The algorithm, which minimizes FTE, considered such parameters as environmental turbulence fluctuation disturbance, aircraft dynamics, and control system parameters. The model was verified using MC simulation. They concluded that FTE was mainly influenced by the atmospheric turbulence disturbance, performance characteristics of AFCS, and system perturbation.

3. Environmental Engineering Applications

Similar to transportation engineering, the PBA concept has been applied in environmental engineering to varying degrees in some areas, including water-structures design and operation, landfill design, building architectural design for evacuation, and urban energy design. The applications in the last area are emerging, compared to the first three areas. In addition, the PB approach in environmental engineering applications is also implemented at the design and operational stages. Although applications in the building evacuation area are somewhat emerging, related design guidelines for PBA have been developed, including performance-based fire safety design [60] and performance-based fire Engineering of Structures [61].

3.1. Water-Structures Design and Operation

Similar to any civil infrastructure, water structures (e.g., water distribution network, channel cross sections, and river structures) require an optimal design to improve serviceability with a minimum life-cycle cost. Various applications in this area [62–74] are summarized in Table A4. Earlier research work on applying reliability in water structures was related to cross section design. Easa [62] applied FOSM to design the dimensions of the cross section such that the runoff exceeds the capacity by a specified P_{nc} . Later, Easa [63] extended this work to design a trapezoidal cross section based on three failure modes (see Figure 3): runoff Q exceeds capacity Q_{max} , water velocity V is less than minimum velocity for deposition V_{min} , and V exceeds maximum velocity for erosion V_{max} . The performance criteria were considered as random variables. AFOSM was used to model the three failure modes, and the system probability of failure P_f that accounts for the correlations among the modes was formulated. Another element of water-structures in which reliability has been implemented was port dredging. Scott [64] applied FOSM for estimating the uncertainty of dredge production measures considering the uncertainties of the component variables. Two types of production systems (pipeline and hopper dredges) were considered. For these dredges, the production criteria were pipeline volumetric flow rate (or hopper volumetric load) and pipeline solids flow rate (or hopper solids load).

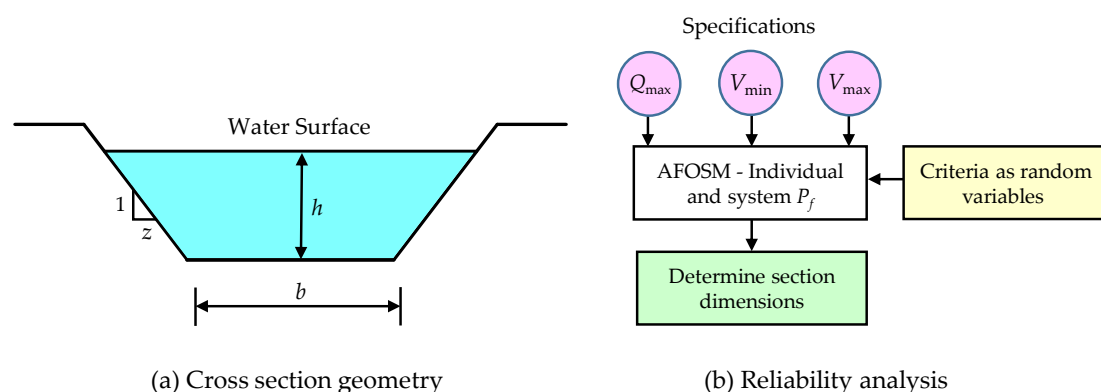


Figure 3. Open channel design using reliability analysis considering three failure modes [63].

Xu and Goulter [65] proposed an optimization model for reliability-based design of water distribution networks. The model considered a number of uncertainty components, including nodal demands, pipe coefficients, and impacts of mechanical failure of system components. The model adopted FORM to compute approximate reliability values. Buchberger and Nadimpalli [66] performed

statistical analysis to assess the design of water distribution network. They obtained continuous measurements of flow rates within a demand monitoring area (DMA) in a residential service zone, and applied a leak-detection algorithm to assess potential water leakage within DMA. An extended model for optimal design and rehabilitation of water distribution network that considered multi-criteria formulation was subsequently proposed by Jayaram and Srinivasan [67]. They used a modified resilience index (MRI) that can handle networks with multiple sources to measure the ability of the network to handle uncertainties. The formulation minimizes life-cycle cost of maintaining and monitoring the pipes and maximizes the minimum MRI.

Coastal structures, such as breakwaters and seawalls, are established for coastline/shore area protection. These structures must be well-designed and installed subject to hostile actions of winds, waves, and earthquakes. Therefore, PBA has been used to assess the stability of the structure with respect to these loads. Thus, similar structural performance criteria such as displacement, sliding distance, and seismic coefficient have been used to measure the performance of the designed structure (Table A4). Goda and Takagi [68] pointed out that the common failure of vertical caisson breakwaters can be categorized as sliding of caissons, displacement of concrete blocks and large rubble stones, breakage and displacement of armor units, rupture of front walls, and circular slip in the foundation and subsoil. Therefore, they proposed a new reliability-based model by adding the concept of economic optimization to design a breakwater structure to cater both shallow and deep waters. The study pointed out that the limit of the expected sliding distance should be reduced from 0.3 m to 0.1 m.

In a subsequent study, Goda [69] further researched the extreme wave height and proposed a spread parameter to characterize tail-spreading performance of external distribution functions (Fisher–Tippett Types I and II, and Weibull distributions) as defined by the ratio of the 50-year return wave height to the 10-year height. Suh et al. [70] further considered the effects of climate change (sea level rise, wave-height increase, and storm surge increase) in PBA of caisson breakwaters. They recommended that the caisson width should be increased by 1.5 m and 0.5 m for linear and parabolic wave heights, respectively, and the return period should be designed only for 30 years with the effects of climate change being considered. Takagi et al. [71] echoed the idea of climate change and used a third-generation spectral wave model to perform simulation. They found that there may be a 10% increase of wind speed caused by tropical cyclones in the Asia–Pacific area leading to a 21%-increase in wave height. Therefore, the engineer should consider such a factor in PBA for caisson breakwater structures. Papadimitriou et al. [72] presented a new method for PBA of earth-dams and tall embankments by estimating the seismic coefficients. The method used statistical regression of decoupled numerical data for pseudo-static stability analysis, and is considered reliable for use in the design of earth dams and tall embankments with heights ranging from 20 m to 120 m.

Recently, Easa [73] developed a new Muskingum hydrological routing model that adopts multiple criteria in model calibration. The model minimizes two conflicting criteria: outflow criterion and storage criterion. The multi-criteria function is expressed as a weighted function of normalized outflow and storage criteria. A criterion weight of 0.4–0.6 was found to produce an excellent trade-off. Another recent area in which uncertainty was incorporated was ice-covered channels. In such channels, the roughness coefficient of the ice cover changes over time and space. Easa [74] presented an optimization model for the best hydraulic section that incorporated the uncertainties of the roughness coefficients of both ice cover and channel bed. The nonlinear discharge equation was linearized using Taylor series expansion and was verified using MC simulation.

3.2. Landfill Design

Landfill applications focus on the design of landfill profiles (liner and cover systems) by minimizing the leakages of landfill gas and leachate. Various applications in this area [75–81] are summarized in Table A5. The practice of PBA for landfills has started as early as 1990s [75]. For example, the solid waste guideline developed by the Wyoming Department of Environmental Quality Solid and Hazardous Waste Division (2013) pointed out that municipal solid waste landfills must contain a

composite liner and leachate collection system, where the approved landfills must ensure that pollutant concentrations will not exceed maximum contaminant levels in the uppermost aquifer at the relevant point of compliance. Therefore, PBA studies in landfill engineering mainly use leachate or landfill gas parameters as the performance criteria to assess landfill profile or liner design. Tarhan and Ünlü [76] proposed a PBA evaluation method to determine the best design component options for landfill sites with three types of final cover and five types of bottom liners. They proposed a component selection matrix with model parameters such as climate/precipitation, hydrogeology, waste properties, and size of the landfill. Subsequently, they evaluated 18 different combinations of final cover and base systems using visual hydrogeologic evaluation of landfill performance (HELP) leachate generation model and VADSAT contaminant transport model. They concluded that the performance of landfill bottom liner is more critical than that of the cover system, and therefore more attention should be paid to the base system during the design process.

Subsequently, there was more focus on different landfill base systems. Katsumi et al. [77] proposed a PBA method to assess the use of geomembrane, clay, or composite liners for landfill by comparing the mass flux of chemicals. They concluded that the composite liner outperformed the other two types with less contaminant leakage at the bottom of liner. Guyonnet et al. [78] compared ten geosynthetic clay liners for the bottom barrier of landfill using four performance criteria: free swell index, cation exchange capacity, CaCO_3 content, and carbon and oxygen isotope. The authors stressed that authorities should assess the suitability of choosing geosynthetic clay liners using these criteria, instead of giving priority to supplier's pricing over liner's product quality.

Recently, more focus has been placed on post-closure monitoring and management of landfills. Morris and Barlaz [79] developed an evaluation of post-closure care method that measured four primary components: leachate management, landfill gas management, groundwater monitoring, and cover maintenance. By sequentially addressing these components, the authority can determine the optimal time and location for active care, rehabilitation, and monitoring. Finally, they presented an economic analysis to determine how the cost of landfill management can be saved with respect to the years of post-closure.

3.3. Building Architectural Design for Evacuation

PBD has been implemented in building architectural design to aid emergency evacuation. Various applications in this area [82–89] are summarized in Table A6. The building evacuation model is one of the important tasks to be designed to assess the level of life safety when a disaster, such as fire or earthquake, happens. Thus, designers use different computer simulation methods during the design stage to evaluate the impact of evacuation.

Depending on the design objective, most PBA applications in building evacuation mainly use evacuation time as a performance criterion. The evacuation time is represented by the required safety egress time (RSET) and the available safety evacuation time (ASET). This criterion is used to assess the design options, such as exit width, fire sprinkler system, and total number of occupants. A design option is considered acceptable if ASET is greater than RSET. Bensilum and Purser [82] proposed an object-oriented building evacuation model, named GridFlow, for PBA with combination of pre-movement and movement behaviors. The model considered individual building spaces as 2D rectangular cells and required specified occupant characteristics. The model output was able to simulate people movements, flow through exits, merges of flows, and predicted evacuation time. Kuligowski and Milke [83] compared two egress models (EXIT89 and Simulex) for PBA of a hotel building. They found that EXIT89 produced a shorter evacuation time by 25% to 40% than that of the Simulex for the same design scenarios. Zhang et al. [84] introduced a stranded-number model for PBA of stadium egress. The authors highlighted the relationship between velocity, crowd density, and crowd flow. They concluded that a 4 m egress is an ideal choice for stadium egress design. Zhao et al. [85] proposed a 2D cellular automata random model for PBA of building exit. They performed simulation of two different scenarios and found that the evacuation time was reduced nonlinearly with the increase

in exit width. Therefore, they recommended that the exit width (0.4 m in their experiment) should be increased by a factor of 6.4 in the case of a single exit and a factor of 4.5 in the case of two exits. In addition, the exit separation should be 30% of the total width of the building.

Wang et al. [86] proposed the adoption of PBA for smoke control and evacuation in a typical building atrium. They used some assessment tools to perform smoke simulation with different smoke density and velocity fields, and subsequently used EVACNET4 software to perform evacuation simulation. They concluded that a 15-min RSET and a smoke screen within 80 cm can ensure safe evacuation. Ma et al. [87] applied PB fire and safety evacuation design for a college library. They used the fire dynamic simulator (FDS) to determine and evaluate evacuation time. With 410 s RSET and 500 s ASET, the design is affirmed to meet evacuation performance. Sujatmiko et al. [88] performed a similar study for a 21-floor building located in Indonesia. They compared the travel time of evacuation experiment using trained and non-trained occupants, and that generated from FDS-EVAC simulation. The authors found that a value of RSET greater than 150 sec is much longer than ASET (35 s to 40 s), and thus further enhancement to the fire protection system should be carried out in the building.

3.4. Urban Energy Design

Smart infrastructure design is an emerging topic that has raised awareness not only from architectural designers and urban planners, but also from the general public. The major goals are to reduce energy consumption and preserve renewable energy. As a result, optimizing urban and building design considering energy performance has recently become popular in the literature. To achieve these goals, PBA has deemed to be a viable approach to leverage multiple design parameters (i.e., building cost, heating, cooling, lighting, solar potential, and electricity) in order to yield the best design solution with respect to the corresponding planning stage. Various applications in this area [90–95] are summarized in Table A7.

Tian and Love [90] conducted a simulation to assess the performance of two cooling systems: conventional variable air volume (VAV) system and radiant cooling-VAV (RC + VAV) system. The system was located in the ICT Building at the University of Calgary, Canada, which is operated in a very cold, semi-arid climate. The authors initially acquired DOE-2 simulation model, but ultimately used EnergyPlus to model heating and cooling to evaluate the building energy performance. They found that the ICT building had 30% lower annual energy use with the conventional VAV system compared with the as-built radiant cooling-VAV combination. However, the building could achieve 80% lower annual energy use by fully exploiting the potential of radiant thermal control, by better control of solar gains and envelope heat losses, and by improved system operation coupled with a dedicated outdoor air system with exhaust air heat recovery and evaporative cooling. Eicker et al. [91] demonstrated a case study in Munich, Germany, where they evaluated different options of urban city quarter to achieve zero energy balances. Considering specific parameters, including building compactness, solar access, and renewable heat distribution, the authors concluded that when the building compactness was reduced, the energy demand for heating was increased by 10–20%. In heating dominated climates with higher winter solar gains (e.g., Munich), mutual shading of building forms increased the simulated heating demand, typically by 10%.

Asl et al. [92] proposed a framework for building information model (BIM) for performance optimization, called BPOpt. The framework was built based on the BIM software, Autodesk Revit, by using visual programming tool, Dynamo. The authors used BPOpt to assess a house project BIM model and to optimize the design of window size (i.e., width and height) and glazing material (casement, clearstory, and curtain panels) by evaluating annual energy cost and percentage of the area with illuminance level within the LEED daylighting acceptable range for three design alternatives.

Delgarm et al. [93] introduced a multi-objective particle swarm optimization model to aid building energy performance by minimizing the electricity consumption of cooling, heating, and lighting. The authors modeled specific building parameters, including building orientation, shading overhang specifications, windows size, and glazing, and wall conductivity. Using the optimization model,

the optimal design achieved 1.6% to 11.3% diminution of total annual building electricity demand. Ascione et al. [94] reported an interesting case study of developing cost-optimal energy retrofit solutions for buildings, and they applied the method to a reference building for hospitals built in South Italy between 1991 and 2005. The proposed multi-stage multi-objective optimization approach first investigated energy performance of the building and implemented a genetic algorithm to optimize the combinations of energy retrofit measures for the reduction of thermal energy demand. The model further improved energy efficiency of the primary energy systems and exploited renewable energy sources. Their case study proved that the optimized retrofit solution can lead to a reduction in primary energy consumption by 12.3% and in global cost by 24.5%, resulting in a reduction of 1260 t/year in CO₂-eq emissions.

4. Structural Engineering Applications

The concept of PBA has been rapidly growing in structural engineering and has been used in several areas, including earthquake engineering, wind engineering, and bridge engineering. The goal of performance-based seismic design (PBSD) is to incorporate a pre-defined level of performance during the design stage so that post-earthquake damage is retained to a certain acceptable level. The damage level and performance differs depending on the type of structure and its usage. The National Guidelines for Seismic Rehabilitation of Building codes (e.g., FEMA 356 and FEMA 445) laid a solid foundation for the PBSD to evaluate the design options with respect to different performance/safety levels, including operational level (OP), immediate occupancy level (IO), life safety (LS), and collapse prevention (CP) (see Figure 4). The pushover analysis is commonly used in PBSD to assess the safety level. It first starts with applying a certain load or base shear (V). Then, the displacement of any weak link can be found within the structure. Through iteratively applying different loads, the displacement (D) can be captured and the V – D relationship is plotted as a pushover curve. Interested readers are referred to [2,96] regarding structural and nonstructural performance levels. Practical implementation of PBA has been aided by the development of design guides and books. Examples include National Performance-Based Design Guide [97], Performance-Based Building Design [98,99], Performance-Based Optimization of Structures [100], Advances in Performance-Based Earthquake Engineering [101], Performance-Based Seismic Engineering [102], and the latest Guidelines for Performance-Based Seismic Design of Tall Buildings, Version 2.03 [103].

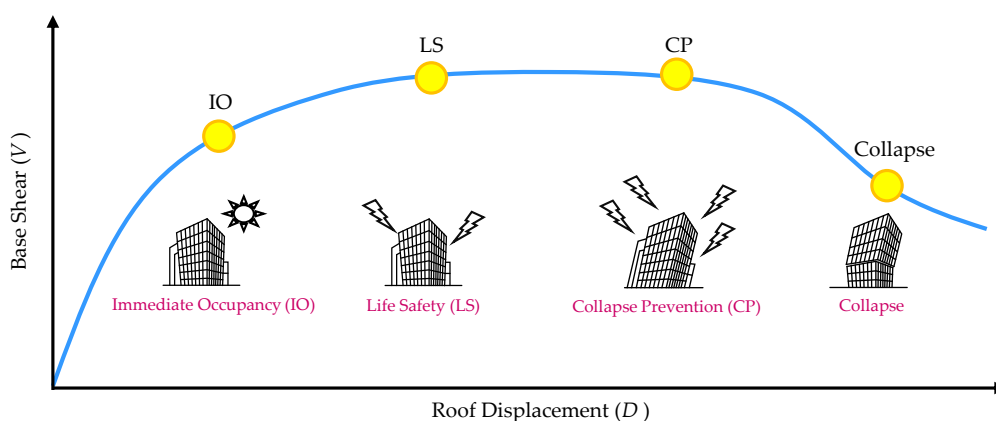


Figure 4. Example of performance-based seismic design (PBSD) performance/safety levels based on pushover analysis.

4.1. Building Earthquake-Based Design (Traditional Structures)

Many applications of PBSD have been conducted for traditional building structures (e.g., reinforced concrete (RC) beam, steel shear wall, and steel moment frame) to analyze earthquake impact. Representative applications [5,104–120] are summarized in Table A8. Early studies mainly

used displacement-based analysis as a criterion to evaluate PBSD of traditional structures, where a single parameter was considered. Whittaker et al. [104] evaluated inelastic and elastic displacements for single-degree-of-freedom (SDOF) system and tested 20 earthquake ground motions on a stiff soil to soft rock site. They concluded that the stated assumption (i.e., the means of elastic and inelastic displacements are equal) is only valid when the elastic periods are greater than the characteristics site period and the value of strength ratio is greater or equal to 0.2. Otherwise, they found that the mean-plus-one-standard deviation of inelastic displacement equals 1.5 times the mean of inelastic displacements for elastic periods greater than 0.3 s. Rosowsky [105] developed a PB framework using partially-coupled reliability method to model the dynamic behavior of wood shear walls. The objectives were to perform sensitivity analysis of different sources of uncertainty to shear-wall performance to statistically characterize the peak response obtained using the suite of ground motions, and to develop a risk-based procedure for PBA.

Hasan et al. [106] proposed a pushover analysis of steel building structure. The analysis included three tasks: (a) applying gravity loads and lateral local increment, (b) determining nodal displacements and member deformations and forces, assessing four performance levels, and (c) employing and updating a “plastic-factor” to trace the elastic-plastic behavior. Gong et al. [107] performed a PBA sensitivity analysis for inelastic steel moment frames subject to earthquake loading. They performed a pushover analysis on a three-storey moment frame to determine the roof and inter-storey drift displacements and plasticity-factor. To improve the reliability and durability of the designed structure, multiple performance criteria were used at the design stage, thus raising the topic of structural optimization in PBSD.

Ganzerli et al. [108] performed structural optimization of nonlinear behavior RC portal frame, including area of beam bottom steel, area of beam top steel, area of column steel, beam width, beam height, and cost. They considered performance constraints on plastic rotations of beams and columns, and behavioral constraints for RC frames. The pushover curve was used to indicate the roof displacement with respect to the lateral loads using Finite Element (FE) program, DRAIN-2DX. Zou et al. [109] proposed a multi-criteria optimization for PBSD of RC frames by minimizing the life-cycle cost as the objective function (initial material cost and expected future structural loss). The inelastic drift response and the plastic rotation were acted as design constraints subject to specific performance levels, and the problem was solved using the ϵ -constraint method. Kaveh et al. [110] improved the performance of structural optimization by using the ant-colony optimization method. The cost function was the weight of the structure, which was based on the material mass density, length, and cross-sectional area. The constraints were related to the lateral drift of the building with respect to four performance levels (OP, IO, LS, and CP). Then, they employed a pushover analysis to assess the first-order elastic and the second-order geometric stiffness properties of the steel frames.

4.2. Building Earthquake-Based Design (Special Structures)

Apart from the seismic induced damage for traditional buildings, PBSD are found useful for special structures, such as tall buildings, wall systems, masonry infill walls, and cultural heritage structures. Various applications in this area [121–138] are summarized in Table A9. Harries and McNeice [121] pointed out that the traditional strength-based design method is not capable of dealing with a large class of coupled core wall systems, since the method does not incorporate preferred yielding mechanism. They proposed a PBA using a nonlinear pushover and dynamic analyses for a 30-storey coupled-core wall structure and proved that the use of PBA yielded an acceptable performance according to the collapse-prevention performance level.

Klemencic et al. [122] addressed several important issues for PBA of ductile concrete core wall buildings, including frequent and maximum earthquakes and acceptable performance for serviceability levels. They pointed out that it was necessary to understand the anticipated building behavior (using response spectra) before performing a detailed analysis. Lagomarsino et al. [123] initiated the use of PBA approach for earthquake protection of cultural heritage with several fundamental steps. The steps

included defining the performance limit states, identifying structural and artistic assets of the cultural heritage, assessing seismic hazard and soil-foundation interactions, and developing structural models for seismic analysis.

Olmati et al. [124] analyzed a precast concrete cladding wall panel subjected to blast load, such as an explosion event. They used MC simulation to compute the fragility curve for the wall panel using several component damage levels (limit states), and the probability of exceeding limit states. Franchin and Cavalieri [125] presented a PBA procedure for analyzing earth-retaining diaphragm walls. They used MC simulation and a nonlinear dynamic model to assess the soil–wall system. The demand hazard curve served as a criterion to reveal the wall bending moments and displacements.

Although most structures are designed to resist the impact of seismic loads, other parameters (e.g., fire and flood) are also considered important to include during the design stage. Kodur (1999) analyzed fire resistance of concrete-filled steel columns and square-hollow structural steel (HSS) using a PBA. They recommended some guidelines for design and construction: (a) fire resistance of columns should be greater than 2 h, (b) carbonate aggregate should be used in concrete filling since it outperformed those of siliceous aggregate by 10%, and (c) bar reinforcement is not recommended for HSS columns smaller than 200 mm. Liew et al. [126] simulated the natural fires using two models (multi-zone and radiation) for a steel structure and studied the effect of fire spread on structural behaviors subject to different fire intensities. Experiments were conducted on a multi-storey frame (car parking) and arched frame structures for fire combustion. The results showed that passive fire protection on these structures is not necessary. However, the analysis should ensure that the structure is safe for post-disaster investigation and rehabilitation. Taggart and van de Lindt [127] proposed to use a PBA for wood frame structures stuffed from flood hazard damage. They used MC simulation to generate fragility curves for different flood scenarios (depth and duration) and model repair and replacement costs. Younsi et al. [128] introduced a PBA to design concrete mixture with different substitution of cement by fly ash using trials of porosity measurements and accelerated carbonation tests. Such a concrete mixture product can lead to a significant reduction in terms of CO₂ emission.

4.3. Building Wind-Based Design

Urban infrastructure, in particular tall buildings/towers, inevitably suffers from extreme winds and hurricanes. Therefore, wind loading should be considered as one of the most important factors during the design stage of these structures. Since strong wind load would cause lateral deflection, resulting in human discomfort or even threats to human life, PBS in wind engineering mainly measures displacement, drift ratio, and human comfort subject to different design wind loads and speeds. As a result, pushover analysis is commonly used to assess the performance level of the structure.

Various applications in this area [4,139–145] are summarized in Table A10. Jain et al. [4] demonstrated how to use a mixed distribution and MC simulation to compute the design wind loads for a 30-storey building. Beck et al. [139] incorporated the principle of PBA to design nonlinear/hysteretic stochastic dynamical systems. Their approach considers a statistical linearization with time-variant reliability analysis to optimize total life-cycle cost of RC buildings subject to wind excitation. Spence and Kareem [140] proposed a PBA framework with reliability-based design optimization to assess large scale uncertain linear systems driven by experimentally estimated stochastic wind loads. A case study was reported for a 45-storey building, located in Miami, simulated with uncertain wind excitation so as to prove the robustness of PBA and the optimization framework.

Bernardini et al. [141] presented a probabilistic framework for PBA of high-rise buildings for occupant comfort using MC simulation. The performance measure was based on the probability that the fraction of people on a target floor who perceive the motion exceeds a specified value under a given wind event. They also developed a web-based information system that allowed users to specify high-frequency base-balance data, which helped in the initial design stage. Do et al. [142] used a simplified coupled dynamic model to compute the vibration of wind turbines for fatigue life problem and fatigue-related design. The authors conducted an experiment to assess the design of wind turbine

tower base connections and concluded that the increase in tower-base diameter and thickness can aid in improving fatigue life of the tower connection. Huang et al. [143] proposed a four-level PBA framework for wind engineering: motion-perception performance objective, operational performance objective, immediate occupancy, and life safety. They developed an augmented optimality criteria method to optimize a PBA considering inelastic deformation with a case study involving a 40-storey residential building.

4.4. Bridge Design and Management

Similar to the earthquake engineering applications, bridge engineering focuses on safety subject to different seismic loads and thus the PB approach has been applied for designing bridge components such as steel arch, bent, and columns, not only at the design stage but most recently at the retrofit stage. Thus, most studies used lateral displacement or drift ratio to assess the behavior of the designed bridge subject to different loadings, while other studies used time dependent reliability analysis. Various applications in this area [146–155] are summarized in Table A11.

Kim et al. [146] used a practical inelastic nonlinear analysis to assess and predict the limit-state system strength and stability of a steel arch bridge. The proposed method considered factors that affect the behavior of the frame and truss members, such as the gradual yielding associated with flexure, residual stresses, and geometric nonlinearity. Mackie and Stojadinović [147] proposed a probabilistic seismic demand model that considered ground motion intensity measures and structural engineering demand parameters for PBA of highway overpass bridges. Shamsabadi et al. [148] presented a model with seven soil-related parameters to predict realistic nonlinear lateral force-displacement capacity of a regular bridge abutment as a function of common backfill properties and structural configurations.

Roy et al. [149] used carbon-fiber-reinforced polymers for retrofitting a highway bridge bent, where the retrofitted structure met prescribed ductility levels corresponding to selected seismic events. They subsequently performed pseudo-dynamic tests to evaluate the performance of the retrofitting technique and compared the results with those predicted from a 3D nonlinear FE model. Mackie et al. [150] considered the ground-foundation interaction in PB evaluation of highway bridges with different soil profiles, where the approach stressed the need to quantify the probabilistic response of the component damage, and repair cost and time. Billah and Alam [151] proposed a multi-criteria decision-making model for PB retrofit selection of a bridge bent that was designed in mid-1960. They evaluated the solutions of both the entropy and TOPSIS methods for performance analysis. Sharma et al. [152] developed a probabilistic demand model to design the desired behavior of reinforced columns under different vehicle impact scenarios. The PB fragility estimates can be used to assess the likelihood of a specified performance of an RC column in a given impact scenario.

Several researchers conducted time-dependent reliability analysis for evaluating existing or rehabilitated bridges [154–160]. For example, using MC simulation, Zhu et al. [154] presented a probabilistic method for evaluating time-dependent reliability of reinforced-concrete bridge components to predict residual capacity after subsequent rehabilitation. The probability distributions of various variables, such as surface chloride concentration, were based on the literature. The reliability analysis was taken one step further by Guo et al. [155] who developed a hybrid reliability method for a pre-stressed box-girder bridge used in high-speed railway. A time-variant deflection reliability analysis was conducted, in which a hybrid method, consisting of the response surface (RS) method, the FE method, and the joint committee on structural safety (called J.C. method) was used [156]. The proposed approach can be used in the design optimization, speed control, and making rational maintenance/repair strategies for such bridges. Wang and Morgenthal [157] conducted a reliability analysis of reinforced concrete bridge piers subjected to barge impact that considered the uncertainties involved in barge mass, impact velocity, oblique impact angle, water elevation, and material properties. A simple coupled multi-degree-of-freedom model for the dynamic analysis was proposed. A simple coupled multi-degree-of-freedom model for the dynamic analysis was proposed. Hedegaard et al. [158] evaluated the interactions between temperature and time-dependent behavior of a post-tensioned concrete box

girder bridge using linear regression of in-situ deformation data. The results showed that bridge service life decreased as the bearing capacity decreased, following the deterioration induced by a collision, fatigue, corrosion, cracking, or concrete spalling.

5. Discussion and Lessons Learned

5.1. Wide Array of Analytical Tools

A wide array of analytical tools is used for PBA in the three civil engineering fields. Early studies in PBA have mainly relied on lab testing or in-situ measurements, such as the use of wind tunnel [4] and pavement deflectionometer [41] to evaluate the physical characteristics of structural and geotechnical systems. Due to the high operational cost and durable testing time, analytical tools have subsequently been developed with the aid of computer simulation and mathematical modeling. This trend is clearly found especially in transportation and structural engineering applications. A summary of the analytical tools is presented in Table 2.

Table 2. Main analytical tools used in performance-based analysis (PBA).

Civil Engineering Field	Area of Application	Analytical Tool	Sample Recent References
Transportation engineering	Highway transportation	FOSM, AFOSM, FORM MC simulation Multi-criteria optimization	Easa [21], Fatema and Hassan [29], Osama et al. [33] El-Khoury and Hobeika [23] Mehmood and Easa [31]
	Pavements	MC simulation FORM, SORM, FOSM, AFOSM Multi-criteria optimization FORM for M-E	Kalita and Rajbongshi [44], Dilip and Sivakumar Babu [51] Easa [46], Dilip and Sivakumar Babu [51], Dilip et al. [52] Easa and Can [37], Deshpande et al. [53] Luo et al. [43]
	Air transportation	Uncertainty analysis MC simulation	Easa [48] Zhao et al. [58], Zhao et al. [59]
Environmental engineering	Water structures	MC simulation FOSM, AFOSM, FORM, SORM Multi-criteria optimization	Goda and Takagi [68], Goda [69], Suh et al. [70] Xu and Goulter [65], Easa [74] Easa [73]
	Landfills	Numerical/analytical models Simulation, GIS	Morris and Barlaz [79], Safari et al. [81] Tarhan and Ünlü [76]
	Building architecture	Analytical models Simulation	Wang et al. [61], Zhang et al. [84], Zhao et al. [85] Ma et al. [87]
	Urban energy	Simulation Multi-criteria optimization	Tian and Love [90], Eicker et al. [91] Asl et al. [92], Delgarm et al. [93], Ascione et al. [94]
Structural engineering	Buildings (earthquake-based)	Pushover analysis FE SDOF, MDOF Multi-criteria optimization Uncertainty analysis MC simulation	Moghimi and Driver [119], Wongpakdee et al. [120] Ganzerli et al. [108], Tort and Hajjar [132] Pampanin et al. [113], Wiebe and Christopoulos [138] Kaveh and Nasrollahi [130], Cha et al. [136], Veladi [137] Rosowsky [105] Olmali et al. [124], Franchin and Cavalieri [125]
	Buildings (wind-based)	Pushover analysis Multi-criteria optimization FE-Fragility analysis Optimization SDOF, MDOF MC simulation Wind-tunnel test	Huang et al. [143] Li and Hu [144] Do et al. [142] Spence and Kareem [140], Li and Hu [144] Beck et al. [139] Jain et al. [4], Bernardini et al. [141], Li and Hu [144] Huang et al. [143], Ozuygur [145]
	Bridges	FE-Fragility analysis Static/dynamic models Uncertainty analysis Reliability-FE-RS	Roy et al. [149], Sharma et al. [152] Kim et al. [146], Mackie et al. [150], Lee and Billington [161] Mackie and Stojadinović [147] Guo et al. [155]

AFOSM = advanced first-order second-moment, FE = finite element, FORM = first-order reliability method, FOSM = first-order second-moment, GIS = geographic information system, MC = Monte Carlo, MDOF = multi degree-of-freedom, M-E = mechanistic-empirical, RS = response surface, SDOF = single-degree-of-freedom, and SORM = second-order reliability method.

As noted, reliability analysis has been used for conducting PBA in all civil engineering fields. The analysis involves establishing a limit state function, which is the difference between supply and demand (called resistance and load, respectively, in structural engineering). Typically, the supply and demand are functions of random variables that are treated in the limit state function explicitly and simultaneously (fully-couple analysis). Examples of related analytical tools are FOSM, AFOSM, FORM, SORM, and J.C. method [51,65,156]. Note that in transportation and environmental engineering applications, the supply is normally considered deterministic, making the analysis simpler, unlike the resistance in structural engineering applications which is not only random, but also time dependent.

When one source of the uncertainty is far greater, as is the case of natural-hazard loads, the response is separated from the hazard (uncouple analysis), which is the basis for the fragility analysis [142,149,152]. Another type of analysis that lies between the preceding two types (partially coupled analysis) has been proposed [105]. Reliability analysis in structural engineering can also be performed using RS method in association with FE and basic reliability principles [155]. The RS method is useful when the LS function is known only implicitly, such as in FE analysis whose direct application would be expensive. In this case, the implicit limit state function is replaced with an artificially constructed RS function (generally a polynomial) around the design point.

The MC simulation is another numerical tool used for PBA. The method is simple and can be applied to almost all reliability problems. However, the limit state function needs to be evaluated many times with random sampling of the component random variables. This can be expensive and time-consuming for problems with implicit limit state functions or where failure probability is low. Further details on the preceding analytical and numerical reliability methods can be found in the literature, see for example [162–164]. Note that MC simulation has also been used to verify PBA analytical tools. For example, Figure 5 shows a comparison of the uncertainty-based mathematical model and MC simulation for the volume of absorbed asphalt (V_{ba}) [47]. The simulation involved generating 50,000 random values of the component random variables, substituting them in the respective equation of V_{ba} , and establishing the frequency histogram. The burble-colored columns in the figure represent a normal distribution with the mean and standard deviation of V_{ba} calculated using uncertainty analysis. According to the central limit theorem [165], when a variable is a function of several random variables, its probability distribution tends to be normal, regardless of the types of distribution of the component variables. This explains the close agreement between the mathematical and simulation results in the figure.

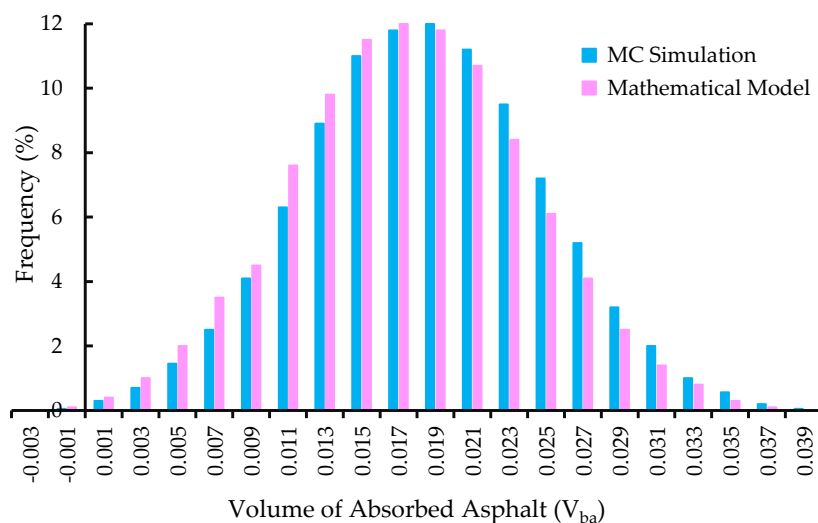


Figure 5. Comparison of uncertainty-based mathematical model and MC simulation [47].

Uncertainty analysis is a useful analytical tool for considering the effect of uncertainty of the measured variables on the uncertainty of the performance variables. Often, the analysis involves propagation of uncertainty through intermediate variables. Although PB models in some applications are deterministic (based only on the mean values of the measured variables), such models may provide misleading results. In considering uncertainty in PBA, the analyst should pay attention to several issues [46–49]. First, all variables (measured, intermediate, and design) should be reliable. Reliability of a random variables is normally measured by the coefficient of variation (CV). In most engineering applications, a variable is considered reliable if $CV \leq 25\%$ and variables with $CV > 40\%$ are certainly unreliable ($25\% < CV < 40\%$ may be acceptable). Secondly, the analyst should ensure that the probability distribution of a random variable does not have a negative tail as negative values

are normally not meaningful. This is ensured when the mean value of the random variable is greater than three times its standard deviation. In practice, if the intermediate or performance variables are found to be unreliable or have negative tails, the analyst should trace the measured variables that affect that variable and try to reduce their uncertainties (see Figure 2). In this figure, CV of the measured variables is very small ($<1\%$). However, due to propagation of error CV of the performance variables (yellow) and the intermediate variables (pink) reaches up to 39%. Third, most PBA applications focus on the uncertainty of the performance measures and neglect the uncertainty of the performance criteria. For example, in asphalt mix design performance criteria are established based on thousands of good-performing pavements and such criteria also possess uncertainty that should be considered in modeling [46].

Although different analytical tools are developed in PBA to deal with multiple criteria or numerous coupled degrees of freedom, genetic algorithms and MC simulation have been found to be effective in estimating optimal different design parameters considering uncertainty and life-cycle analysis. This can be found in diverse applications, including breakwater design [70], cladding wall panels [124], diaphragm wall [125], wood frame structure [127], pavement design [44], and flight control systems [58]. Different solution methods, such as ϵ -constraint method [109], ant-colony algorithm [110], and gene manipulation method [136] have been proposed to improve the computational efficiency of multi-criteria optimization. The reader is referred to a recent successful case study by Lamperti Tornaghi et al. [166], where the authors proposed a sustainable structural design method that optimizes energy performance (in monetary unit), life cycle (environmental) assessment, and structural performance (repair and downtime cost) in order to obtain a global assessment parameter of the proposed design. Similar approaches of multi-criteria optimization have been incorporated into some standards [167] and pre-standards [168].

Recently, M–E models have been emerging in pavement design. Such models explore the relationship between the physical causes and the phenomenon using a mathematical model. These models are advantageous over mechanistic models which mainly rely on the use of physical principles (e.g., look-up table) or equations to determine the design parameters. The M–E models are also more accurate than empirical models which are typically based on establishing empirical relationships that may change if the input slightly changes.

In structural engineering, pseudo static/dynamic tests are commonly used to assess the imposed displacement or inter-storey drift subject to different loads [72]. Physical approaches based on SDOF and MDOF systems have been used to model displacement with respect to velocity and acceleration, which are the fundamental principles found in structural and seismic studies [138]. Thus, different FE models are developed to aid in assessing the geometric design subject to stress analysis, where software such as DRAIN-2DX and LS-DYNA are used in various studies [152]. Another popular analytical tool adopted in structural engineering applications is the pushover analysis. This analysis is one of four procedures commonly used in PBA: linear static, linear dynamic, nonlinear static (pushover), and nonlinear dynamic. Pushover analysis is attractive for PBA because it is simple to perform and involves less calculation than NL dynamic analysis. It also uses a response spectrum rather than ground accelerograms. Its main weakness is that it is approximate as it is static and cannot account for dynamic structural behavior, and is reliable only if the building behaves essentially as a SDOF structure. However, for most structures the analysis can be effectively used for preliminary performance evaluation, but the final evaluation may best be done using dynamic analysis. For more details on the accuracy of several of pushover methods and the most promising one, the reader is referred to Powell [169].

5.2. Broad Functional and Process-Related Areas

The review of applications in this paper showed that the PBA concept has been applied to all the stages of infrastructure life, including planning, design, operation, and management. A quick scan of the reviewed applications showed that design-related applications have been more dominant (75%), compared with planning applications (15%) and operation/management applications (10%). Thus,

great opportunities exist for researchers to explore various ways of implementing the PB concept in functional areas other than design.

In addition to its application to academic civil engineering fields, PBA has emerged in processes related to these fields. One example is assessment of engineering education. The traditional input-based assessment of engineering education has primarily focused on the resources that are available to the students with little attention to whether students ever learned any of the materials. In addition to this traditional assessment, a relatively new type of assessment based on performance has been incorporated in engineering education. Performance or outcome-based assessment focuses on empirically measured outcomes that include a range of skills and knowledge that undergraduate students should acquire. More details on this system can be found in “Framework and Guidelines for Graduate Attribute Assessment in Engineering Education” [170]. Twenty countries from around the world have adopted this approach in higher education since 1990s as part of the Washington Accord [171], including Australia, Canada, China, Hong Kong, Russia, United Kingdom, and United States. The main objective of the PB assessment is continuous improvement of the engineering program.

A typical process of graduate-attribute assessment is illustrated in Figure 6. The blue-shaded activities are performed at the faculty level, while other activities are performed at the academic program level. The faculty-level activities include the development of common indicators associated with each graduate attribute, a common assessment schedule, and common indirect assessment methods. Feedback from constituents and stakeholders (e.g., advisory council and faculty members) are sought when identifying/revising program objectives and developing program improvements.

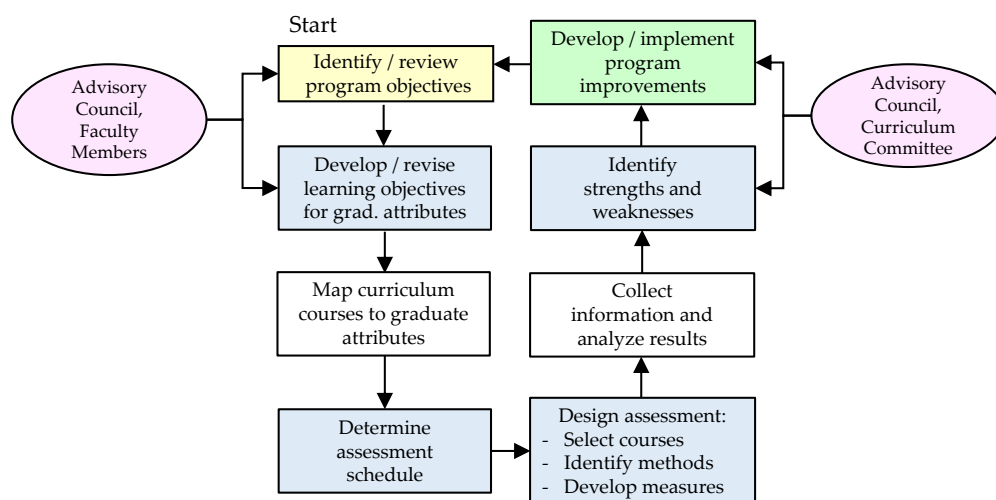


Figure 6. Typical process of graduate-attribute assessment (faculty-level activities are shaded in blue) [170].

Another example of process-related PBA is performance-based contracting (PBC) [172]. The main parties involved in PBC are an agency that contracts the work to an external provider (a contractor) who is responsible for completing the work specified in the contract. PBC is a support strategy that focuses on optimizing system support to meet the needs of the user. As such, PBC involves outcome performance goals, provides incentives for reaching these goals, and aids overall life-cycle management. PBC is popular around the world and in industry sectors, including defence, health services, energy sector, and construction. However, civil engineering as a discipline seems to be lagging in PBC implementation. According to a study in 2015 by Selviaridis and Wynstra [173] that reviewed 241 PBC applications across disciplines, the share of construction applications was only 4.1%. Another related area in which the PB concept has been implemented is performance-based contractor prequalification [174]. It is expected that the PB approach will be the future vision in all professional and academic aspects of civil engineering.

5.3. Advantages, Challenges, and Opportunities

As previously mentioned, PBA focuses on the desired objectives rather than the means by which they are achieved. As such, PBA is believed to be a more cost-effective approach than the prescriptive approach. Specifically, there are three main advantages of the PB approach [175]: (1) PBA enables desired performance to be attained with demonstrated confidence and reliability, (2) since the performance objectives are explicitly defined, PBA allows decision makers to select appropriate performance levels that satisfy applicable criteria, and (3) since performance is evaluated directly as part of the design process, PBA promotes research and innovation, and the use of new design solutions (new materials and systems). These advantages give the analyst the freedom to solve harder problems with better tools.

As an example of PBA advantage, common PBA objectives can be found to guarantee the safety level of the design scheme regardless of the civil engineering application. Examples include the reduction in potential hazard in landfill engineering, minimization of inter-storey drift displacements in seismic engineering, and improving the safety evacuation time in building architectural design. These objectives would lead to a common ground for PBA, regarding how safety levels are defined. Indeed, this was a major topic for PBA research during the past decades, to which different research and professional organizations have contributed to standardize the performance level. For example, the FEMA has established guidelines for buildings that define seismic performance levels and rehabilitation objectives. Structural performance levels (three) and ranges (two) were defined. Each level has a clear definition of how the designed building looks like after a seismic event and how much efforts should be allocated for rehabilitation. Thus, civil engineers can map the design scheme to the corresponding performance level.

The challenges associated with PBA arise because it is a new creative alternative that substantially differs from the traditional perspective approach. The challenges may slightly vary from one discipline to another. However, based on this review, the common challenges are as follows [175,176]:

- Lack of knowledge. One major challenge is lack of knowledge. For example, in structural engineering, application of PBA includes completely new features, such as nonlinear modeling and response-history analysis. There is a need to provide design engineers with appropriate design tools to help them, at least at the preliminary design stage, to smoothly transit to PBA. A related challenge is lack of PBA knowledge among owners of the infrastructures, insurance providers, and the public.
- Lack of proficiency. The use of codes and standards of the perspective approach is straightforward. However, PBA is more complex and requires broader skills in using new design techniques, new materials, and new systems for which no consensus guidelines exist. Thus, greater knowledge of the engineering process and competence in reliability and optimization would be required.
- Lack of decision tools. Innovative decision-support systems (DSS) for PBA are needed. The DSS should explicitly allow for demand and supply concepts and multi-criteria analysis. Early research work in PBA used a single performance criterion. However, recent research has adopted multi-criteria optimization along with criteria weights, where the criteria are often conflicting. When the criteria are conflicting, many Pareto optimal solutions exist and finding such solutions is not straightforward. Innovative ideas to decompose and breakdown the problem into different sub-systems that would eliminate the need for complex multi-criteria optimization are emerging [176].
- Lack of Data. Another technical challenge of PBA, especially in transportation and environmental engineering, is related to the lack of data on the variability of the input random variables. Reliability analysis methods require information on the mean and standard deviation of the random variables (some require the type of the probability distribution as well) and the correlations among the variables, but often such data do not exist. There is a need for establishing databases in various areas of civil engineering to promote PBA applications [47].
- Resistance to change. At present, many companies and organizations favour the perspective approach as its application is routine and resist the PBA approach because of the associated cost

or required skills to perform the evaluations. This, however, may change as better methods and guidelines are developed. In addition, some engineers believe that PBA need not be implemented for all structures, which is true. However, identifying the structures or elements for which the perspective approach is adequate remains a challenge.

Opportunities to address PBA challenges are numerous. Clearly, a thorough knowledge and practical experience are required for professionals to perform PBA. This can be aided by organizing regular conferences and workshops, developing white papers, developing best-practice guidelines, and developing continuing education courses. International organizations that can help in this effort include International Organization for Standardisation, International Association for Bridge and Structural Engineering, Institute of Transportation Engineers, and Association of Environmental Engineering and Science Professors. Several professional bodies have been organizing regular conferences on PBA, such as 1st International Conference on Safety and Crisis Management [177] and International Conference on Performance-Based Codes and Fire Safety Design Methods. Learned societies are becoming involved in promoting PBA. For example, the Structural Engineering Institute (SEI) of the American Society of Civil Engineers has developed a report in 2018 that has recommended formation of a permanent SEI Board-level committee to advance the profession toward PBD [175]. Professional associations, such as Structural Engineers Association of British Columbia, are starting to incorporate PBA into their certificate programs. New books on PBA have been published; see for example Kasimzade et al. [178] and Bryan et al. [179]. All these efforts have stimulated the practical use of PBA in the diverse civil engineering fields.

Several academic research centers have been established in North America. For example, the Pacific Earthquake Engineering Research Center, located at University of California at Berkeley, has a vision “to develop and disseminate technologies to support PB earthquake engineering”. The center includes investigators from over 20 universities, several consulting companies, and researchers at various state and federal government agencies. Another example is the Canadian Seismic Research Network which is funded by the Natural Sciences and Engineering Research Council of Canada. The center includes 26 researchers from eight universities across Canada. The themes of the network directly contribute to the development of PB seismic assessment and rehabilitation guidelines.

In graduate studies, PBA has been incorporated as one of the core research areas of graduate programs in civil engineering at several universities, including Lakehead University, Colorado State University, Stanford University, and University of Maryland. For example, the Department of Civil and Environmental Engineering at Stanford University [180] has developed a graduate program on performance-based engineering. We recommend that civil engineering programs at universities should at least incorporate a new course on performance-based civil engineering in the curriculum as a core or elective course. Alternatively, in case this not possible, existing courses should be revised to incorporate relevant elements and case studies of PBA.

5.4. Potential Applications of PBA

The review presented in this paper shows that PBA has been implemented in various civil engineering fields not only at the design stage, but also at the planning, construction, operation, and management. Table 3 presents a summary of past and potential future applications of PBA in the three civil engineering fields. The third column presents the elements that have already been modeled in the reviewed applications as presented in Tables A1–A11. The fourth column presents potential future applications that are mostly identified from recent research journal papers and reports.

Table 3. Potential applications of PBA.

Civil Engineering Field	Application Area	System Element Already Modeled	Potential PBA Application or Consideration
Transportation engineering	Highway transportation	– Traffic lights (yellow, LT offset) – Roundabout design – Uncontrolled intersections (SD) – Stop-controlled intersections (SD) – Railroad crossings (SD) – Horizontal alignments (safety)	– Pedestrian crossing (SD) – Two-lane highways (SD) – Truck escape ramp design – Dilemma zone at traffic lights – Roundabout design – Transportation logistics – Autonomous vehicles
	Pavements	– Aggregate blending – Asphalt mixture design – Pavement design – Thermal cracking prediction	– Combined pavement failure modes – LID for improving drainage – Thermal effect under all weather conditions – Recycled aggregates
	Air transportation	– Terminal operation – Route planning in terminal	– Noise modeling – Trajectory negotiation – Performance with big data analytics – Facility location within existing system
Environmental engineering	Water structures	– Breakwater – Water channel cross section – Dams, River, Port dredging	– Artificial island – Offshore windmill, data barges – Offshore oil rig, sea dikes – Ocean wave hazard – Resilience of built environment to natural hazard
	Landfills	– Composite liners – Cover systems – Landfill gas collection for monitoring methane/ odour emission	– Landfill mining – Air injection / gas extraction wells – Other landfills: coal mine waste, earthquake generated debris
	Building architecture	– Evacuation routes and paths – Exit, stairs and egress for atrium – Library, stadium, gallery, building	– Human behavioral effect – Communication and hearing effect – Design for disabilities and sclerosis – Landscape architecture
	Urban energy	– Window size and material – Building geometry & orientation – Shading overhang – Glazing and the wall conductivity	– Local microclimate and energy demand – Building cluster, district and city – Building occupants' behavior model – Access to measured building energy use
Structural engineering	Buildings (earthquake-based)	– Wall structure – Steel frame, Wood frame	– Evaluation of special structures – Integrated soil/ rock-structure interaction – Structures with non-rigid connection – Skycraper – Carbon fire exterior rods – Non-building structures
	Buildings (wind-based)	– Tall building – Steel frame	– Wind and acoustics – Wind energy in built environment – Sports aerodynamics
	Bridges	– Reinforced concrete – Steel arch, Column bents – Truss, cantilever – Suspension, bridge – Cable-stayed bridge	– Abutment bridge – Automatic bridge – Bascule bridge – Floating bridge – High speed rail effect – Integral abutment bridge – Use of mage-based systems

LID = low impact development, SD = sight distance.

In transportation engineering, the opportunities for future research are enormous. For highways, PBA can be applied to several transportation engineering areas, including SD analysis for pedestrian crossing, SD analysis for two-lane highways, length of truck escape ramps, and dilemma zones at signalized intersections. Another potential area is infrastructures of smart cities that will embrace the next generation of transportation technologies (e.g., autonomous vehicles, self-flying air taxi, and high-speed rail). This area requires more research effort to leverage the balance among operating cost, safety, comfort, and efficiency. For pavements, the focus on the serviceability can be further expanded by improving surface drainage and layer infiltration. For example, low impact development (LID) technologies such as porous pavements and bio-retention can be retrofitted in existing urban areas to improve rainfall infiltration and evapotranspiration, resulting in a reduction in flood risk [181]. With the development of new materials and technologies, related analytical tools and performance criteria should be re-visited to improve life-cycle performance and functionality. For air transportation, future research on PBA may address modeling of aircraft noise, trajectory negotiation, improving transportation performance with big data analytics, and facility location (e.g., new factory, warehouse, and distribution center) within the framework of an existing distribution system.

In environmental engineering, many opportunities for future research on PBA have been identified. For water structures, PBA can be adopted for offshore structures such as artificial island, windmill, oil rig, and data barges installed near-shore platform, similar to PBA of breakwater structures to resist extreme weather conditions involving strong wave and wind. Other potential applications include ocean wave hazard and resilience of built environment to natural hazard. For landfills, potential applications include design of air injection and gas extraction wells, landfill mining, and consideration of other landfill types (e.g., coal mine waste). For building architectural design, future research areas include incorporating the effect of human behavior and communication/hearing, design for disabilities and sclerosis, and landscape architecture. In urban energy design, further improvements of building energy performance and substantial use of green energy can further aid in designing smart homes and low carbon neighborhood cities. Other factors including local microclimate and its relationship to building-energy demand and occupants' behavior modeling should be considered [182]. In addition, authorities should address the privacy issue of releasing measured building energy use so that this information can be used to calibrate urban building-energy models [183].

In structural engineering, potential new elements for PBA are relatively limited since the PBA concept has already been well implemented for decades. However, there are opportunities for improving the already developed methods. For buildings (earthquake-based), current practice for traditional structures can be slightly modified so that similar approaches can be implemented for special structures considering other performance criteria. Another area that deserves more focus is soil/rock-structure interaction, where reliability analysis of structural elements has been far ahead of that of geotechnical elements. This research would be particularly useful for integral abutment bridges that offer numerous advantages over traditional bridges [184]. For building (wind-based), it is foreseeable that more tall buildings are being built in different metropolitan areas as landmarks or condominiums, and thus other aspects of building design considerations that integrate building information modeling and smart homes/cities are expected. In this respect, Blocken [185] highlighted the following five potential research areas that computational wind engineering should consider: surface convective heat transfer, wind and acoustics, wind-borne debris, wind energy in built environment, and sports aerodynamics. For bridges, PBA can be applied to other types of bridges, including abutment bridges, bascule bridges, and floating bridges. In addition, non-contact image-based systems for measuring bridge deformation are emerging, but their performance needs to be evaluated compared with contact-based methods [186].

6. Concluding Remarks

This paper has presented a comprehensive review of PBA applications in different civil engineering fields: transportation, environmental, and structural engineering. The review shows

that PBA implementation in structural engineering has been more advanced and systematic than in other fields, where the implementation has been sporadic and incomprehensive. In all fields, most applications of the PBA concept focus on design and more applications in other functional areas and processes should be promoted. It is also found that there are several challenges to the application of the PBA approach, but many efforts were simultaneously emerging to address them, including educational outreach, creation of research centers, and graduate studies.

As the PBA concept advances, will the traditional approach to design become obsolete? To answer this question, note that although the benefits of PBA are significant, it is more complex and expensive than the traditional perspective approach. Therefore, the traditional approach will continue to be useful in the design of many situations, especially for simple projects, while the PBA approach will become an accepted protocol for complicated, mission-critical, and high-value structures, such as hospitals and high-rise buildings [175]. In addition, adopting PBA at every step of the project (planning, design, operation, and management) is unlikely in the foreseeable future and a blend of the two approaches will continue to be used for some time. For example, the Australian PB building code allows the design of elements using PBA, the traditional approach (for elements that are deemed to satisfy performance), or a combination of both [187].

There is a need for developing a formal PBA process in transportation and environmental engineering, similar to that of structural engineering. In addition, a civil engineering field that has not been addressed in this paper is geomatics engineering. This field seems to be substantially lacking in PBA implementation compared with other fields. In most geomatics engineering applications, accuracy has been traditionally the only performance criterion and consideration of multiple performance criteria should be explored. This fact is clear in the areas of remote sensing and satellite positioning. To move fully toward PBA, additional criteria, such as computational time, risk, environmental impact, and operating/maintenance cost should be considered. There is also a need to develop analytical tools for PBA that are more adaptable to this unique field of civil engineering.

The literature review presented in this paper is based not only on peer-reviewed journal articles, but also on other sources such as design codes and guidelines, books, conference papers, and technical reports. Therefore, we believe that the review reflects, to a large extent, the current state-of-the-art of PBA in civil engineering. It is hoped that the presented vertical and horizontal scans of the literature will help inspire systematic research efforts to make the performance-based concept an accepted practice in civil engineering.

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Abbreviations

The following abbreviations are used in this paper:

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
AFCS	automatic flight control system
AFOSM	advanced first-order second-moment
AISC	American Institute of Steel Construction
ASCE	American Society of Civil Engineers
ASET	available safe egress time

ATC	Applied Technology Council
BSI	British Standards Institute
CASHEW	Cyclic Analysis of SFEar Wall
Caltrans	California Department of Transportation
CHBDC	Canadian Highway Bridge Design Code
CSA	Canadian Standards Association
CV	coefficient of variation
DMA	decision support system
EN	European Standards
EPBD	Energy Performance of Buildings Directive
FAA	Federal Aviation Administration
FE	Finite Element
FEMA	Federal Emergency Management Agency
FEMP	Federal Energy Management Program
FORM	first-order reliability method
FOSM	first-order second-moment
FRP	fiber-reinforced polymer
FTE	Flight Technical Error
PBC	performance-based contracting
PBD	performance-based design
PBN	performance-based navigation
PBSD	performance-based seismic design
PGA	peak ground acceleration
PSD	passing sight distance
RSET	required safe egress time
RC	reinforced concrete
RNAV	area of navigation
RNP	required navigation performance
RS	response surface
RSET	required safety egress time
RZ	restricted-zone
SD	sight distance
SDOF	single-degree-of-freedom system
SETAC	Society of Environmental Toxicology and Chemistry
SID	standard instrument departure
SORM	second-order reliability method
STAR	standard terminal arrival route
Superpave	superior performing asphalt pavements
TAC	Transportation Association of Canada
TOPSIS	technique for order preference by similarity to ideal solution
TSR	tensile strength ratio
TSS	terminal sequencing and spacing system
UBC	Uniform Building Code
UNEP	United Nations Environment Programme
USEPA	United States Environmental Protection Agency
VAV	variable air volume

Appendix A. List of Tables with PBA Applications

Table A1. Characteristics of highway transportation applications.

System Element	Analysis Objective	Performance Criterion	Analytical Tool	Specification/ Code	Country/ Region	Reference
Horizontal and vertical curves	Perform PBD of to determine H and V curves	- Safety margin - Safety index	FOSM	Agency specifications	Canada	Navin [20]
Railroad crossing	Perform PBD of limited SD for highway vehicles	- Safety margin for highway leg - Safety margin for railway leg	- AFOSM - Multi-criteria	AASHTO	Canada	Easa [21]
No-control, yield, and stop control intersections	Perform PBD of SD along approach legs	Safety margin	FOSM	AASHTO	Canada	Easa [22]
PSD on two-lane highways	Perform PBD of PSD for passing vehicles	Reliability index	MC simulation	AASHTO	United States	El-Khoury and Hobeika [23]
3D alignment involving H-V curves	Perform PBD of SD on combined H-V curves	Probability of hazard	FOSM	- AASHTO - TAC	Canada	Sarhan and Hassan [24]
Horizontal alignment (two-lane highways)	Perform PBD of horizontal alignment	Mean collision frequency	- NL optimization - Collision models	- AASHTO - TAC	Canada	Easa and Mehmood [25]
Framework of design elements (Case study: crest curves)	Perform PBD of risk in geometric design	Performance function	- FOSM - FORM Calibration factors	Past practice	Canada	Ismail and Sayed [26]
Highway cross section with two directions	Determine optimum cross section dimensions to minimize risk	- Risk balance - Number of collisions - Overall risk	- FOSM, FORM - Multi-criteria - NL optimization	AASHTO	Canada	Ibrahim et al. [27]
Freeway acceleration distance	Develop a probabilistic method for acceleration distance	Significance level	- FOSM - MC simulation	TAC	Canada	Hassan et al. [28]
Freeway speed-change lane (SCL)	Develop a probabilistic design of SCL considering acceleration and gaps	- Target merge speed - Acceptable gap	- FOSM - Multi-criteria	- AASHTO - TAC	Canada	Fatema and Hassan [29]
Roundabout geometric design	Perform PBD of roundabout design	Design consistency	NL optimization	Roundabout Guide	Canada	Easa and Mehmood [30]
Roundabout geometric design	Perform multi-criteria PBD of roundabout design	- Design consistency - Mobility	Multi-criteria optimization	Roundabout Guide	Canada	Mehmood and Easa [31]
Pedestrian green interval	Perform PBD of pedestrian green interval	Safety margin of minimum green	- FOSM - MC simulation	MUTCD	Canada	Easa and Cheng [32]
Signalized intersections	Perform PBD of SD of left-turn vehicles	Safety margin of available left-turn SD	- FORM - Importance Sampling	- AASHTO - TAC	Canada	Osama et al. [33]
Signalized intersections	Perform PBD of left-turn offset	Safety margin of available left-turn SD	FOSM	- AASHTO - TAC	Canada	Hussain and Easa [34]

ASHTO = American Association of State Highway and Transportation Officials, AFOSM = advanced first-order second-moment, FORM = first-order reliability method, FOSM = first-order second-moment, H = horizontal, MC = Monte Carlo, MUTCD = manual of uniform traffic control devices, NL = nonlinear, PSD = passing sight distance, TAC = Transportation Association of Canada, and V = vertical.

Table A2. Characteristics of pavement design/management.

System Element	Analysis Objective	Performance Criterion	Analytical Tool	Specification/ Code	Country/ Region	Reference
Aggregate blending	Predict the proportions of three types of aggregates	• Cost • Blend specifications	• Stochastic quadratic optimization	• Agency specifications	Canada	Easa and Can [37]
Asphalt concrete pavement	Design a reliability-based approach for pavement	• Thermal fatigue cracking • Low-temperature cracking	• AFOSM two-failure modes • MC simulation	• Agency specifications	Canada	Easa et al. [38]
2-layer asphalt pavement with limestone aggregates	Design cost-effective pavement with min. life-cycle (LC) disutility	• Initial serviceability index • Terminal serviceability index • LC disutility index	• Performance prediction model	• AASHTO design method	Palestine	Abaza and Abu-Eisheh [39]
Asphalt pavement overlay	Assess severability of overlay thickness and design rehab	• Serviceability index • Pavement condition indicator • Service time	• Performance prediction model	• AASHTO • Caltrans methods	Palestine	Abaza [40]
Crushed concrete, sandy gravel, crushed rock	Assess stability of recycled aggregates for foundation	• Material stiffness • Strength • Water content	• Lab and in-situ assessment with deflectometer	• UK Standards (IAN 73, 2006)	United Kingdom	Lambert et al. [41]
Extended-life and perpetual pavements	Minimize life-cycle cost of construction and maintenance	• Structural response • Fatigue distress • Rutting distress	• Mechanistic - empirical design • optimization	• MEPDG	United States	McDonald and Madanat [42]
Asphalt layer and granular layer	Develop a method considering fatigue and rutting failures	• Layer thickness • Modulus of layers • Wheel spacing • Tire pressure	• FORM	• MEPDG	United States	Luo et al. [43]
Asphalt concrete pavement	Develop reliability design of pavement thickness	• Fatigue • Rutting	• MC simulation	• MEPDG design guideline	India	Kalita and Rajbongshi [44]
Aggregate blending	Predict proportions of three aggregate types	• Material cost • Plasticity index • Fineness modulus • Gradation	• Fuzzy optimization	• Agency specifications	United States	Kikuchi et al. [45]
Aggregate blending (Superpave)	Predict proportions of three aggregate types	• Closeness to upper, lower, and middle specifications	• Stochastic Optimization	• Agency specifications	Canada	Easa [46]
Aggregate structure (Superpave)	Evaluate performance of aggregate structure	• VMA, VFA, %G_{mm}@N_i and DP	• FOSM	• Agency specifications	Canada	Easa [47]
Asphalt mixtures (Superpave)	Determine optimum asphalt content	• Volumetric criteria • Flow, stability, unit weight	• FOSM • MC simulation	• Agency specifications	Canada	Easa [48]
Design asphalt mixture (Superpave)	Evaluate moisture susceptibility	• Tensile strength ratio	• FOSM	• Agency specifications	Canada	Easa [49]
Pavement alternatives for maintenance	Model life-cycle sustainability assessment for pavement alternatives	• Cost analysis • Environmental assessment • Social assessment	• Life-cycle cost analysis	• MEPDG • UNEP / SETAC Guideline	China	Zheng et al. [50]
Three-layer asphalt concrete pavement	Perform pavement design using reliability approach	• Elastic moduli • Poisson's ratios • Layer thickness • Wheel spacing • Tire contact pressure	• MC Simulation	• IRC: 37-2001	India	Dilip and Sivakumar Babu [51]
Three-layer asphalt concrete pavement	Perform reliability analysis for design of flexible pavements	• Elastic moduli • Poisson's ratios • Layer thickness • Wheel spacing • Tire contact pressure	• FORM • SORM • MC simulation	• Agency specifications	India	Dilip et al. [52]
3-layer asphalt concrete pavement	Design a reliability-based approach for pavement rehab	• Rehabilitation time • Rehabilitation budget • Rehabilitation cost	• Multi-criteria genetic optimization	• Agency specifications	United States	Deshpande et al. [53]

AASHTO = American Association of State Highway and Transportation Officials, AFOSM = advanced first-order second-moment, Caltrans = California department of transportation, DP = dust proportion, FORM = first-order reliability method, FOSM = first-order second-moment, IRC = Indian roads congress, LC = life-cycle, MEPDG = mechanistic-empirical pavement design guide, MC = Monte Carlo, SETAC = Society of Environmental Toxicology and Chemistry, SORM = Second-Order Reliability Method, UNEP = United Nations Environment Programme, VMA = Voids in mineral aggregate, VFA = Voids filled with asphalt, and %G_{mm}@N_i = max. density at N_i.

Table A3. Characteristics of air transportation applications.

System Element	Analysis Objective	Performance Criterion	Analytical Tool	Specification/ Code	Country/ Region	Reference
Route planning in terminal	Perform PB analysis for routes sequencing	• Airline direct operating cost • Flight time reduction	• Relative position indicator tool	• Roadmap for PBN	United States	MacWilliams and Porter [55]
Terminal system	Evaluate PBN of TSS	• RNP and RNAV • Learning effects • Controller's feedback	• Air traffic control simulation	• FAA Next Generation	United States	Thippavong et al. [56]
Terminal operation	Assess SID and STAR using PBN procedure	• SID • STAR	• TARGETS software	• PBN Manual	United States	Timar et al. [57]
AFCS	Model the FTE of AFCS	• Lateral FTE	• MC simulation	• PBN manual	China	Zhao et al. [58] and Zhao et al. [59]

AFCS = Automatic Flight Control System, FAA = Federal Aviation Administration, FTE = flight technical error, MC = Monte Carlo, PBN = performance-based navigation, RNP = required navigation performance, RNAV = area of navigation, SID = standard instrument departure, STAR = standard terminal arrival, and TSS = terminal sequencing and spacing.

Table A4. Characteristics of water-structures design and operation applications.

System Element	Analysis Objective	Performance Criterion	Analytical Tool	Specification/ Code	Country/ Region	Reference
Channel cross section	Perform reliability-based design of channel cross section	• Channel capacity/runoff	• FOSM	• Agency specifications	Canada	Easa [62]
Channel cross section	Perform reliability-based design of channel cross section with multiple failure modes	• Channel capacity/runoff • Maximum velocity • Minimum velocity	• AFOSM for multi-failure modes	• Agency specifications	Canada	Easa [63]
Port dredging	Incorporating uncertainty dredge production	• Volumetric flow rate/load • Solids flow rate/load	• FOSM	• Agency specifications	United States	Scott [64]
Channel cross section	Perform reliability-based design	• System capacity reliability index	• FORM method	• Agency specifications	Australia	Xu and Goulter [65]
Water distribution network	Estimate water leakage for monitoring area	• Leakage rate	• Leak detection algorithm	• Agency specifications	United States	Buchberger and Nadimpalli [66]
Water distribution network	Determine optimal design and rehabilitation	• Modified resilience index	• Genetic optimization	• Agency specifications	India	Jayaram and Srinivasan [67]
Breakwater	Design breakwater with optimal wave height/return period	• Sliding distance • Total cost	• MC simulation	• Agency specifications	Japan	Goda and Takagi [68]
Breakwater	Perform PBD for coastal structures considering spread parameter	• Spread parameter	• MC simulation	• Agency specifications	Japan	Goda [69]
Breakwater	Perform PBD considering climate change effect	• Total sliding distance • Probability of exceeding sliding distance each year	• MC simulation	• JPHA and OCDI standards	Japan	Suh et al. [70]
Breakwater	Perform PBD considering climate change effect	• Total sliding distance	• Spectral wave model	• Agency specifications	Japan	Takagi et al. [71]
Earth-dams/embankment	Estimate seismic-based PBD	• Seismic coefficient	• Pseudo-static analysis	• ICOLD guide	Greece	Papadimitriou et al. [72]
River	Estimate optimal outflows that best match observed ones	• Outflow criterion • Storage criterion	• Multi-criteria optimization	• Agency specifications	Canada	Easa [73]
Ice-covered cross section	Perform reliability-based design of best hydraulic section	• Hydraulic efficiency reliability index	• FOSM • MC simulation	• Agency specifications	Canada	Easa [74]

AFOSM = advanced first-order second-moment, FORM = first-order reliability method, FOSM = first-order second-moment, ICOLD = International Commission on Large Dams, JPHA = Japan Port and Harbor Association, MC = Monte Carlo, OCDI = Overseas Coastal Area Development Institute of Japan, PBD = performance-based design.

Table A5. Characteristics of landfill design applications.

System Element	Analysis Objective	Performance Criterion	Analytical Tool	Specification/ Code	Country/ Region	Reference
Three cover systems and five base systems	Develop design matrix for PBD of landfill	- Leachate leakage rate - Maximum chloride concentration	GIS, simulation models (Visual HELP, VADSAT)	Agency specifications	Turkey	Tarhan and Ünlü [76]
Bottom liners (geomembrane, clay, composite)	Conduct PBD of landfill liners	- Leakage rate - Solute flux	1D advection–dispersion reaction model	Agency specifications	Japan	Katsumi et al. [77]
10 GCLs	Develop PB criterion to assess landfill GCL	- Swell index - Cation exchange capacity - CaCO₃ level	Oedo-permeameter test	Agency specifications	France	Guyonnet et al. [78]
Closed landfill	Design post closure care of landfill	Leachate, gas, and groundwater monitoring data	Analytical modules (leachate, gas, groundwater)	USEPA 2008	United States	Morris and Barlaz [79]
Stabilized-waste disposal sites	Estimate impact of waste disposal on groundwater	Peak aquifer concentration	Numerical models (CONFINE and MARTHE)	Agency specifications	France	Guyonnet et al. [80]
Compacted clay liners (CCL)	Determine CCL effective thickness	- Hydraulic measure - Saturation depth of compacted soil	HYDRUS-1D	USEPA 1995	Iran	Safari et al. [81]

GCL = geosynthetic clay liner, GIS = geographic information system, HELP = hydrogeologic evaluation of landfill performance, MARTHE = modelling aquifers with an irregular rectangular grid, transport, hydrodynamics and exchanges, and USEPA = United States Environmental Protection Agency.

Table A6. Characteristics of building architectural design for evacuation applications.

System Element	Analysis Objective	Performance Criterion	Analytical Tool	Specification/ Code	Country/ Region	Reference
Building floor with 1800 m ² and four exits	Estimate building evacuation time	- Evacuation time - Exist flow capacity	GridFlow model	UK prescriptive guidance	United Kingdom	Bensilum and Purser [82]
21-storey hotel building two major exits	Conduct PB analysis	Evacuation time	Two egress models	Hotel / motel fire statistics	United States	Kuligowski and Milke [83]
Tianjin Olympic Stadium	Perform PB analysis of stadium egress	- Evacuation time - Stranded crowd number	Stranded-crowd model	Design code for sports building for China	China	Zhang et al. [84]
Different building floor plans	Perform PBD of building exits	- Exit separation - Exit width - Evacuation time	Cellular automata model	Building Fire Protection Code (GB)16-87)	China	Zhao et al. [85]
Atrium Perform	PBD of atrium	Safety egress time	EVACNET4 model	Agency specifications	China	Wang et al. [86]
College Library	Perform PBD of library	Safety egress time	Fire simulator	Design codes, fire guidelines	China	Ma et al. [87]
21-storey high-rise building	Perform PBD of building	Safety egress time	FDS-EVAC software	NFPA, National Standards	Indonesia	Sujatmiko et al. [88]
National Gallery	Conduct PB fire safety analysis	Evacuation time	EVACNET+ model	Agency specifications	Australia	Johnson et al. [89]

ASET = available safety evacuation time, and RSET = required safety egress time.

Table A7. Characteristics of urban energy design applications.

System Element	Analysis Objective	Performance Criterion	Analytical Tool	Specification/ Code	Country/ Region	Reference
A multi-floor radiant slab cooling system	Evaluate the optimal building energy performance	Indoor temperature	- DOE-2 simulation model - EnergyPlus V2.0	- IPMVP - US DOE FEMP	Canada	Tian and Love [90]
Urban 3D building form model	Determine the optimal geometry of building clusters	- Integral energy concept - Induced energy demand - Solar access - Renewable supply	- Google Sketch-up - DIN V 18599 - INSEL meteorological database	Effizienzhaus	Germany	Eicker et al. [91]
Window size and glazing material	Minimize the annual energy use and maximize the occupied area of the residential unit	- Annual energy cost - Percentage of the area with daylight illuminance level	Nondominated Sorting Genetic Algorithm-II	LEED Version-4 Daylight Option-2	USA	Asl et al. [92]

Table A7. Cont.

System Element	Analysis Objective	Performance Criterion	Analytical Tool	Specification/ Code	Country/ Region	Reference
A single room model in a multi-storey building	Enhance building energy performance	Electricity consumption of cooling, heating and lighting.	- Multi-objective particle swarm optimization - EnergyPlus	Agency specifications	Iran	Delgarm et al. [93]
Reference buildings for hospital	Develop robust cost-optimal energy retrofit solutions for buildings	- Energy retrofit measure - thermal energy demand	- Multi-stage and multi-objective optimization - EnergyPlus	- Delegated Regulation (EU) No. 244/2012 - EPBD 2010/31/EU (EPBD Recast)	Italy	Ascione et al. [94]
A building information model	Integrate building performance assessment into design stages	- Heat losses (windows, walls, roofs and floors) - Lighting power - Solar gains - Ventilation - Internal gains	Design Performance Viewer	German Energy Savings Regulation EnEV	Switzerland	Schlueter and Thesseling [95]

Effizienzhaus = Energy efficiency standard of Kreditanstalt für Wiederaufbau (German credit institute for reconstruction), EPBD = Energy Performance of Buildings Directive, FEMP = Federal Energy Management Program, IPMVP = International Performance Measurement and Verification Protocol, LEED = Leadership in Energy and Environmental Design.

Table A8. Characteristics of building earthquake-based design applications (traditional structures).

System Element	Analysis Objective	Performance Criterion	Analytical Tool	Specification/ Code	Country/ Region	Reference
RC beam	Perform PBD of RC beam under impact	- Collision energy - Time response - Max. displacement, other	Low speed impact tests (experiment)	Agency specifications	Japan	Tachibana et al. [5]
Building on a stiff soil	Estimate displacements in building frames	Ratio of mean inelastic to mean elastic displacement	SDOF system	- FEMA 222A - FEMA 273 - FEMA 274	United States	Whittaker et al. [104]
Wood shear walls (WSW)	Develop PB framework for WSW using reliability analysis	Peak displacement (for seismic weight)	Partially-coupled reliability model	- Uniform building code - NEHRP guide	United States	Rosowsky [105]
Multi-storey steel moment frame	Assess earthquake resistant capacity of a building frame	- Plasticity-factor - Elastic geometric stiffness	Pushover analysis	- FEMA 273 - FEMA 274	Canada	Hasan et al. [106]
Three-storey steel moment frame	Perform PBD sensitivity analysis of inelastic SMF	- Roof displacement - Inter-storey drift - Plasticity factor	Pushover analysis	FEMA 273	Canada	Gong et al. [107]
RC portal frame	Perform PBSO of beam steels and column steels	Roof Displacement	FE software (DRAIN-2DX)	- FEMA 273 - FEMA 274 - ACI building code	United States	Ganzerli et al. [108]
10-storey, two-bay concrete frame	Perform PBD of RC frames	- Inter-storey drift - Material cost - Damage loss	- Multi-criteria optimization ϵ-constraint method	Chinese seismic design code	China	Zou et al. [109]
Three-storey and nine-storey steel frame	Perform PBD of steel frame	1st order elastic 2nd order geometric stiffness - Plasticity index	- Pushover analysis - Colony optimization - Genetic algorithm	- FEMA-273 - FEMA-350	Iran	Kaveh et al. [110]
Shear Wall	Perform PBSO of wood frame building	Displacement	- SDOF system - CASHEW model	- FEMA - Uniform building code	United States	Filiatrault and Folz [111]
Multi-storey RC frame building	Model structural response of residual deformations	- Residual deformation damage index - Performance index	- SDOF system - MDOF system	- NEHRP - SEAOC Vision 2000	New Zealand	Christopoulos et al. [112], Pampanin et al. [113]
Four-storey RC building	Perform PBSO of RC building	Target displacement	- Direct displacement model - DRAIN-2D	FEMA 273	Taiwan	Xue and Chen [114]
Five-storey frame structure	Perform PBSO with residual deformations	Residual displacement	- SDOF system - MDOF system	International building code	Canada	Christopoulos and Pampanin [115]

Table A8. Cont.

System Element	Analysis Objective	Performance Criterion	Analytical Tool	Specification/ Code	Country/ Region	Reference
Two-storey special moment frame	Perform PBD of structural/ non-structural elements	- Inter-storey drift angle - Peak floor acceleration	- Inelastic time-history analysis - Genetic algorithm	- FEMA 350 - HAZUS	United States	Rojas et al. [116]
Three-storey, three-bay RC frame	Perform PBD of FRP seismic retrofit	- Material cost - FRP Jacket thicknesses	Optimality criteria approach	Chinese seismic design code	China	Zou et al. [117]
Two-storey and six-storey RC frames	Perform PBSO of RC structures	Maximum inter-storey drift	- Nonlinear response analysis - OpenSEES software	- ATC 40 - FEMA 356	Greece	Fragiadakis and Papadrakakis [118]
Three-steel plate shear wall	Perform PBD of column demands in steel plate shear walls	- Roof deflection - Yield displacement - Ductility factor	Pushover analysis	- NBCC - CSA S16 - AISC 341 - AISC 360	Canada	Moghimi and Driver [119]
Four-storey truss frame building	Perform PBD and of buckling- restrained frame	- Collapse probability - Inter-storey/roof drifts - Collapse ratio, other	- Pushover analysis - Incremental dynamic analysis	FEMA P695	Thailand	Wongpakdee et al. [120]

ACI = American Concrete Institute, AISC = American Institute of Steel Construction, ATC = Applied Technology Council, CASHEW = Cyclic Analysis of SFear Walls, CSA = Canadian Standards Association, FEMA = Federal Emergency Management Agency, FRP = fiber-reinforced polymer, MDOF = multi degree-of-freedom, NBCC = National building code of Canada, NEHRP = National Earthquake Hazards Reduction Program, PBSO = performance-based seismic design, RC = reinforced concrete, and SDOF = single degree-of-freedom.

Table A9. Characteristics of building earthquake-based design applications (special structures).

System Element	Analysis Objective	Performance Criterion	Analytical Tool	Specification/ Code	Country/ Region	Reference
30-storey coupled wall structure	Perform PBD of high-rise coupled wall systems	Normalized base shear	- Pushover - NL time history (RUAUMOKO)	- FEMA 356 - ASCE 7–02 - ACI 318–02, other	United States	Harries and McNeice [121]
40-storey tower with three-level parking	Assess serviceability of ductile concrete core wall building	- Response spectra - Inter-storey drift - Wall shear/ moment	Linear elastic analysis (CSI ETABS)	Agency specifications	United States	Klemencic et al. [122]
Cultural heritage structures	Assess vulnerability and design strategies for cultural heritage	Displacement	NL static pushover analysis	- FEMA 356 - Italian code 2008, other	Italy	Lagomarsino et al. [123]
Cladding wall panels	Perform PBD for cladding wall panels subjected to blast load	- Scaled distance - Probability of exceeding limit state	MC simulation	- ACI Building Code - Eurocode 2	United Kingdom	Olmati et al. [124]
Diaphragm wall	Perform PBSO for flexible earth-retaining diaphragm walls	Wall top displacement	- MC simulation - NL dynamic model	Eurocode 8	Italy	Franchin and Cavalieri [125]
Multi-storey/ arched frame structures	Perform PBD of steels structure exposed to fires	- Horizontal/vertical displacement - Exposure time	Radiation fire model (SINTEF)	BSI BS5950 Parts I and 8	Singapore	Liew et al. [126]
Residential wood-frame building	Perform PBD of building against flood hazard	- Flood depth - Damage percentage	MC simulation	- ASCE-7 - FEMA-15	United States	Taggart and van de Lindt [127]
High-volume fly ash concrete	Perform PBD for concrete with high fly ash content	- Porosity - Carbonation depth	- Porosity measurements - Accelerated carbonation tests	- AFPC-AFREM, - EN 206-1 Standard	France	Younsi et al. [128]
75 concrete-filled steel columns	Perform fire resistance design for concrete-filled steel columns	Fire resistance time	Design equation for fire resistance	- CAN/CSA - ASTM E119-88 - NBCC, other	Canada	Kodur [129]
Four-bay three-storey, five-bay nine-storey steel frames	Perform PBSO of steel frames	Base shear	- Pushover - Charged system search optimization	AISC code	Iran	Kaveh and Nasrollahi [130]
26-storey steel-frame building	Perform PBD with semi-active structural techniques	- Seismic stress - Deformation - Acceleration	Seismic response analysis	Agency specifications	Japan	Kurata et al. [131]

Table A9. Cont.

System Element	Analysis Objective	Performance Criterion	Analytical Tool	Specification/ Code	Country/ Region	Reference
Concrete-filled steel tube (RCFT)	Perform PBD of RCFT and beam-columns	- Deform. damage - Energy damage - Ductility	FE analysis	- FEMA 273 - FEMA 350	United States	Tort and Hajjar [132]
Firm soil site	Estimate exceedance of max. inelastic displac. (MID) demand	Maximum inelastic displacement	SDOF system	FEMA 356	United States	Ruiz-García and Miranda [133]
Masonry Infill Walls	Design RC building with consideration of infill walls	- Target displacement - Peak ground acceleration	- NL analysis - Genetic algorithm	- FEMA 227 - FEMA 273 - FEMA 350 - FEMA 356	Greece	Lagaros et al. [134]
20-storey steel/ RC moment frames	Perform PBD for earthquake-resistant structures	- Target drift - Yield mechanism	- Pushover analysis - Time history analyses	- FEMA - ASCE 7-05 - ACI 318R-05	United States	Goel et al. [135]
Nine-storey moment frame building	Perform PBD of magnetorheological dampers	Max. inter-storey drift	Multi-criteria genetic optimization	- FEMA 350 - FEMA 356 - FEMA 450	United States	Cha et al. [136]
Four-bay three-storey, five-bay nine-storey steel frame	Perform PBSO for steel frames	Roof drift	- Pushover analysis - Colliding bodies optimization	FEMA 350	Iran	Veladi [137]
Two-storey, six-storey and 12-storey frames	Perform PBSO of controlled rocking steel braced frames	- Peak drift - Global uplift - Residual displacement - Post-tensioning strain	SDOF system	FEMA P695	Canada	Wiebe and Christopoulos [138]

ACI = American Concrete Institute, AISC = American Institute of Steel Construction, ASCE = American Society of Civil Engineers, BSI = British Standards Institute, EN = European Standards, FE = finite element, FEMA = Federal Emergency Management Agency, MC = Monte Carlo, NBCC = National Building Code of Canada, PBSO = performance-based seismic design, NL = nonlinear, RC = reinforced concrete, and SDOF = single degree-of-freedom.

Table A10. Characteristics of building wind-based design applications.

System Element	Analysis Objective	Performance Criterion	Analytical Tool	Specification/ Code	Country/ Region	Reference
30-storey steel frame building	Perform PBD of tall buildings with extreme wind load	Inward and outward pressure	- MC simulation - Wind tunnel testing	ASCE 7-95	United States	Jain et al. [4]
20-storey RC building	Perform PBD of RC structures (stationary wind)	- Displacement - Stiffness	Bouc-Wen MDOF hysteretic system	Agency specifications	Brazil	Beck et al. [139]
45-storey building	Perform PBD of wind-excited building systems	Inter-storey drift	Auxiliary variables vectors optimization	- ASCE 7-10 - FEMA 273 - FEMA 445	United States	Spence and Kareem [140]
High-rise building	Perform PBD of high-rise building with human comfort	Human comfort	- Wind tunnel tests - MC simulation	- Japan Arch. Institute code - ISO 10137	United States	Bernardini et al. [141]
5-MW Wind Turbine	Perform PBD of a wind turbine tower	- Probability of failure - Fatigue life (years)	- Time-domain analysis - FE model	FAST or ADAMS codes	United States	Do et al. [142]
40-storey building	Perform PBD of tall framed structure with wind excitations	- Inter-storey drift ratio - Lateral displacement	- Wind tunnel test - pushover analysis	Hong Kong code of practice	Hong Kong SAR	Huang et al. [143]
45-storey tall steel frame	Perform PBD of wind resistance for tall buildings	- Stiffness - Vibration	- Multi-criteria optim. - MC simulation	AISC code	China	Li and Hu [144]
50-storey RC building	Perform PBSO of irregular tall building	- Lateral displacement - Drift ratio - Shear/axial forces - Chord rotation	- Wind tunnel model - elastic seismic - time history analysis	Seismic design and Turkish earthquake codes	Turkey	Özüygür [145]

ASCE = American Society of Civil Engineers, FE = finite element, FEMA = Federal Emergency Management Agency, MDOF = multi degree-of-freedom, PBSO = performance-based seismic design, and RC = reinforced concrete.

Table A11. Characteristics of bridge design and management applications.

System Element	Analysis Objective	Performance Criterion	Analytical Tool	Specification/ Code	Country/ Region	Reference
Steel-arch bridges	Perform PBD for steel-arch bridges	Displacement	Inelastic NL analysis	AASHTO-LRFD	South Korea	Kim et al. [146]
RC concrete bridge	Perform PBD using damage/loss limit states	- Peak ground acceleration - Arias intensity - Displacement - Pseudo-spectral acceleration	Uncertainty analysis of damage and loss to structure	FEMA	United States	Mackie and Stojadinović [147]
Two-span non-skewed bridge	Estimate abutment backfill force-displacement capacity	- NL displacement - Force displacement Response	Hyperbolic stress-strain model	Caltrans	United States	Shamsabadi et al. [148]
Carbon FRP	Perform PBSD for bridge retrofit using CRFPs	Displacement Ductility	3D FE model - dynamic tests	CHBDC 2000	Canada	Roy et al. [149]
Two-span bridge with four soil types	Perform PBSD of bridge with ground-foundation interaction	- Lateral deformation - Residual displacement	- OpenSees - NL time history analysis	Caltrans seismic design criteria	United States	Mackie et al. [150]
Bridge with multi-column bents	Perform PBSD of bridge using different retrofit techniques	- Shear capacity/demand ratio - Residual displacement - Energy dissipation capacity	TOPSIS method	FEMA P695	United States	Billah and Alam [151]
Bridge RC columns	Perform PBD of RC columns with vehicle collisions	- Dynamic shear force demand - Fragility of velocity and mass	FE analysis (LS-DYNA)	AASHTO-LRFD	United States	Sharma et al. [152]
Four-span highway bridge	Perform PBSD for bridge designed according to CHBDC	- Damage response factor - Force-displacement - PGA-displacement response	NL monotonic static analysis	CHBDC	Canada	Sheikh and Legeron [153]
Reinforced concrete bridge	Estimate time-dependent reliability and residual service	- Durability failure of reinforcement - Reliability index	MC simulation	Specifications for corrosion durability	Australia	Zhu et al. [154]
Pre-stressed concrete HSR bridge	Perform PBA to predict bridge service life	- Bridge deflection - Reliability index	- J.C. reliability method - RS method, FE	Chinese design code	China	Guo et al. [155]

AASHTO = American Association of State Highway and Transportation Officials, Caltrans = California Department of Transportation, CHBDC = Canadian Highway Bridge Design Code, FRP = fiber-reinforced Ppolymer, LRFD = load and resistance factor design, NL = nonlinear, PBSD = performance-based seismic design, PGA = peak ground acceleration, RS = response surface, and TOPSIS = technique for order preference by similarity to ideal solution.

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