IALA GUIDELINE

GNNNN
SUSTAINABLE STRUCTURAL DESIGN OF MARINE AIDS TO NAVIGATION

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1. BACKGROUND

Recommendation *R1018 Responsible Design, Operation and Maintenance in the Provision of Marine Aids to Navigation* [1] states that Marine Aids to Navigation (AtoN) managers should:

- Implement systematic procedures for AtoN to meet or exceed the required performance.
- Use appropriate design and building codes and sound engineering principles to ensure fit for purpose assets.
- Seek to reduce environmental impact and improve safe working environments.

Undertaking AtoN design that complies with relevant national and international design regulations, codes, standards and best practice guidelines is considered fundamental to help achieve these recommended aims.

The complexity of AtoN design depends on various factors including focal height, foundation conditions and environmental loadings. It is important that the design complies with the regulations, codes, standards and guidelines, applicable for the geographical region and that these are incorporated into AtoN design and construction. It is particularly important in countries with extreme climatic conditions such as cyclones, extreme waves, or seismic induced activity, that AtoN are designed for relevant environmental conditions.

It is important that the AtoN manager understands:

- The requirement for and benefits of, appropriate AtoN structural design, using geographically appropriate design criteria.
- The value of identifying and providing clear AtoN structural design requirements that can be understood by suppliers and held with the AtoN records. This is referred to as “requirement traceability” in Guideline *G1033* [2].
- When there may be a need to request appropriately qualified assistance, to undertake the structural design and construction of new AtoN or structural assessment of existing AtoN.
- The structural engineering design and assessment of AtoN should be undertaken by engineers with the relevant qualifications and design experience, appropriate to the AtoN complexity and environmental setting.

Please note that definitions of various design guidance documentation are included in section 7.1 but for simplicity, within this Guideline the terms codes, regulations, guidelines and standards will be referred to collectively as codes, unless being described separately.

2. PURPOSE

The purpose of this Guideline is to help the AtoN Manager:

- Understand the elements of AtoN structural design and assessment.
- Understand how structural design is undertaken in practice by illustrating some practical applications of design codes.
- Acknowledge where the complexity of the proposed AtoN structure requires external design assistance by appropriately qualified professionals.
- Develop a basis of design, with stated design life and appropriate levels of environmental conditions.
- Feel confident to discuss the structural design principles of AtoN with external designers and suppliers and be able to ask appropriate questions regarding the suitability of design proposals.

The Guideline should also provide reassurance to external AtoN service providers and suppliers that AtoN managers understand the principles and application of structural design codes, thus facilitating good technical communication and the global implementation of harmonized AtoN solutions.

3. SCOPE

3.1. WITHIN SCOPE

This Guideline covers the principles of structural design and construction of new or appraisal of existing fixed AtoN. There are several other guidelines that provide specific technical information on detailed light and floating AtoN design and these are listed in the References or Further Reading sections.

This Guideline introduces the generic elements of AtoN structural design and provides guidance to the AtoN manager when checking that AtoN will be designed and constructed to appropriate design and construction codes.

It is anticipated that this generic Guideline could also be used as a basis for providing further regional guidance for cyclonic regions. The regional guidance could describe the specific design codes used in the design and construction of typical AtoN and replicate the generic figures from this Guideline, with regionally applicable information. A proposed framework for regionally applicable information is detailed in **Erreur ! Source du renvoi introuvable.**.

3.2. OUTSIDE SCOPE

Detailed guidance for the structural engineering design of major AtoN structures is beyond the scope of this Guideline.

This Guideline does not cover:

- The design of buildings such as VTS centres (although many of the structural design principles discussed will be applicable to the design of buildings).
- The design of floating AtoN. Guidance on the design of floating AtoN and their moorings can be found in other IALA guidelines including *G1066 The Design of Aid to Navigation Moorings* and *G1099 The Hydrostatic Design of buoys*.
- The design of light vessels or other major floating aids (see *R1001 The IALA Maritime Buoyage System* [3] for distinction between major and minor floating aids)
- Cladding or renovation of historic lighthouse structures.
- Inspection or maintenance or AtoN. Extensive detail can be found on these topics in Guideline *G1151 Maintenance of AtoN Structures* [11].
- Methods of determining functional AtoN light requirements such as colour, characteristic and visibility. Extensive guidance can be found in IALA documentation associated with Standard *S1020 AtoN Design and Delivery* [35]
- Radio navigation equipment siting and licensing requirements.
- Electrical and other utility infrastructure.
- National or local, terrestrial or marine planning requirements.

The principles of good structural engineering design practice detailed in this Guideline do apply however, irrespective of the item being designed. The structural engineering design of any AtoN infrastructure should be undertaken for the relevant environmental setting and using recognised codes. The Further Reading section also list several sources of reference that the reader can gather further information on the topics listed above.

4. THE ATON STRUCTURAL DESIGN PROCESS

4.1. THE OUTLINE PROCESS

The structural engineering design of new (or assessment of existing) AtoN includes consideration of characteristics including function, durability, sustainability, safety and quality. It is important that the AtoN manager is aware of how these characteristics are considered and appraised through the design process. They help form a checklist for design that the AtoN manager can discuss with suppliers, consultants and contractors to ensure a sustainable design approach will be taken. These characteristics are discussed in further detail in the following sections, with reference to additional IALA recommendations and guidelines.

Figure 1 summarizes the process and highlights key documentation that is produced or referenced during the process, with the relevant reference to the sections of this document...

Key design information includes:

- *AtoN manager's requirements (initial Basis of Design)* - The provision of clearly written functional and performance requirements means that the AtoN manager can be sure, based on the designer's completed Basis of Design (see below) whether the structural design satisfies the requirements. The AtoN manager may also provide the designer with site information such as geotechnical surveys, meteorological and hydrographic data.
- *Design codes* – these are discussed in greater detail in section 7 but use of the appropriate design codes relevant for the environment and geographical location is essential to producing a sustainable AtoN structural design.
- *Basis of Design* – The Basis of Design is the designer's confirmation of the relevant codes and criteria that they will use in the design. It combines a summary of the AtoN manager's requirements with the appropriate values of design criteria. It is a reference for the designer of the parameters and values of those parameters to be used during the structural design and confirmation for the AtoN manager for future reference.
- *Design output documents* – together with the Basis of Design, these include specification, design drawings, installation instructions, operation manuals and health and safety risk assessments. Together with the appropriate construction codes covering workmanship and site preparation they are used to construct the AtoN. A specification is also a point of reference and ensures clarification on points of subsequent dispute.

With reference to Figure 1, purchase of pre-designed AtoN products such as beacons or lights and light towers will not be subject to the same bespoke design procedure every time the product is purchased. The principles of Figure 1 still apply, however, the AtoN manager must state the requirement and performance criteria through a requirements statement and the supplier should confirm that the products are appropriate for use in the geographical location and when subject to the anticipated environmental loadings for the location.

Structural engineering design should be carried out by suitably qualified and competent engineers who are duly registered with an appropriate professional engineering body.

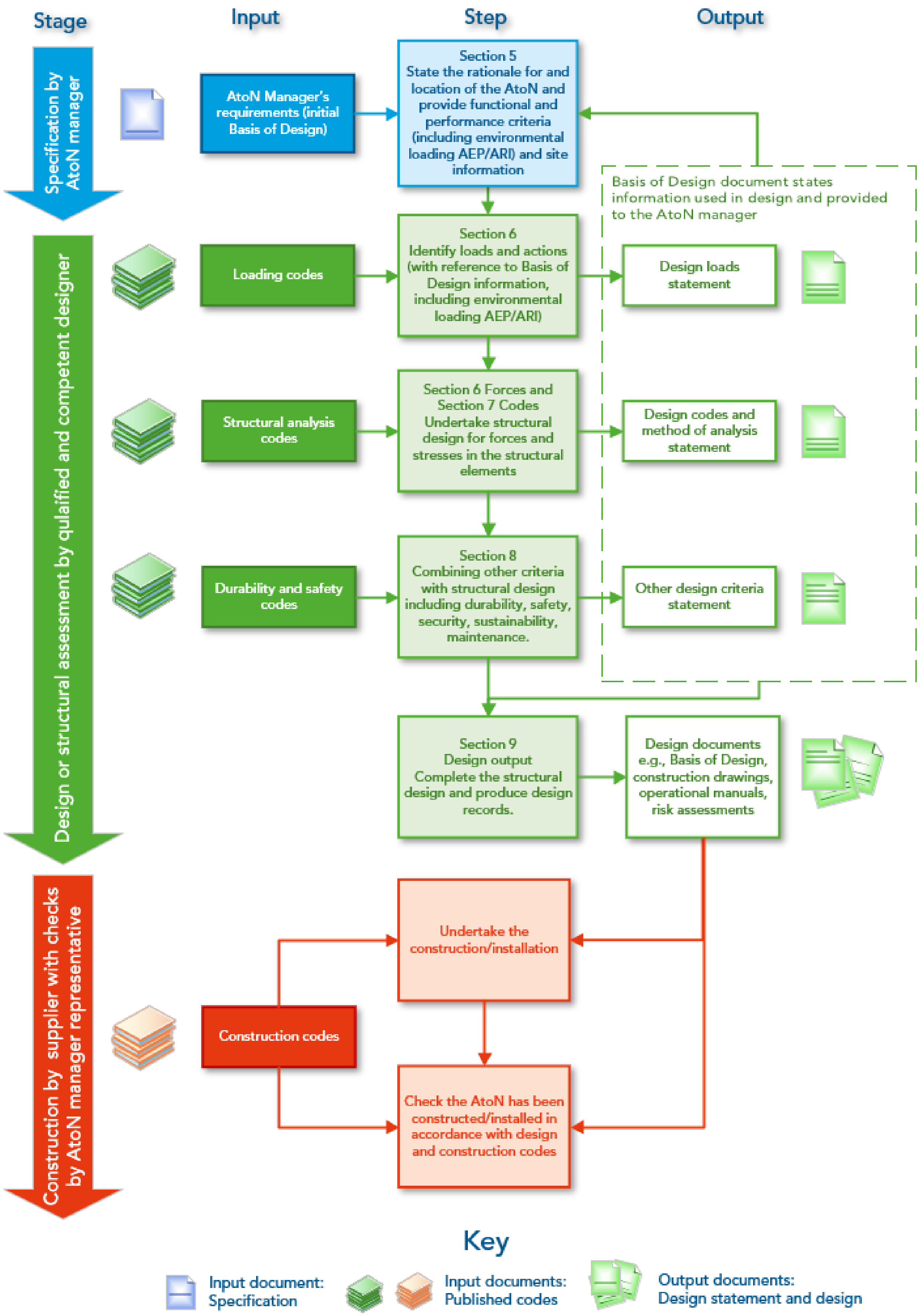

Figure 1 AtoN structural design process

4.2. PRINCIPLES OF QUALITY IN ATON STRUCTURAL DESIGN

4.2.1. QUALITY IN STRUCTURAL DESIGN

The use of the term quality can be open to interpretation. For some, it can mean the quality control of the finished product and for others a measure of how well the finished product meets the client's expectations. It can also be reflected in how easy it is to find operational manuals or drawings, some years after installation. With reference to AtoN structural design, all these aspects apply.

Any project is a balance of cost, time and quality. It may not be cost effective to install the best quality AtoN but it may be applicable to install a fit for purpose AtoN that meets the required design life functional and technical requirements, when assessed under the appropriate codes for its geographical location. Each project will have its specific requirements.

4.2.2. QUALITY MANAGEMENT SYSTEMS

It is recommended that the AtoN manager appoints designers, suppliers or contractors who undertake work within a quality management system (QMS), preferably based on the principles of ISO 9001: 2015 [15] . The principles of such a system include product traceability from design to decommissioning and consistency in their supply. This is particularly reassuring when AtoN managers may be purchasing off the shelf products such as beacons or buoys and expect the same quality of product or service at each purchase.

For bespoke AtoN provision, it is particularly important to have rigorous records of the basis of structural design or structural assessments, design changes, and a set of "as-built" documentation. Suppliers working to a QMS will have procedures for the issue of documentation and a means of document control that ensure the AtoN manager receives the current version of all documents. Further information on the principles and characteristics of a QMS are included in *G1052 Guideline Quality Management in AtoN Service Delivery* [14].

Figure 2 Example of multi-steel piled, concrete light platform with GRP light tower, access ladder and tape wrapped piles within the splash zone

5. BASIS OF DESIGN

One key aspect in achieving quality in AtoN structural design solutions is the presence of a Basis of Design document, including a clear requirements statement supplied by the AtoN manager. This principle is expressed in Guideline *G1133 Requirement Traceability* [2]

5.1. REQUIREMENTS STATEMENT

The purpose of the Basis of Design is to summarize the structural design criteria that has been used during the design. That information includes the AtoN manager's initial functional and operational requirements. Table 2 contains typical information that a designer requires from the AtoN manager to complete the Basis for Design. Please note the table is not exhaustive and there may be other parameters to be considered. If any of the criteria in the table or requested by the designer are unclear, AtoN managers could seek information from the following sources:

- Their organization's strategic investment and maintenance plans and policies regarding, for example, typical design life requirements or annual exceedance probability (AEP) value (see section 6.2.12 for AEP).
- Professional peers in other AtoN authorities may be able to provide information on similar projects (extreme caution should be taken not to purely copy the same figures for another design without justification or understanding about why the values or sources were used and if they are appropriate).
- The AtoN manager's designer again may be able to provide guidance on typical criteria used in similar designs.

Table 1 Typical AtoN manager Basis of Design input parameters

Parameters	Examples
Functional	e.g., focal height, location
Availability	e.g., in accordance with IALA categorization.
Design life	In years. Often informed by organization and/or design codes.
Environmental conditions	e.g., temperature, wave height, wind speed, tidal flow, depth of water, prevailing weather direction, likely extreme events.
Dimensions	e.g., plan dimensions, maximum or minimum height, site constraints, orientation.
Materials	e.g., material grade, type or thickness, paint systems, protective coatings, sustainable sources.
Standards adherence	e.g., design standards, environmental levels of performance (AEP/ARI), specific loadings of e.g., winches, radar equipment, lights.
Site information	e.g., site survey, geotechnical investigation, meteorological/hydrographic information.
Services	e.g., if mains services are available or not.
Safety	e.g., access systems, ladders, safety rails, design for fire, accessibility to public.
Maintainability	e.g., access requirements/frequency, availability of replacement elements.
Third party requirements	e.g., restrictions on height, 24 hour access, ownership of access routes.

It is important that the AtoN manager's requirements are stated, where relevant for all design life stages of the goods or works including commissioning, operation, maintenance and decommissioning.

5.2. SITE INVESTIGATIONS

On more complex AtoN projects, for example, the design of a structural steel or concrete tower with foundations, the AtoN manager may need to provide information about the site to facilitate the design. If the information is not available, the AtoN manager may be required to commission site investigations. Such investigations can include:

- Geotechnical investigation, to establish soil characteristics and ground conditions
- MetOcean study to determine wave, wind, current applicable to the site or to validate modelling.
- Topographical site survey, to establish ground levels and line of sight
- Services investigation, to identify utilities such as electricity or water supply infrastructure that could constrain the design
- Environmental impact assessments, to understand the effects of the installation on the local environment

Regulations, guidelines, standards or model specifications for undertaking geotechnical and topographic surveys are available in many countries and these are written to ensure the output data quality. Environmental impact assessment requirements are often stated within national regulations. It is important at an early stage to establish the required design information and the appropriate codes that should be used for the investigation (if conducted within the AtoN manager's organization) or to specify to a site investigation contractor or consultant.

5.3. BASIS OF DESIGN SUMMARY

For more complex structural designs, once the designer has been appointed and provided with an adequate requirements statement, the AtoN manager can then anticipate the receipt of a Basis of Design from the designer. This document incorporates the requirements of the AtoN manager's requirements statement, states the elements that will be designed and confirms the relevant codes and loadings that will be used in the specific AtoN structural engineering design. The Basis of Design provides confirmation of one of the key requirements of appropriate AtoN structural engineering design, which is, that the geographically appropriate codes have been used to design the AtoN. Section 9 provides more detail.

5.4. FUNCTION

The primary purpose of any AtoN is to provide navigation safety related information to mariners. The type of information provided is derived from the attributes of the AtoN, such as its surface colour, geometrical shape (daytime) as well as the colour and character of its light (during the night). The mariner must be able to detect and understand the signalling information provided within the operational range of the AtoN.

The physical size of the structure, contrast of the surface colour against its surroundings and the intensity of the emitted light in the direction of the mariner determines the visual range. The elevation of the signalling part of the AtoN (focal point) determines the possible geographical (line of sight) range.

The height of an AtoN structure is therefore dictated by its fundamental functional requirement to act as a visible mark (either illuminated or unlit) or as a signal transmitter/receiver. The height of the structure line of sight above land or the seabed therefore will be a prime factor in its overall size and complexity. The level of design complexity will also depend on the structure's foundation requirement and the nature of its environment.

Smaller daymarks in shallow water may require minimal structural design scrutiny by the AtoN manager compared to a larger monopile or a tower structure. Such items may be subject to regular purchase and as such, designed and manufactured to accepted standards. The specific colour, shape and topmark (where relevant) will be selected by reference to the IALA Maritime Buoyage System [3].

For lit AtoN, the focal height of the light source is a critical functional requirement.

With kind permission of Andrew Wallace (left) and Korean Ministry of Oceans and Fisheries (KMOF) (right)

Figure 3 Examples of small pre-fabricated beacons (left) and large, specifically designed leading light tower (right)

5.5. LEVEL OF SERVICE AND AVAILABILITY

Availability, in relation to AtoN, means the probability that the AtoN is performing its function at any time. There are IALA level of service categories for availability, expressed as a percentage of time that the AtoN is performing its function(s). The designation of a category is an indication of the criticality of the function of the AtoN. This in turn will influence the required reliability of the AtoN and the associated maintenance regime (see section 8.3). Guidance on selecting an appropriate category for a new AtoN is provided in Recommendation *R0130 Categorization and availability of Objectives for Short Range Aids to Navigation (0130)*[4].

Other requirement examples provided in Table 1 will be discussed throughout sections 6 to 8.

6. LOADING OF ATON STRUCTURAL ELEMENTS

The structural stability of an AtoN is essential to the functional performance of the AtoN and it is important that structural integrity is assessed through an appropriate design process, with due consideration of cost and environmental impact during the design life of the AtoN.

6.1. ATON STRUCTURAL ELEMENTS

There are common elements for which structural design and specification is undertaken, irrespective of the AtoN geographical location and specific codes used. These include:

- Steel elements, including member cross-sectional area, dimensions and fabrication.
- Concrete elements, including dimensions, strength, concrete durability and reinforcement.
- Timber elements, including dimensions, strength and moisture content.
- Connections between elements including welds and bolted connections.
- Foundations, where the designer considers the underlying soil properties and the ways the combined foundation and soil structure can fail.

The height of the AtoN determines the maximum achievable geometrical range and is a key design parameter that influences the design of the AtoN structural elements.

For AtoN, typical elements that require appropriate design and specification include the following, as illustrated in Figure 4:

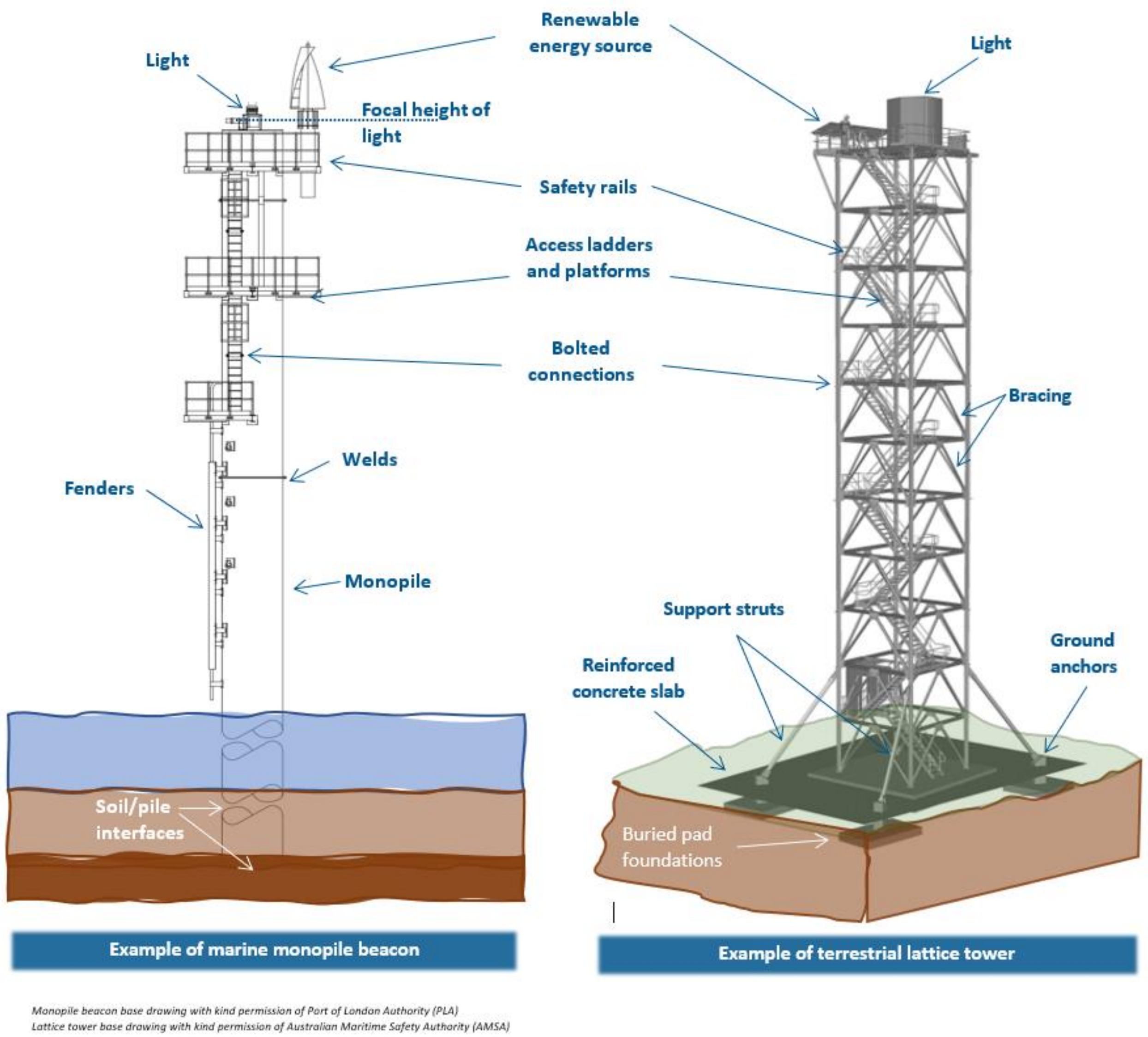

Figure 4 Examples of AtoN design elements - marine monopile beacon and terrestrial lattice light tower

6.1.1. MATERIALS AND THEIR USES IN ATON

The AtoN designer will specify the use of material manufactured to certain quality and safety standards. Table 1 provides examples of materials commonly used in AtoN and the characteristics that are commonly specified through the design process:

Table 2 Materials typically used for AtoNs and their key characteristics

Material	Typical AtoN uses	Key characteristics
Metal **(e.g., mild steel, stainless steel, aluminium)**	– Tower members and fencing – Monopiles – Wires, ropes and tensioners – Connection bolts and welds – Reinforcing bars and mesh – Sacrificial anodes (zinc and magnesium)	– Type and grade (including tensile strength and thermal expansion properties) – Thickness – Weldability – Corrosion potential – Malleability and ductility

Concrete	– Slab foundations
	– Structures
	– Piles (pre-formed and cast in-situ)
	– Marine platforms
	– Pre-cast units e.g., retaining walls, kerb stones
		– Concrete mix i.e., water/cement/aggregate /additive ratio which defines:
		  o Compressive strength
		  o Workability
		– Flexural strength (increased by inclusion of reinforcement)
		– Reinforcement detail and cover to reinforcement

Timber	– Piles – Structural elements of platforms – Protective fenders	– Species – Source – Strength – Moisture content – Resistance to marine boring insects – Abrasion resistance
Plastic and rubber	– Towers – Protective fenders – Insulating material for dissimilar metals	– Strength – Thickness – UV stability for colour integrity and material strength

Protective coatings and systems	– Piles:
	  o Paint
	  o Cathodic protection
	  o Tape wrappings for tidal zone
	– Tower elements and fencing
	  o Paint
	  o Galvanised coating
		– Paint thickness, type and number of coats (paint system)
		– Environmental impact of product
		– Galvanised coating thickness
		– Method of coating application
		– Thickness and placement of tape wrappings

Glass fibre reinforced plastic (GRP)	– Beacons – Modular equipment housings – Walkway gratings	– Strength – Thickness – UV stability

6.2. LOADS, ACTIONS AND FORCES

Irrespective of the specific size, material and structural requirements it is essential that any AtoN structural design considers the loadings to which it will be subject. It is important therefore that appropriate design codes are used (either by the supplier or by the AtoN manager's structural design engineer) and that these will reflect actual loadings and environmental conditions. Not all AtoN designs will require extensive structural load analysis so the level of information that a supplier may provide will be reflective of the complexity of the AtoN.

Loads may be applied statically, for example the self-weight of the structure, or dynamically such as wind action. Dynamic loads can also be cyclical, that is they can be repetitive and regular, such as in the case of wave loading on monopiled structures. The effect of vibrations induced in the structure by such dynamic loads is dependent on the natural frequency of the structure and its ability to dissipate the vibrations. This ability is known as damping.

Wind loading is an important factor to incorporate in the design of AtoN and design standards appropriate to the geographical location should be used. It is also important to design connections for the anticipated loads as these can be the weakest link in the integrity of the structure. For example, a robust tower could withstand high wind loads without deforming, but if the connections to its concrete foundation are insufficient, the structure may fail.

Modern design codes often refer to structural design loadings as "actions". Assessment of the loads listed in the following sections are typically required by most structural design standards, irrespective of the national or international source. Live loads are generally considered as anything other than dead loads, but a third category of environmental loads is often used to describe loadings that may act on a structure because of topographic or climatic conditions. Various codes have rules for the combination of loads in certain scenarios and how these should be applied to the structure in the structural design process.

Any design should incorporate the potential for climate change effects on environmental loads including sea level rise and increased storminess. The Intergovernmental Panel on Climate Change publishes updated assessments every five to seven years on the effects of climate change and many regions base updated guidance for environmental impacts on that guidance. For clarity, environmental loads are described in turn individually in paragraphs 6.2.4 to 6.2.11. The concept of the annual exceedance of probability (AEP) is an important one to understand when specifying the level of environmental loadings for structural design and this is discussed in 6.2.12.

With kind permission of Australian Maritime Safety Authority (left) and Estonian Transport Administration (right)

Figure 5 Examples of marine based AtoN Queensland, Australia (left) and Tallinn, Estonia (right)

6.2.1. LIMIT STATES AND FACTORS

It is useful to clarify some terms that are referred to often in structural design codes, namely ultimate limit state (ULS) and serviceability state. These describe what level of design is being undertaken and for what aspect of the design. Limit state design is a commonly used method of structural analysis

ULS is designing to limit the stresses in the materials to manage the probability of collapse. It involves the inclusion of combinations of safety factors and if all factored stresses are below the calculated resistances, it will satisfy the ULS design. The designer will check the structure for deformation of the structural members or stability, such as buckling of lattice tower structural members.

Serviceability is the design process that manages the probability of the structure remaining fit for purpose without the need for repair. It is about the items that make the structure comfortable for the user or contribute to the durability of the AtoN. Exceedance of a serviceability state limit, therefore, may not result in structural failure but it may make the user experience less satisfactory. For example, certain strength wind loads may not cause a light tower structure to collapse, but it may cause the structural members to deflect sufficiently such that this translates to distracting vibration of the light, if deflection is not limited in the design.

Similarly, cracking in concrete foundations due to insufficient steel reinforcement (used to limit bending of the concrete under tension forces) will not cause immediate structural failure, but will cause deterioration of the structure over time due to the ingress of water and corrosion of the reinforcement. Serviceability loads may be applied with a safety factor of 1.0 (i.e., unfactored), depending on the codes used.

Note the distinction that serviceability, in the context of structural design, is not the same as maintainability. Serviceability is a specific set of structural analysis conditions related to the structure remaining fit for purpose without the need for repair. Maintainability is related to the ease of access and required frequency of repair of a structure. Designing for maintenance is discussed further in section 8.3.

6.2.2. DEAD LOADS/PERMANENT ACTIONS

Dead loads (also referred to as permanent or static loads or permanent actions, depending on the codes) remain relatively consistent over time and include non-structural finishes. The main dead load is the self-weight of the AtoN structure. Dead loads are calculated by calculating the volume of AtoN material and multiplying it by the relevant density of the material.

6.2.3. LIVE LOADS/VARIABLE ACTIONS

Live loads (also referred to as imposed loads or variable actions) are loads created by dynamic forces such as pedestrians or machinery. They are usually temporary, changeable and dynamic. The weight of a maintenance engineer climbing a tower ladder would be considered a live load for the purpose of structural assessments. Live loads can be considered as uniformly distributed over an area, such as a group of engineers standing on a tower platform or as a point load such as the weight of machinery being lowered on a hoist from an AtoN structure.

Lighthouse visitors represent an important live load which must be taken into account.

6.2.4. WIND

Wind loading is an essential environmental load used in AtoN design and is subject to specific and detailed calculation.

Typical design codes provide tables for a design wind speed estimation. These vary due to factors including the surrounding terrain and the geographical location. Alternatively, locally sourced meteorological information may be available for predicted maximum wind speeds. Where the designer has decided to collect wind data, certain standards may specify the methodology for collection.

Maximum anticipated wind speeds are then converted to wind pressure (a force per unit area) which is used to calculate the forces on the AtoN. Calculations for wind pressure consider the shape of the structure (for which a shape coefficient is included in the calculations) and its cross-sectional area.

6.2.5. Snow/Ice floes

In polar regions and areas prone to cold winters, the potential for accumulation of ice or snow on fixed AtoN structures should be considered over the design life of the structure. Both ice and snow can impose additional loading on structures and the potential for additional load should be considered in the design.

Dynamic movement of ice flows can impose multiple point loads on marine based structures, increasing bending moments and creating vibrations, which in turn can affect structural integrity. In addition to additional loading, the movement of ice can degrade the structure material through abrasion and associated material fatigue.

6.2.6. Seismic

Seismic loads are caused by the effects of earthquakes acting on structures. Certain regions of the world are more prone to seismic activity than others. The designer is required to use specific standards to calculate the loads and undertake specific checks. The derived loads are a function of geographical location, the type of structure, the geological conditions and statistical probability factors.

6.2.7. Earth

If certain elements of land based AtoN are designed to retain earth, the loads imposed by the earth should be accommodated in the design of the element. For example, a boundary retaining wall for a tower site or a partially buried pad foundation. The loads imposed by the earth are a function of the soil properties, the retained height of earth and the natural level of water in the ground (the water table level). Consideration is also given to any vertical surface loading of the earth being retained, which is known as surcharge.

Water pressure can exert an uplift force on a structure due to e.g., high rainfall causing clay expansion of the soil. This can be problematic if the upward forces are greater than the forces being exerted downwards by the structure. To overcome this risk, the structure must be appropriately designed to provide greater resistance against uplift forces.

Soil properties and the water table level are a key parameter in calculating the performance of concrete and piled foundations (see 6.2.13).

With kind permission of Estonian Transport Administration (left) and Australian Maritime Safety Authority (right)

Figure 6 Examples of terrestrial based AtoN lights and towers- Panga light beacon, Estonia (left) and Cairncross, Australia (right)

6.2.8. THERMAL

Daily and seasonal thermal changes can affect AtoN materials and an allowance for such effects should be incorporated into the design. This can be particularly important for steel component connections and for composite structures made from dissimilar materials, with differing thermal properties. Thermal differences will be moderated in a marine environment due to the cooling effect of a body of water.

6.2.9. WAVE

When designing marine based AtoN it is necessary to obtain the expected wave loadings as essential information in determining normal and extreme operating conditions. AtoN should be designed to withstand safely the effects of the extreme range of wave conditions expected during the design life of the structure.

For fixed marine AtoN, a design wave with a height and period is considered and used to calculate a force on the AtoN structure. The methodology used in the design calculation is related to the ratio of wave height to the submerged depth of the structure. Wave conditions are also a significant consideration during the installation of marine based AtoN and their consideration should be part of the designer's and marine contractor's risk assessments.

6.2.10. HYDROSTATIC

Marine based AtoN should be designed to withstand safely the effects of the range of water levels from extreme low water to extreme high water expected during the design life of the structure. Hydrostatic pressure is considered to act linearly from a minimum at the water's surface to a maximum at the seabed and is a function of water density and depth.

6.2.11. CURRENT/FLOW/IMPACT

The water loads imposed on marine based AtoN by tidal and wind-derived flows should be considered over the design life of the structure. Forces may act in different directions on a structure over a tidal cycle in a fast-flowing tidal estuary. The loads are a function of water density, water velocity and the shape of the structure. There is a possibility that debris can impact and/or accumulate on structures in estuaries and consideration should be given to the possibility that a "debris mat" can form which can act as an additional point load on a structure.

Although they are not generally also designed to act functionally as a vessel mooring or berthing structure, marine based AtoN can be subject to vessel impact. The risk of such an impact should be considered in the design.

6.2.12. ANNUAL RECURRENCE INTERVAL / ANNUAL EXCEEDANCE PROBABILITY

During the design stage the AtoN manager may be requested to determine the appropriate Annual Recurrence Interval (ARI) or Annual Exceedance Probability (AEP). ARI is the average or expected value of the periods between exceedances of a certain condition (such as wave height and/or wind speed) over a given duration. AEP as a percentage (%) and may be expressed as the reciprocal of ARI, is the probability that a given condition over a duration will be exceeded in any one year.

This is relevant to structural design, the larger the ARI (period between exceedances of a certain conditions) the more extreme the environmental conditions the structure needs to be designed to. When assessing the ARI and AEP, AtoN managers should ensure they understand this risk-based concept and the impact that it can have on the design solutions.

As an example, a structure designed to a 200-year ARI (designed to withstand a 1 in 200-year storm) has an AEP of 0.5%, which therefore means a 0.5% chance each year that the design conditions such as wave height, wind speed etc will be exceeded and chance of damage or failure is likely. Over a 50-year design life this equates to a 25% chance of exceeding the design conditions.

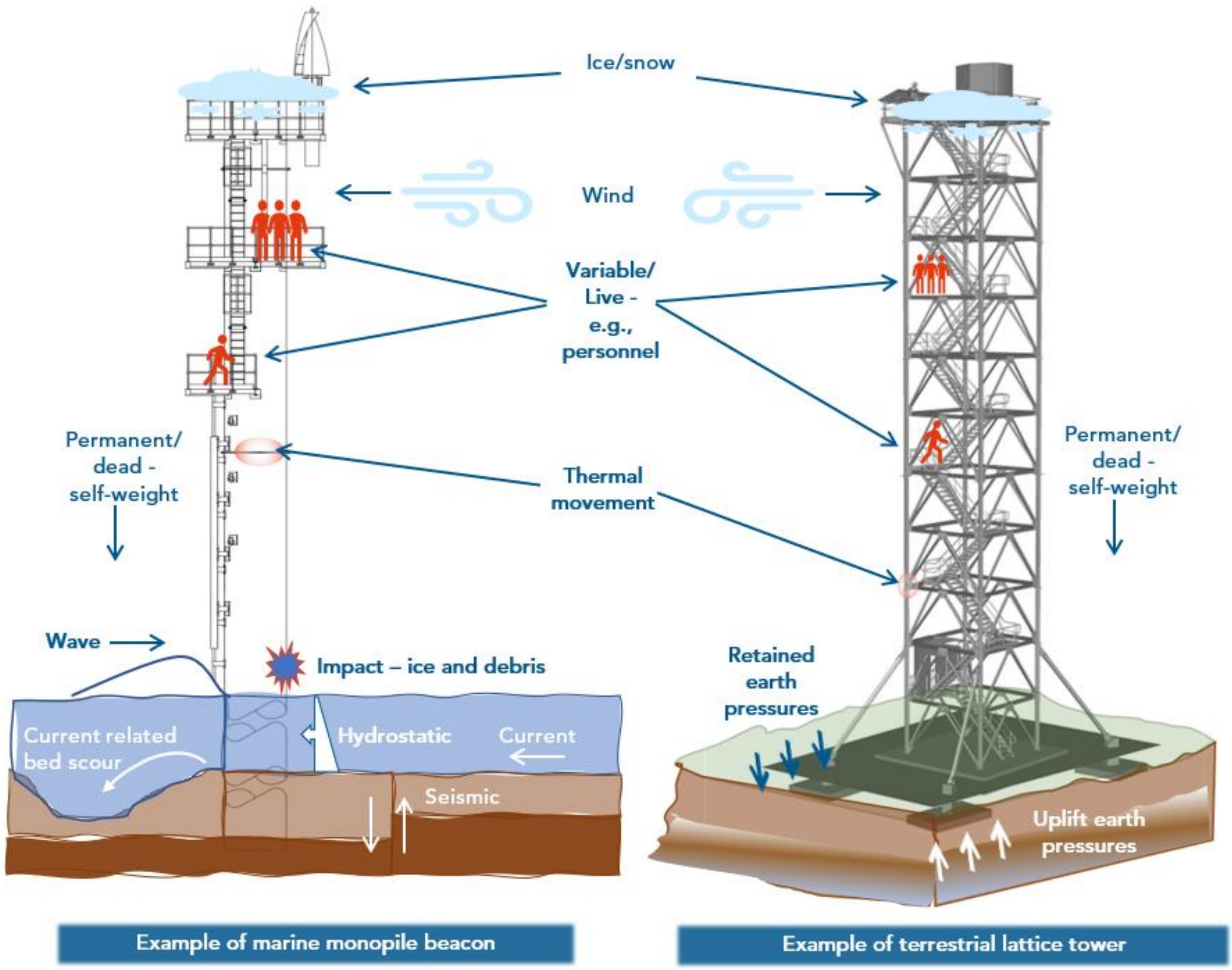

Figure 7 Examples of loads to be considered in AtoN design - marine monopile beacon and terrestrial lattice light tower

6.2.13. FORCES AND REACTIONS

It is useful to state some of the forces that are experienced by AtoN structures under loading, to understand the common load combinations that structural design codes consider. With reference to Figure 8 below:

Compression forces crush a material by squeezing it together. In AtoN, compression may be seen for example, in a buoy being crushed by ice. Concrete is a very strong material when subjected to compression forces.

Tension forces stretch a material by pulling its ends apart. In AtoN, tension forces might be seen by failure of a mooring chain. Concrete is reinforced with steel bars because it is very weak when subjected to tension.

Torsion forces twist a material by turning the ends in opposite directions. In AtoN, this might be observed in a lattice tower secured at four corners on a base plate or steel walkways that are secured at both ends and subject to loadings in high winds.

Bending is a combination of tension and compression. In AtoN, this might be observed by deflection in a vertical pole or lattice tower member when it is subject to a combination of loads including wind or excessive additional equipment.

*Shearing forc*es tear a material by material being loaded in opposite directions at the same time. In AtoN, this might be seen by a bolt connecting two steel beams in a lattice tower being pulled apart by loads acting in opposite directions. Shear forces can also be observed by the movement of a foundation or retaining wall if the soil/structure is designed incorrectly

Bearing forces on soil or end of pile. A shallow foundation transmits loads from a structure (e.g., a tower) to the soil over the area of a foundation. If this bearing pressure is too great for the bearing capacity of the soil, there is a risk the foundation will sink. Similarly, a deep end-bearing pile is designed to transfer the bulk of its load directly to the base or toe of the pile once a solid layer is penetrated.

A deep friction pile transfers its load along the entire shaft using friction between the pile and soil to achieve the required load when a solid layer cannot be penetrated. *Skin friction* is the resistance of the soil to the downward forces created when the pile is loaded by the structure upon it. If the skin friction is insufficient to support the loads the structure will not be supported. Figure 9 illustrates the reactions that can provide the pile/soil structural support, depending on the soil conditions, i.e., shear force resistance of the soil or bearing capacity of the founding strata.

Dynamically applied loads, particularly cyclical loads can have significant adverse effects on structural connections and the strength of structural members. In structural steel for example, microcracks in the material caused by dynamic cyclical tensile loads (such as those caused by wave action acting against a monopile) may gradually increase in a process called fatigue until the steel permanently deforms and fails. The ability of a material to return to its original size and shape once a load has been removed is known as its capacity for “elastic deformation.”

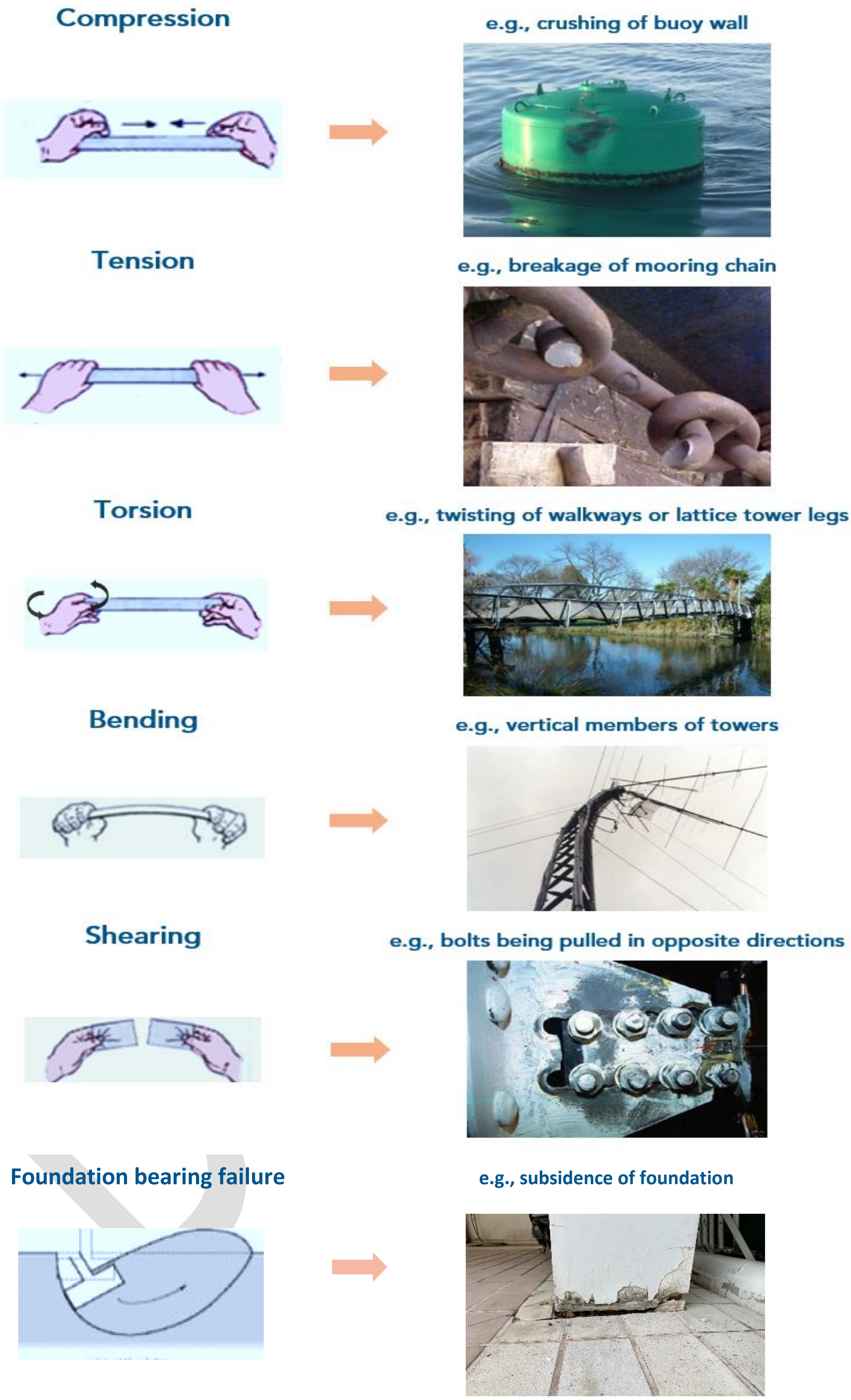

Figure 8 Typical design forces

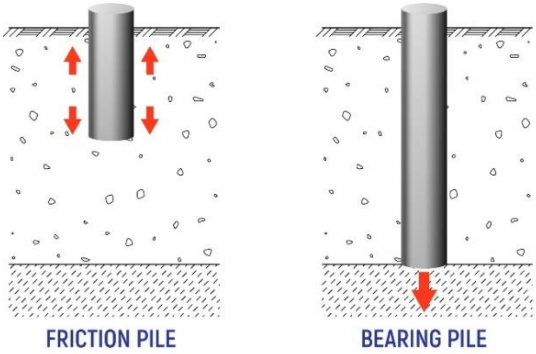

Figure 9 Typical pile foundation design forces and reactions

7. CODES

7.1. DEFINITIONS OF REGULATIONS, CODES, STANDARDS AND GUIDELINES

Regulations or codes are generally mandatory requirements in construction and design that apply in individual countries. They are usually enacted by law and are regulated and enforced. Standards are developed using a consensus process that includes all stakeholders and publicised by a national or international organization such as Standards New Zealand, BSI or ISO. Standards are often referenced by codes as a requirement to be met but are not necessarily legally enforceable.

Approved Codes of Practice in some countries are recommended methodologies against which users will be scrutinised if there is a need to challenge the design. Guidelines are generally examples of best practice to help achieve regulations and standards.

Including all relevant codes, regulations standards and guidelines into AtoN structural design will help the AtoN manager be reassured that the design is appropriate and compliant and help prove that in case of future challenge. Recording and justifying deviation from normal practice is also useful to record in a Basis of Design (see section 9).

7.2. TYPICAL STANDARDS

Irrespective of the global location, the regional design standards often cover common themes to assist designers, and compliance with such standards is generally considered to be best practice. In certain regions e.g., in Fiji, the Insurance Council of Fiji requires insured buildings to be “cyclone certified” in accordance with Australian Standard AS4055 by a council-approved engineer [36]. Deviation from the standards is permissible but any deviation from normal design procedures or recommended data should be explicitly recorded in the design statement so that the decision can be referred to and justified if necessary.

Regional areas tend to use differing standards for structural design, but the aspects of the design standards are similar. Regional standards often include the following areas:

- Principles for design.
- Loadings
- Structural steelwork.
- Reinforced concrete.
- Geotechnics
- Piling
- Timber

Codes relating to the design of marine structures are also often specifically referenced by AtoN designers. These tend to complement regionally relevant codes for the specific areas above but with specific recommendations for loadings such as wave, debris and vessel berthing loads.

There are globally applicable standards relevant to fixed AtoN, published by PIANC. Two specific national codes that are often cited by PIANC in their published documents are British standard BS 6349 Maritime works (all parts) *(ref)* and the Australian standard AS 4997:2005 Guidelines for the design of maritime structures [19] .

The following sections describe generic standards that the AtoN manager may see reference to in design documents and records, including more detail about where they may be applied in the design of AtoN and the loadings that may be considered in the design.

7.2.1. LOADINGS

Design criteria for loadings are often provided in a specific separate standard by many standards publishers. In many countries the permanent and variable actions as described in sections 6.2.2 to 6.2.8 are included within a specific document. Example documents are the European *Eurocode 1: Actions on Structures* [20] and the Indian *IS: 875 (Part-3)* [21].

Criteria and data for assessment of maritime specific variable actions (environmental loads) included in section 6.2.9 to 6.2.11 will often derive from specific documents such as *AS 4997* [19].

Loading standards also provide guidance on combining loads for different situations and applying safety factors depending on the structural analysis methodology (see 6.2.1).

Wind loads are a critical environmental load in cyclonic areas and both wind and wave loadings should incorporate regional climate change predictions.

If the structures are likely to be exposed to loadings that could cause vibrations such as wind loading of monopoles or wave action on monopiles they will consider the potential for vibrations (see 6.2). Assessment of vibrations in structures is a specific and complex process, where the designer will try and limit the natural frequency of the structure by either making the structure stiffer or adding mass, in an iterative process.

7.2.2. STRUCTURAL STEELWORK

Steelwork elements of typical AtoN may include structural members of lattice towers or monopoles supporting land-based lights. The elements are assessed for how they work as a structure (globally) and on an individual element level (locally). The analysis method can depend on the cross-sectional dimensions of the steel and the method of connection.

The steel elements are assessed for stresses caused in the steel due to individual shear, bending and torsion forces and combinations of those. They are also assessed for deflection.

Connections are an important aspect of structural steel design. The capacity of both welds and bolts are calculated to withstand shear, bearing and tension.

Design of steel elements will also be accompanied by a statement about the grade of steel assumed or required. It is usually described in terms of its thickness and strength.

Examples of structural steelwork codes include the Australian *Steel structures code AS 4100* [22] and the North American *AISC 360* [23]

7.2.3. REINFORCED CONCRETE

Examples of reinforced concrete used in AtoNs includes pad foundations of tower bases, concrete towers/structures, concrete piles and concrete platforms of multi-pile beacons.

The properties of concrete mix can change due to its composition, primarily the water to cement ratio but also the inclusion of other constituents to improve its workability, curing time or resistance to sulphate salts. The concrete design will have a specified mix of water, cement, aggregate and other constituents and be expected to have a certain value of compressive strength. It is therefore important that the design mix is recreated as specified if the concrete is being mixed on site, rather than delivered by a concrete company.

Concrete is often tested on a site by using the slump test which checks for workability of the concrete. Any ready mixed concrete delivered from reputable firms will also have regular compressive test carried out on concrete samples. The concrete is tested by creating a test cube or cylinder and its compressive strength tested after specific periods of time including seven days and 28 days.

Steel reinforcing bars are what provides the concrete with its tensile strength and stops it cracking under bending loads and shearing forces. Individual reinforcing bars are specified as a specific diameter at a certain spacing. These are arranged into "cages" in a specific sequence known as a bar bending schedule. Pre-welded reinforcing meshes are often used in slabs and shallow foundations.

The environment is a criterion used in concrete design. How exposed to aggressive chemical deterioration and physical abrasion the concrete will be is a factor in the concrete mix and the amount of "cover" required to the reinforcing bars. Steel reinforcement can be supplied untreated, galvanised, covered with other protective coatings or as stainless steel.

Concrete can also be used in pre-formed units such as kerb stones or retaining walls. The principles of the design mix and reinforcement specification will all still apply. Additional on-site checks should be made that the precast units are installed to the manufacturer's instructions and to the relevant tolerances.

Examples of concrete codes in use are the British National Annex for Eurocode 2, *BS EN 1992 Design of Concrete Structures* [25] and the New Zealand *Concrete structures standard* [26].

Figure 10 Examples of concrete pile cap (group of piles) and pad foundations

7.2.4. GEOTECHNICAL, SEISMIC AND PILING

The consideration of soil conditions is essential for any AtoN structural design. The way the structure and soil behave together is considered during design. For shallow or pad foundations the bearing capacity of the soil underneath the structure is considered. For piled foundations and monopiles the "skin friction" at the soil pile interface and the bearing capacity of the soil underneath the end of the pile are parameters that are checked during the structural analysis.

The location of the water table for land-based foundations is important as this can influence the soil properties. Examples of geotechnical and piling codes include (the Canadian Standards CSA A23.3 [38].

Piles are checked during design for bending and deflection, and in the case of end bearing piles for the bearing capacity. The grade and thickness of steel will also be specified in the design. Marine based monopiles also must be designed for the hydrostatic and hydrodynamic forces of the sea or river, as well as the soil properties into which they are embedded.

The design of structures to consider seismic activity is often the subject of a separate national or international design standard. The purpose of the standard is to complement, the equivalent structural design codes with specific loads or actions and design criteria, to ensure the design of earthquake resistant structures. Examples include the Iranian standard *No.2800* [28] and the Brazilian Standard *NBR 15421:2006* [27].

7.2.5. TIMBER

The use of timber in AtoN structures is common, particularly for simple marine based beacons. Timber is used for piles and timber posts. Commercial timbers are termed hardwood or softwood according to their botanical classification (rather than their physical strength). Timbers are often classified by their strength and their timber species to give an indication of structural strength.

There are design codes specifically for the design of structural elements, but the material considerations are equally important including moisture content, shrinkage potential, fire resistance and density. Resistance to marine boring insets and abrasion resistance are also important features. The assessment of bending, shear and torsion forces is similar to other structural elements and the assessment of connections also requires explicit consideration.

Many marine timbers used historically are tropical hardwoods and it is no longer considered sustainable to use many of these products. Any timber design specification should be for timbers that have been purchased through ethical trading and for which there is a validated “chain of custody” for their source and production.

7.2.6. MARINE/ATON SPECIFIC

The design of floating AtoN should be undertaken with reference to the several IALA documents listed in the references including *G1006* [30] *G1066* [29] and *G1099* [31]. PIANC also produce internationally applicable design guidelines for specific maritime installations, and these often cite some specific codes including the British Standards BS6349 and the Australian AS4997. Many other countries have also developed their own design guides for maritime structures.

In addition to referencing national structural guidelines these, maritime specific guidelines specify wave and hydrostatic loadings. In addition to AtoN design, they provide information for the design of vessel berths and fendering.

7.3. CONSTRUCTION CODES

Workmanship is an explicit aspect of many design codes and a specific example of quality control. The way in which the design is implemented at the construction stage is critical in ensuring the structural stability and durability aspects of the design are achieved. Many countries ensure the workmanship of the specified designed is incorporated into building regulations or codes. Examples include the placement of wet concrete to ensure adequate distribution within and around a reinforcing bar cage and the compaction of earth in appropriate layers before constructing a tower foundation, to reduce the potential for settlement of the structure. Some national organizations publish model project specifications for use in technical and contract documents.

Ensuring compliant and consistent product quality can be particularly challenging in extreme climates. For example, high temperatures can lead to premature evaporation of water from concrete mixes which adversely affects the desired compressive strength. It can also lead to expansion of metals that can affect the connections of steel structures leading to stresses on joints if such expansion has not been accommodated in the design. Hot temperatures can also make steelwork difficult to handle and is generally debilitating for personnel, which again can lead to mistakes and hurried construction of AtoN elements. Guideline G1136 *Providing AtoN Services in Extremely Hot and Humid Climates* [13] provides further commentary on the impacts and mitigation measures that can be undertaken to address the challenges of workmanship in hot climates.

Finally, the construction phase will also be accompanied by regulations or standards for temporary works. for example, temporary access platforms or concrete formwork.

With kind permission of Commissioners of Irish Lights

Figure 11 Example of GRP light tower and foundation base, during and after construction

8. NON-STRUCTURAL DESIGN CRITERIA

8.1. DURABILITY

Certain standards also specify the design of elements to resist the physical or chemical deterioration due to the environmental setting. AtoN structures and foundations installed within an estuarine or coastal waterway are particularly susceptible to deterioration due to the saltwater environment. Certain tidal levels, such as the low water area can be particularly detrimental for steel structures and can encourage microbial activity (Accelerated Low Water Corrosion, ALWC). The action of soils containing high concentrations of sulphate salts can be damaging for concrete.

Mechanisms for deterioration of AtoN also include wave erosion and windblown debris. The abrasive nature of cyclonic winds can be particularly damaging to structures. The design process will ensure specification of element characteristics to reduce the risk of deterioration. Some examples are:

- Member size – steel elements may be designed with a corrosion allowance to ensure minimum dimensional requirements are always maintained.
- Sacrificial protection such as a galvanised coatings and cathodic protection systems.
- Physical protection including the application of finishes or bituminous tape wrappings.
- Materials, for example the moisture content of structural timber or a concrete mix to resist sulphates in soil.
- Placement and fixing of e.g., in reinforced concrete the use of sufficient reinforcing bars to withstand tension forces that could induce unwanted cracks.

- Housing of electrical equipment, lights and batteries, from water and dust ingress and specification of ingress protection (IP) ratings.
- Elimination of dissimilar metal connectivity to control galvanic corrosion.
- Protecting and shielding electrical equipment and cabling from UV degradation.
- Geometric consideration to limit corrosion potential such as eliminating, sharp edges, bolted connections, trapped water, and good access for protective coating maintenance.

8.2. SUSTAINABILITY

Sustainability is a core philosophy at the heart of any design process. Guideline *G1036 Environmental Management in Aids to Navigation* [5] provides numerous examples of how sustainability can be incorporated into AtoN design.

The whole life impact of AtoN should be considered in the design and the AtoN manager should feel confident in asking suppliers and designers how they have maximised the sustainability of any design solution. It may ultimately not be economically feasible to design structures for the worst-case loadings, for example, but it should be demonstrated that consideration of the options for sustainable design have been considered and compared over the design life of the AtoN. Sustainability considerations include those described in the following paragraphs.

8.2.1. DESIGN LIFE OF ATON, WHOLE LIFE MAINTENANCE AND DECOMMISSIONING REQUIREMENTS

The design life is the period during which the item is expected by its designers to work within specified parameters. The actual life of the structure realized is dependent on environmental exposure and maintenance regime. The robustness of the design to resist current and future climatic changes, including extreme weather is therefore important in ensuring the design life duration is realized. A more durable design may be more expensive as an initial solution but may remove the need for one or more replacement AtoN over its design life, thus reducing the manufacturing, installation, and disposal costs of additional AtoN.

An AtoN that is designed for durability may also require less maintenance and therefore have less impact due to the reduced use of materials and maintenance vessels and vehicles. This in turn will reduce the whole life carbon footprint of the design. Consideration should also be given to the decommissioning or replacement of AtoN structures and how they can be refurbished, recycled or disposed of. It is important to consider the extraction of piled structures within the river or seabed such that any legacy structures do not become a navigational hazard.

8.2.2. PREFERRED TECHNICAL SOLUTION

The preferred solution may be a compromise between cost, technical preference and environmental or societal impact. For example, the use of anchors for moorings in coral seabed habitats can be destructive and should be avoided, where possible [5].

Figure 12 shows an example of a light tower on the northern end of Aegna island in Estonia. The figure shows the original light, how it was destroyed in a storm and finally a replacement structure that was modified to improve its structural stability. This demonstrates how important it is to design for the environmental conditions.

With kind permission of Estonian Transport Administration

Figure 12 Aegna Island northern light – (left to right) original, destroyed and replacement

Consideration should also be given to making AtoN temporarily demountable or stowable in extreme events, during which vessels may not be transiting (and therefore requiring AtoN services) or be at anchorage to await the passage of dangerous weather conditions. Although this approach means establishing and practising extreme event preparation procedures and the use of manual resources (and associated costs) to mobilize and demobilize after an extreme event, it may reduce the replacement costs of damaged AtoN.

Another example of how design criteria can be exceeded by environmental conditions is shown in Figure 13 below. This shows how a front lead structure was originally placed on land, but coastal erosion gradually undermined the light foundation, ultimately resulting in failure of the foundation and the light function. To reduce the risk of this situation reoccurring, the light foundation was redesigned as a monopile and re-sited within the waterway.

Figure 13 Front Lead dayboard and light – (left to right) rear and front view of land sited light and monopile replacement

8.2.3. Waste reduction and alternative materials

It is essential to identify the opportunities for the reduction of waste materials for the whole life of the AtoN. The design should consider the use of:

- Alternative environmentally friendly products that will have no or minimal, potential toxic effects on the environment.
- Utilization of recycled materials.
- Minimal through life maintenance by implementing corrosion resistant materials and wrapping systems.
- Consider items which can be refurbished opposed to single use products.
- Products that are easily recyclable or reusable at the end of their design life.
- Construction methodologies that will reduce the potential for waste and associated environmental impact. For example, this could include using prefabricated concrete products to minimise the potential for mixing too much concrete on-site and having to dispose of the excess and utilization of existing foundations where suitable for replacement assets.

8.2.4. Materials storage

If potentially toxic products cannot be eliminated from the design, they should be stored to minimize impact in case of spillage or leakage This may mean creating a specific housing or bunded area to contain such materials.

8.2.5. Stakeholder consultation

Undertaking timely and appropriate stakeholder management is a fundamental component of sustainable design. For example, the noise from generators or night-time illumination by lit AtoN could impact a local community and it is essential to understand any constraints on the selected AtoN solution at an early stage. Similarly, the timing of works could impact environmentally designated areas or interrupt seasonal recreational activities. Guideline *G1079 Establishing and Conducting User Consultancy by AtoN Authorities [12]* provides extensive information on identifying and consulting stakeholders.

Whilst stakeholder management is not a specific designer's task, it is important that the designer and AtoN manager identify any issues that could impact or be impacted upon by stakeholders, for example timing, visual impact or the impact on environmentally designated habitats.

There are national and regional sources of information that can assist in stakeholder identification. National examples are the UK Magic Map [34]and the American EnviroMap, [33] both publicly available interactive map layer that can be interrogated for environmental designations and used therefore to help identify any local or regional groups that may have an interest in the construction or installation of AtoN.

8.2.6. Renewable energy

Power requirements and the ability to employ renewable energy sources such as solar power are another sustainable consideration. It is important to consider the requirement for services within the design at an early stage. For example, it may be necessary to ensure ducting for electricity cables is accommodated in the concrete foundations of a tower base design to prevent the need for breaking out and relaying the concrete foundation at a later stage.

8.3. MAINTENANCE

As discussed in section 8.2, design for whole life maintenance involves the consideration of balance between sustainability and cost. Maintenance costs can be a significant consideration over the AtoN design life, so it is therefore important to consider the optimal balance of initial investment and durability of the selected AtoN, and maintenance costs together with the sustainability considerations highlighted in section 4.4. *Guideline G1035 Availability and Reliability of Aids to Navigation – Theory and Examples* [6] and Guideline *G1077 Maintenance of*

Aids to Navigation [16] provides detailed guidance on establishing an optimised maintenance programme for AtoN with reference to functional availability and reliability requirements (see section 5.5).

The geographical location can impose its own constraints on the maintenance options and the maintenance regime anticipated at design stage should incorporate those. Physical accessibility to undertake monitoring, inspection and maintenance design life is an important consideration. Any design should consider the need to access all parts of the structure as appropriate and under any seasonal, climatic, or tidal limitations. These considerations should be explicitly recorded in a designer's risk assessment document.

Guideline *G1023 The Design of Leading Lines [37]* provides information regarding the design of light platforms to facilitate access for maintenance.

It is important that technical design information such as "As-built" drawings or operating manuals are passed from the supplier to the AtoN manager and that this is easily accessible for inspection, health and safety purposes and in case of emergency.

The design should also consider the opportunity for remote monitoring or inspection and how that could optimise the sustainability of the preferred AtoN solution. Guidance on the maintenance of AtoN, including the characteristics of typical AtoN materials can be found in Guideline *G1151 Maintenance of AtoN Structures* [11].

With kind permission of Australian Maritime Safety Authority (AMSA) left and Andrew Wallace (right)

Figure 14 Examples of marine based AtoN with multiple structural elements requiring sustainable design

8.4. SAFETY AND SECURITY

8.4.1. SAFETY

All persons have a duty to manage risk by eliminating health and safety risks so far as is reasonably practicable, and where removal is not feasible, to minimize the risk. Many national and regional regulations include the requirements for the designer to undertake a risk assessment for the construction, maintenance and decommissioning risks posed by their design (and similarly for contractors and installers for their respective tasks). Even when this is not specifically required by national or regional interpretation it should be considered a best practice safety activity during the design process.

AtoN managers and designers have the duty of care to ensure that structures are safe to personnel throughout its life, covering, construction, maintenance, and decommissioning. Safety in design review should identify all hazards and risks for these activities and as far as practical eliminate or implement appropriate controls. It is recommended to undertake a risk management approach to the safety in design review, incorporating input from managers, designers, construction crews and AtoN technicians where relevant.

For example, if a functional requirement is that an AtoN light is situated 5m above ground level, the initial structural design may suggest a fixed pole structure with a top bracket to support the light. The maintenance requirement may be that a means of access is required to facilitate inspection and maintenance activities due to the height, and the design suggests a small access ladder attached to the structure. Personnel then need to be able to use the ladder such that the risk of falling from it is minimized.

Assessing the design risks will therefore include appraisal of whether an alternative design can remove the need for access at height, for example a mid-hinged tower that can be lowered to the ground. If it is not possible to remove the need for working at height, then consideration is made of whether alternative access to the top of the tower is achievable, such as the use of a mobile access platform. If this is not feasible due to access or availability issues, adequate structural design of the ladder and its connections to withstand the loadings imposed by its use is required. It is also necessary to consider features such as adequately sized work platforms or fall restraint systems that the personnel attach to when using the ladder.

Designing for safety is generally interpreted at a national or local level by governments or local authorities and an explicit requirement of many countries' building codes and regulations. Guideline *G1092 Safety Management for AtoN Activities* [10] provides further overview and practical guidance to the management of AtoN at all stages of design life.

Other safety considerations include fire resistance properties (often an explicit part of structural design standards), adequate handrails and edge protection on walkways and platforms and safe access to facilities where work boats are used as the primary access.

Consideration should be given to facilities at remote sites for maintenance personnel for example shelters in case of bad weather or the installation of waterless toilets. Reducing the need for maintenance visits through sustainable design also reduces the safety risks.

Measures should be taken to protect persons and equipment from the effects of lightning on AtoN structures. Guideline *G1012 The Protection of Lighthouses and Other Aids to Navigation against Damage from Lightning* [7] provides extensive guidance on the assessment of the risk of lightning strikes and the requirements to protect structures, equipment and personnel from its effects.

8.4.2. SECURITY

It is important that the design incorporates security features to ensure maintenance of function and minimization of the need to reactively maintain or replace AtoN elements. Damage to AtoN can be caused by wilful actions or by the indirect activities of wildlife or climatic events. It is important, particularly on remote sites that the AtoN designer considers the security risks and suggests design features to mitigate the risks. It is also essential, as for any structural element that the design is undertaken with reference to appropriate codes and anticipated environmental conditions. Mitigating security features can include:

- Security fencing.
- Remote monitoring cameras.
- Anti-climb barriers and paint.
- Installation of bird spikes.
- Arrangement of desirable components positioned out of view or in relatively inaccessible areas.
- Use of collapsible bollards or concrete barriers to prevent unauthorized vehicular access.

It should be noted that national and local regulations should be consulted to ensure the use of compliant security features. For example, the use of anti-climb paint may require the installation of a visible sign warning that it has been applied to a tower structure. Guideline *G1109 Theft and Vandalism Deterrents* [8] provides further useful suggestions on the measures that can be incorporated into AtoN design to reduce the potential impacts of wilful damage. Guideline *G1091 Bird Deterrents and Bird Fouling Solutions* [9] similarly describes methods of deterring birds from nesting or congregating at AtoN sites.

9. DESIGN OUTPUT

Once the designer has completed the design, the AtoN manager can expect to receive a set of documents that will then facilitate procurement of a contractor or supplier and enable them to construct or install the AtoN in accordance with the design. Design output documents can include:

- Specifications
- Design drawings
- Installation instructions
- Operation and maintenance manuals
- Health and safety risk assessments.

Together with site information and appropriate construction codes covering workmanship and site preparation, these documents can then be used to construct the AtoN.

It is also best practice (and required under some national regulations) that the designer should also undertake a designer's risk assessment that assists identifying and mitigating risks that could be associated with the design. This may require several iterations before the design is finalized.

9.1. BASIS OF DESIGN

On more complex AtoN projects, the AtoN manager can expect to receive a Basis of Design document from the designer. This document incorporates the AtoN manager's requirements, states the elements that have been designed and confirms the relevant codes, loadings and other specific criteria that have been used in the AtoN structural design. The Basis of Design provides confirmation of one of the key requirements of appropriate AtoN design, which is that the appropriate codes have been used to design the AtoN.

Not all works will be accompanied by a lengthy Basis of Design, only where there is complexity of design. For a simple prefabricated beacon, the AtoN manager may simply require confirmation from the designer or supplier that it will perform in the environmental setting for its design life (as described in the AtoN manager's requirements statement) and the details of any specific installation or maintenance instructions. For a tower design, for example, the AtoN manager can expect to receive a detailed Basis of Design document from the designer, listing the relevant design criteria and including confirmation of the design codes used.

Annex A contains a typical Basis of Design document structure for the design of a monopile structure and includes examples of the type of information that could be included. For simple off-the-shelf purchases many of the specific queries will not apply, but basic questions regarding the use of the product for the environmental conditions anticipated are still relevant and important to satisfy.

10. DEFINITIONS

The definitions of terms used in this Guideline can be found in the *International Dictionary of Marine Aids to Navigation* (IALA dictionary) at http://www.iala-aism.org/wiki/dictionary and were checked as correct at the time of going to print. Where conflict arises, the IALA Dictionary should be considered as the authoritative source of definitions used in IALA documents.

In addition, for this document:

Serviceability limit state– the structural design conditions related to ease of use and potential for repair.

Maintainability - refers to the ease with which maintenance activities can be performed on an AtoN structure and the probability that an AtoN can be restored to normal operating conditions after undergoing maintenance.

Ultimate limit state (ULS) - ULS is designing to limit the stresses in the materials to manage the probability of collapse.

Curing (of concrete) - providing adequate moisture, temperature, and time to allow the concrete to achieve the desired properties for its intended use. When these parameters are properly specified and provided, the design properties of the concrete mixture should be achieved.

Cathodic protection systems – utilise the physical and chemical properties of seawater and a sacrificial metal to force the corrosion of anodes consisting of the sacrificial metal, *rather* than the steelwork of the marine structure to which they are attached. Systems can be passive, whereby the system relies on the dissimilar (see below) potential conductivity of the anode and the structure, or actively charged with an electrical current – impressed current cathodic protection (IPPC) – to provide additional current to force the corrosion of the anode.

Formwork - the process of creating a temporary mould into which concrete is poured and formed. Traditional formwork is fabricated using timber (plywood), but it can also be constructed from steel and GRP.

Cast in-situ – the process of constructing formwork and casting concrete or reinforced concrete elements on site, rather than purchasing readymade concrete products.

Cover (to concrete reinforcement) - the distance between the steelwork reinforcement and the outside face of the concrete.

Dissimilar metals – the characteristics whereby one metal is likely to corrode more quickly than another when they are placed together in the presence of water. The difference in potential for corrosion in different metals is the reason why for example, stainless steel (low potential) and aluminium (high potential) structural components would not be assembled in direct contact, without using an insulating material between them.

Shallow foundation – A type of building a foundation that transfers building loads to the earth very near to the surface, rather than to a subsurface layer or a range of depths Shallow foundations are constructed where soil layer at shallow depth can support the structural loads. The depth of shallow foundation is generally less than its width.

Piled foundation - A piled or deep foundation transfers building loads to the earth to a subsurface layer or a range of depths. A deep foundation is required to carry loads from a structure through weak compressible soils or fills on to stronger and less compressible soils or rocks at depth, or for functional reasons. Deep foundations are founded too deeply below the finished ground surface for their base bearing capacity to be affected by surface conditions. An end-bearing pile is designed to transfer the bulk of its load directly to the base or toe of the pile once a solid layer is penetrated, whereas a friction pile transfers its load along the entire shaft using friction between the pile and soil to achieve the required load when a solid layer cannot be penetrated.

Commissioning – To commission an AtoN structure, means to carry out all the necessary test and procedures, using industry codes where appropriate, to show that it is fit for the purpose for which it was designed. For AtoN structures, this includes checks that the focal height provides the functional requirements as identified in the AtoN manager's specification.

Decommissioning – Decommissioning of an AtoN structure means the retirement from service of the structure and the necessary procedures to undertake this in a safe and sustainable way. In addition to recycling, refurbishment, dismantling or removal of the structure, decommissioning should include a risk assessment of the AtoN no longer performing a functional role (i.e., the navigational risk) and the health, safety and environmental risks of refurbishing or dismantling the structure.

Workability - how easily freshly mixed concrete can be placed, consolidated and finished with minimal loss of homogeneity. Generally, the workability of concrete is determined by how fluid the mix is (i.e., the cement to water ratio).

11. ABBREVIATIONS

AEP	Annual exceedance probability
ARI	Annual recurrence interval
GRP	Glass fibre reinforced plastic
PIANC	World Association for Waterborne Transport Infrastructure. The name originally stands for Permanent International Association of Navigation Congresses
VTS	Vessel traffic service(s)

12. REFERENCES

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[4] IALA. Recommendation R0130 Categorization and Availability Objectives for Short Range Aids to Navigation (0-130)

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[6] IALA. Guideline G1035 Availability and Reliability of Aids to Navigation - Theory and Examples

[7] IALA. Guideline G1012 The Protection of Lighthouses and Other AtoN against Damage from Lightning

[8] IALA. Guideline G1109 Theft and Vandalism Deterrents

[9] IALA. Guideline G1091 Bird Deterrents and Bird Fouling Solutions

[10] IALA. Guideline G1092 Safety Management for AtoN Activities

[11] IALA. Guideline G1151 Maintenance of AtoN Structures

[12] IALA. Guideline G1079 Establishing and Conducting User Consultancy by AtoN Authorities

[13] IALA. Guideline G1136 Providing AtoN Services in Extremely Hot and Humid Climates

[14] IALA. Guideline G1052 Quality Management in AtoN Service Delivery

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[30] IALA. Guideline G1006 Plastic Buoys

[31] IALA. Guideline G1099 The Hydrostatic Design of Buoys

[32] IALA. Guideline G1108 The Challenges of Providing AtoN Services in Polar Regions

[33] EPA. EnviroAtlas (epa.gov)

[34] DEFRA. Magic Map

[35] IALA. Standard S1020 AtoN Design and Delivery

[36] Pacific Regions Infrastructure Facility. (2021) Regional Diagnostic Study of Constraints in the Application of Building Codes in the Pacific, Fiji Case Study

[37] IALA. Guideline G1023 The Design of Leading Lines

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13. FURTHER READING

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[2] Pack, L. (2018) Australian Guidebook for Structural Engineers

[3] PIANC Guidelines for Marina Design

[4] BS EN 1990:2002 Eurocode basis of structural design

[5] Maritime works –Part 1-1: General – Code of practice for planning and design for operations

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[7] Part 1-3: General – Code of practice for geotechnical design;

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[10] https://www.construccionenacero.com/sites/construccionenacero.com/files/u11/ci38_38221_comparative_study_of_codes.pdf

[11] ocean engineering division united states coast guard Washington, D.C august 2013 specification for fabrication of steel ocean buoys specification no. 464 revision k

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14. INDEX

No index entries found.

ANNEX A BASIS OF DESIGN EXAMPLE – MONOPILE MARINE AID TO NAVIGATION

A.1. INTRODUCTION AND BACKGROUND

A.1.1. PROJECT DESCRIPTION

The initial section could include a description of the project, along with a summary of the key aims.

A.1.2. LOCATION

This section may include a reference to locations within the project. Consideration could be made to include all details in a table format, including coordinates, AtoN types, depths etc. A chart or figure with the locations marked for geographical reference would also be of benefit.

A.1.3. PROJECT OBJECTIVE

This section may include a description of the project objective including any historical information that is relevant.

A.1.4. PURPOSE OF THE DOCUMENT

A Basis of Design document sets out the minimum functional requirements and technical criteria for the project. This can be stated in a leading section like this. It can reference the inclusion of guiding design parameters that are outlined in the report, including but not limited to:

- Legislative requirements
- Site conditions
- Functional requirements
- Maintenance requirements
- Design loads
- Materials and durability requirements
- Electrical requirements.

It can also make a reference to design drawings, which are best placed in an annex.

A.2. DESIGN STANDARDS, REFERENCES AND LEGISLATION

A.2.1. LEGISLATIVE REQUIREMENTS

All applicable legislative requirements can be referenced in this section.

A.2.2. DESIGN STANDARDS

Relevant design standards, according to the region or country can be listed here.

A.2.3. DESIGN GUIDELINES

All applicable IALA recommendations and guidelines can be listed here.

A.2.4. PROJECT REFERENCE DOCUMENTS

It may be beneficial to list all reference documents used in the Basis of Design.

A.3. SITE AND ENVIRONMENTAL CONDITIONS

A.3.1. DATUMS

Listing of project datums are critical in structural design, particularly for water-based structures. Include reference to relevant site survey and topographical information that was used to establish ground/bed levels

Those may be listed as follows in the example:

Example

> *"The project datums are as follows:*
>
> - *Horizontal datum: GDA94, UTM MGA Zone 50*
> - *Vertical datum: The chart datum for the location in which the AtoN are to be installed should be listed."*

A.3.2. BATHYMETRY

If bathymetric data has been used in the design process, it may be referenced in this section, ideally in a table with As-Built and initial survey levels, including any differences noted.

A.3.3. TIDAL INFORMATION

References to tidal plans/tide tables can be made, including a table can be added with a summary of that information.

A.3.4. SEA LEVEL RISE (SLR)

A reference can be made to Sea Level Rise (SLR) that is to be applied to the end of asset design life.

A.3.5. METOCEAN CONDITIONS

A.3.5.1. Ambient

Ambient (non-cyclonic) conditions in the vicinity of the locations should be summarized here. It can be tabulated for ease of reference.

A.3.5.2. Cyclonic

An analysis of cyclonic conditions can be referenced here, including references to any external reports used.

A.3.5.3. Seasonal occurrences

For example, the timings of annual monsoons/cyclones, tidal currents, snow/ice, extreme tidal levels.

A.3.6. GEOTECHNICAL

Geotechnical information should be referenced here, stating of the level of detail available and limitations of interpretation.

It can reference any previous geotechnical studies or reports done in the area, including historical pile driving records.

Some attempt should be made to summarize/interpret the geotechnical information and provide general characteristics.

Identified areas of contaminated land, aggressive soil conditions or potentially hazardous landfill can also be included here.

A.3.7. Existing AtoNs

Details should be provided on any existing drawings, and where possible, including historical drawings.

An analysis and report should also be provided on conditions of existing structures, and where relevant, a reference or report on underwater inspections.

A.3.8. Adjacent land use

Provide relevant information regarding adjacent land use, ownership, fellow site occupants, access issues and any constraints or local, regional or national planning requirements previously identified.

A.4. FUNCTIONAL REQUIREMENTS

A.4.1. Design life

The AtoN user/manager may decide on the required design life(s) for all elements of the AtoN or they may be stated in the organization's existing maintenance plans. They should be summarized in here.

Example:

"The AtoN's design life shall be:

- *Primary elements (including; mast, platform): 25 years*
- *Ancillary elements (including ladder system, berthing, and mooring system, stanchions and railings): 10 years*
- *Cathodic protection system: 10-15 years.*

The design lives nominated assume routine maintenance of the structures. The asset shall be inspected regularly to confirm acceptable performance of durability systems (e.g., jackets, anodes, corrosion levels) with programs of minor and major maintenance undertaken in accordance with the asset management plan."

A.4.2. Design events

The design events can be stated here, as they form a critical part of the design and engineering process.

Example:

"The AtoN's shall be designed to the following limit states:

Ultimate Limit State (ULS): designed for ultimate limit state live loads and wind loads defined by the relevant codes (not to be designed for specific survival of global environmental wave and current loading due to limitations of retained base pile).

Serviceability Limit State (SLS): designed to operate for worst case of; combination of 10 year ARI wind, wave, water level and current, serviceability access criteria and 25 year ARI wind load (independent).

The AtoN's are not designed to withstand vessel (e.g., commercial shipping) impact beyond abnormal berthing of the nominal maintenance vessel and are expected to sustain substantial damage or collapse in this event."

A.4.3. Operational requirements

Key operational requirements should be stated here.

Example:

"The following criteria sets out the functional operational and maintenance requirements for AtoNs:

- *The structures are to support navigation lights and daymarks of the nominated size and characteristics and at the nominated focal plane.*
- *The structures are to allow for trained personnel access from the maintenance design vessel in up to SLS environmental conditions to undertake inspections and servicing of installed equipment.*
- *Ladder cages are to be at the platform entry only (i.e., not over full length of ladder); to be considered and confirmed in Safety in Design process.*
- *Ladders for access are to be angled at 2 degrees back (i.e., maximum outstand from pile at lowest rung).*
- *Ladders are to be positioned on the leeward side of the pile to the predominant ambient wave conditions, being orientated on the south-east side of the pile.*
- *The offset distance between the ladder and buffer (i.e., chafer) rails shall be minimized with consideration of step-off distance from the maintenance vessel onto the ladder, whilst providing sufficient crush protection. The minimum requirement in AS 4997 for crush protection offset for buffer rails is 250 mm.*
- *Daymark elements (e.g., battens) are to be replaceable by rope access or gantry method engineered and commensurate for maintenance procedures.*
- *Any clamps on the pile and mast are to be removable to allow maintenance or replacement.*
- *The platform to mast connection is to be removal (e.g., bolted flange) to allow future replacement.*
- *The platform shall provide sufficient clear distance for walkways (minimum 600 mm) and workspace appropriate to maintenance activities on the equipment. Platform access is not restricted via locks although fall prevention shall be provided between the access point (i.e., ladder opening) and the 'work area'.*
- *Electrical and instrumentation equipment is to be stored in weatherproof and durable housing, with sunshades and IP66 rating.*
- *Devices to prevent birds fouling the solar panels, light, instrumentation and enclosures are to be provided.*
- *AtoN identification signs shall be provided on all markers; on three sides (facing inbound, outbound and inwards towards channel). Signs are to be clearly visual with lettering and the bordering in coloured retroreflective tape.*
- *AtoN 'restricted access' signs to be provided as per text provided on the design drawings. One per AtoN to be provided on the platform entry swing gate."*

A.4.4. MARINE AIDS TO NAVIGATION

A.4.4.1. General

A reference to the availability parameter could be considered a primary requirement even for structural design. An example is shown below:

Example:

Aids to navigation are to be in accordance with IALA Guidelines and be Availability Categories noted below:

- *AtoN Nos -: 1 (99.8%)*
- *Aton Nos -: 2 (99.0%).*

A.4.4.2. Lights

Whilst characteristics of the lights/lanterns themselves do not affect structural design, the focal plane height is a critical part of the design of an AtoN and can be referenced in the Basis of Design, to avoid having multiple reference/design documents. An example is shown below:

Example:

> ***Characteristics***
>
> *The characteristics of all AtoN lights, including colours, flash characters and range, should be referenced and preferably provided in a tabulated format. References to IALA Recommendations and Guidelines may be important inclusions.*
>
> ***Focal Plane***
>
> *The required focal plane can be listed here, including related levels of other structural elements, like platforms, etc. This is a critical part of any AtoN design and has impacts on structure height and design calculations.*
>
> ***Electrical Components***
>
> *Electrical standards could be referenced here, including the key parameters of the design, including voltages, autonomies* etc.

A.4.4.3. Daymarks

Daymarks are an important part of any AtoN design, and their size, wind loadings and other aspects do have impact on structure design. Requirements of daymarks can be referenced and those references could include IALA recommendations and guidelines or any local legislative requirements.

At a minimum, the following could be referenced:

- Shapes.
- Colours.
- Wind loads.
- Widths and heights.
- Profiles.
- Chromaticity
- Materials.
- UV resistance.
- Mounting methods

A.5. MATERIALS AND DURABILITY

A.5.1. MATERIALS

A section on materials provides a detailed summary of the materials to be used in the AtoN, including minimum standards of durability and design, fabrication and installation. Standards could also be referenced.

The following sub-headings are examples:

A.5.1.1. Carbon Steel

A.5.1.2. Stainless Steel

A.5.1.3. Fibre Reinforced Plastic (FRP)

A.5.1.4. Polyethylene

A.5.2. CORROSION ALLOWANCE

Corrosion allowances are a critical part of any structural design containing corrodible elements and could be referenced to clarify design life and the corrosion prevention methods to be applied.

A.5.3. COATINGS AND PROTECTIVE JACKETS

Details on corrosion protection systems could be referenced, including surface preparations, coating design life, details of proprietary corrosion protection systems to be used and reference to IALA chromaticity requirements.

A.5.4. CATHODIC PROTECTION SYSTEM

Details on cathodic protection systems could be referenced, including the relevant standards, types of cathodic protection required, impacts on corrosion loss and design life and methods of installation and attachment to the structures.

A.6. DESIGN CRITERIA AND PARAMETERS

A.6.1. GENERAL LOADS

This could include a general reference to the over-riding standards to which construction loads, including temporary design works, transportation and installation shall comply.

A.6.1.1. Dead loads

This could include a statement of self-weight of the structure and could include reference to a standard.

A.6.1.2. Live/imposed loads

This could include a statement on the platform live loads.

A.6.2. BERTHING AND MOORING LOADS

This could include a statement on berthing and platform loads if the AtoN structure is ever expected to have vessels moored alongside.

It could include reference to standards for the design of fender systems or wharf structures and could reference berthing speeds in m/s and vessel sizes.

A.6.3. ENVIRONMENTAL LOADS

Environmental loads are a critical aspect of any structural design, and this information can be provided in detail in this section.

Some examples are provided in the following sub-headings.

A.6.3.1. Wave combined environmental loads

Include any information from Metocean stations or locally obtained data and how the data was obtained.

A.6.3.2. Wind loads

Confirm the value of wind loading used and how the value was derived at e.g., standards or local information or a combination of both.

A.6.4. LOAD EFFECTS

A.6.4.1. Hydrodynamic coefficients

Confirm the standards and values used to determine the hydrodynamic coefficients.

A.6.4.2. Marine growth

Include If marine growth is likely to be a significant additional environmental load.

A.6.5. LOAD COMBINATIONS

As specified by relevant design standards.