# Failure Analysis Framework

## Roads and Bridges


**Local Government Engineering Department**

Local Government Division

Ministry of Local Government, Rural Development, & Cooperatives

Government of the People's Republic of Bangladesh



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Local Government Engineering Department

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The 'Failure Analysis Framework: Roads and Bridges', is a follow up to the previous document 'Failure Analysis Diagnosis Report', prepared through a collaborative and consultative process between Local Government Engineering Department (LGED) and the United Nations Office for Project Services (UNOPS). It aims to provide support documentation and a tool (Tool Kit) for assessing the shallow and deep causes of structural failures, identifying the triggering effects, and determining the most likely origin of failures in the life cycle of rural infrastructure roads and bridges.

This document is one of the deliverables of LGED and United Nations Office for Project Services (UNOPS) Sub-project, under the Joint National Resilience Programme (NRP) for the Government of Bangladesh. UNOPS provided technical assistance and advisory support to LGED in the implementation of the Sub-project.

The NRP is a joint programme of UNOPS, UN Women, and UNDP in partnership with the Local Government Engineering Department, Department of Disaster Management, Department of Women Affairs and Programming Division of the Government of Bangladesh (GOB). The Programme is funded by the governments of the UK, Sweden, and Bangladesh.

# Preface

As part of the National Resilience Programme's Failure Analysis workstream, the Local Government Engineering Department (LGED) and the United Nations Office for Project Services (UNOPS) collaborated to develop a series of technical documents, including:

**Diagnosis Report:** This report aims to identify hazards and risk factors throughout the lifecycle of transport infrastructure (roads and bridges) in Bangladesh. It covers areas such as Governance, Legal Framework, Planning, Detail Design, Construction, Operation, and Maintenance, and utilizes a Forensic Engineering Approach.

**Failure Analysis Framework:** This report provides support documentation and a toolkit for assessing both shallow and deep causes of structural failures in rural infrastructure roads and bridges. It also identifies the triggering effects and the most likely origin of the failures.

**Guidance Material for Road and Bridge Pathologies:** It offers guidance for analyzing 15 specific pathologies related to rural infrastructure, including 10 for bridges, 3 for pavement, and 2 for embankment.

**ToolKit and Toolkit User Manual:** This document provides a toolkit along with a user manual. The toolkit supports the assessment of structural failures in roads and bridges, while the user manual offers guidance on how to effectively utilize the toolkit.

This specific document pertains to the Failure Analysis Framework for Roads and Bridges.

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# TERMINOLOGY

**Failure Analysis Report:** The primary document of the sub-project, the FAR includes the theoretical basis of the project can be reviewed, the primary structural pathologies identified, first steps after failure along with the decision-making of the infrastructure from planning to operations. It also includes the road and concrete technology references.

**Fault Tree Analysis:** Fault analysis approach where the Boolean combinations of different factors lead to a parent case that is likewise combined with others. The process can be extended ad-infinitum until reaching the higher parent case, which is the fault to study. Thus, the tree can be read deductively (Top-Down) from some causes to the eventual apparition of the pathology or inductively (Bottom-Up) from the pathology to its latest causes.

**Analytic Hierarchy Process**: Multicriteria decision making approach, based on the comparison by pairs of the different possibilities, that results in the sorting of the possibilities according to their relevance.

**Top-Down Approach**: A type of forensic Engineering Study in which the designed engineer parts from the documentation available of the infrastructure project, from the Planning stage, Design, Construction and Operation/Inspection & Maintenance stages, and with the help of the ToolKit and Failure Analysis Report can investigate and narrow down the causes of a failure or pathology.

**Bottom-Up Approach**: A type of forensic Engineering Study in which the designed engineer parts from the visible field data extracted from an inspection and with the help of the ToolKit and related Guidance Material can deduce the Shallow and Deep Causes, which in other words, narrow down the causes that generated the observed pathology.

**Pathology**: Undesired phenomenon that produces a decrease in the comfort or the safety of a structure, deviating from its expected behavior.

**Shallow cause:** One of the situations that can lead to a pathology. Shallow causes are potentially visible and can be detected under inspection. Shallow causes are produced after a combination of flaws,

**Deep cause:** One of the situations that can lead to a shallow cause of a pathology. Deep causes reside in the documentation of the project and are not visible under an inspection of the structure, in other words, the root cause of the pathology.

**Toolkit:** The working tool for assessing the pathologies. On it, the Top-Down Approach and the Bottom-Up Approach can be selected to explore a wide variety of pathologies. It works conjunctively with the Guidance Material of the Pathology or with the Failure Analysis Report depending on the Analysis.

**Guidance Materials:** The main working documentation for the operators of the ToolKit. Within the Guidance Materials the Shallow and Deep Causes of the pathologies identified in the FAR can be found, along with the scoring helping system to the Toolkit.

**Operator**: Person who develops the analysis of an existent pathology. The operator is the user of the Toolkit.

**Programmer (ToolKit):** Person or people who develop the toolkit to be used by the operators.

# 1. BACKGROUND AND OBJECTIVES

## Background

Following the work performed at the previous stage related to a The Failure Analysis Diagnosis Report, which has set the ground for a series of typical structural failure pathologies, the present Failure Analysis Report is developed for the Local Government Engineering Department (LGED) in order to provide support documentation and a tool (Tool Kit) for the assessment of the Shallow and Deep causes of structural failures, the identification of the triggering effect, and most likely origin of the failure related to the life cycle of the structural design process of a rural infrastructure roads and bridges (Forensic Engineering).

The aim of this work is to develop an understanding of the importance of a) the design process of rural infrastructures in Bangladesh, b) the decision-making process, c) amended with additional knowledge on Material Technology for completeness of this report, which (the later) shall not be taken for granted, for the full benefit of this work.

## Objectives

The objectives of this report are:

- To understand the range of hazards and drivers of risk that may compromise the planning, design, reconstruction, repair and retrofitting, and operation of rural transport (bridges and roads) infrastructure in Bangladesh;

- To increase the understanding of resilient infrastructure in Bangladesh, by establishing a baseline of the rural transport infrastructure. This will include understanding the existing rural road infrastructure system, most common bridge and road pavement typologies, infrastructure distribution as well as the government's plans to expand and/or consolidate its infrastructure;

- To understand the institutional and policy environment and regulatory framework within which rural transport (roads, bridges) infrastructure is planned, designed, constructed, operated, maintained, repaired and retrofitted in Bangladesh and identify the main challenges the government faces to ensure sustainability and resilience of the growing investments in rural transport infrastructure;

- To identify advances and gaps in resilient infrastructure practices regarding planning, design, construction, maintenance, repair and retrofitting and provide an overview of the capacity and capability of the local engineering and construction industry.

- To understand the financial environment in which infrastructure are planned, designed, constructed, operated and maintained;

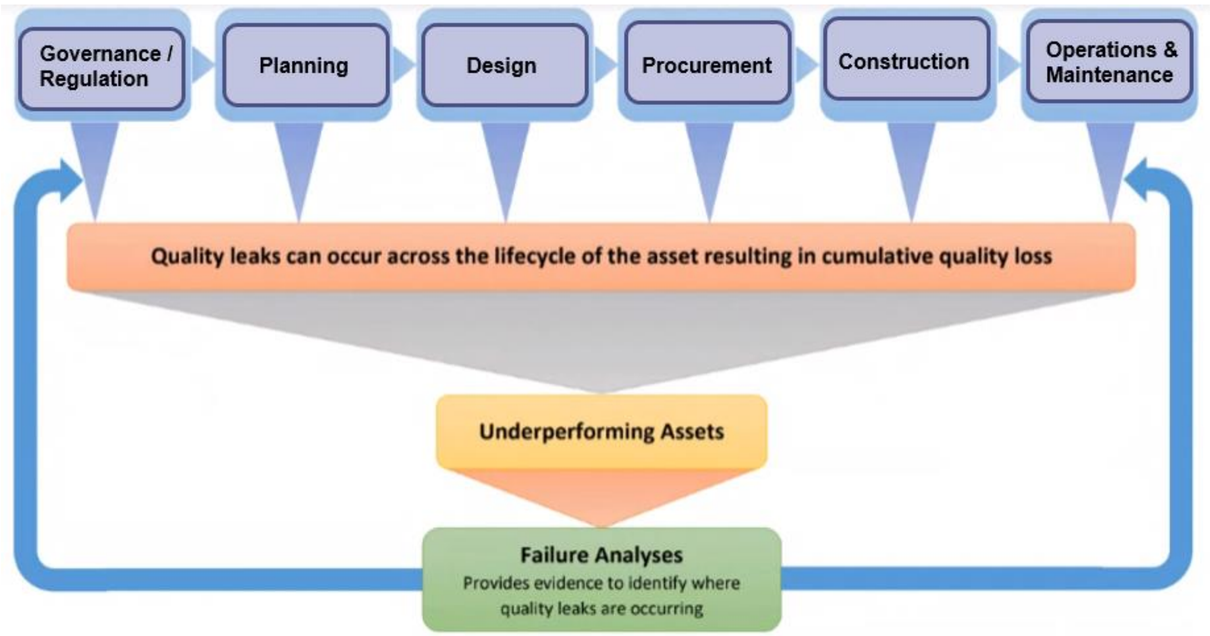
- Make recommendations to support the LGED advance infrastructure resiliency by highlighting and prioritizing key activities and investment opportunities throughout the implementation process (planning, design, construction and operation and maintenance) of rural transport infrastructure, and policy reforms and steps to ensure that new infrastructure is safe and resilient;

Moreover, a series of technical documents have been developed on the basis of this Failure Analysis Report for clarity and ease of the implementation of the Forensic Engineering Assessment process for LGED's engineers. These technical documents are:

- Workshop Presentation, including side Notes;
- Guidance Material;
- ToolKit and Toolkit Functioning;
- Pilot Test for Road and Bridges, for the calibration of the Toolkit;

Through this process, LGED will also be in a position to identify the principal investment areas and technical training required to improve the safety and resilience of transport infrastructure (roads and bridges) in Bangladesh.

Finally, this Failure Analysis Report has been prepared through a collaborative and consultative process between LGED and the United Nations Office for Project Services (UNOPS).



# 2. STRUCTURAL FAILURE TYPOLOGIES

It is important to note that any pathology generally has more than one possible cause. Each of these causes will have a percentage of the root cause of the failure and therefore it is more in the early stage to not rule out any plausible cause. The engineering failure analysis process shall be sufficiently robust to contemplate such causes and to identify those with the highest probabilistic effect given the gathered factual data of the investigation.

The structural pathologies in Bridges and Roads have been categorized as follows, following the preliminary assessment performed under the Diagnostic Report (Desk Study) and later adjusted based on the development of the study. The Guidance Materials and ToolKit will be the instruments of identification of the root cause of the observed pathology.

## Concrete Structures Pathologies

Regarding of the nature of the identified pathologies, they can be categorized in:
**Surface Decay (SD):** Surface Decay relates with pathologies not directly produced by the structural performance of the concrete element:

- **Spalling (SD1):** There is a material loss of concrete that might result in rebar exposing.
- **Corrosion (SD2):** Corrosion of rebars is the most common pathology in reinforced concrete, it is due to the exposure of the rebar to chlorides or moisture.
- **Honeycombs (SD3):** Honeycombs are the result of aggregate segregation, normally caused by a poor vibration or poor aggregate grading;
- **Scour and erosion (SD4):** Scour and erosion refer to the loss of concrete or ground as a result of a dynamic action such as water flow or traffic;


SD1. Spalling


SD2. Corrosion


SD3. Honeycombs


SD4. Scour and erosion

**Mechanical Decay (MD):** Pathologies in this category are normally related with the structural performance of the concrete element. Any deficiency can potentially lead to them.

- **Crackings (MD1):** Crackings are linear discontinuities on the concrete mix, most commonly on its surface. They are originated by a wide range of causes, and according to their cause their morphology can differ;

- **Deformations (MD2):** Every structure, due to its elastic nature, experiences deformations. However, by referring to deformations as pathologies it means deformations out of the admissible range. These excessive deformations can be related to loads the structure is not able to withstand;

- **Structural failure (MD3):** Structural failures are local or global collapses of structural elements;

MD1. Crackings. Crackings due to shrinkage

MD1. Crackings. Crackings due to loads

MD2. Deformations

MD3. Structural Failure

**Structural Components Behaviour (SCB):** In the structural component behaviour category, pathologies that induce malfunctions in the structural performance and therefore a different mechanical behaviour from expected are described.

- **Bearing malfunctioning (SB1):** Inadequate behaviour on the bearings;
- **Movement joints malfunctioning (SB2):** Inadequate behaviour in the joints;
- **Lack of continuity (SB3):** The connection between two elements does not have the required continuity and adhesion.

SB1. Bearing Malfunctioning

SB2. Movement joints malfunctioning

SB3. Lack of continuity

## Road structures pathologies

Following pathologies have been identified in roads:
**Embankments Material (EM):** Pathologies related to road embankments.

- **Scour and wash-out (EM1):** Material loss on embankments;
- **Excessive deformations (EM2)**: Settlements or lateral deformations;

EM1. Scour and wash-out

EM2. Excessive deformations

**Flexible pavement (FP):** Pathologies related to flexible (bituminous) pavements.

- **Surface cracking (FP1):** Apparition of cracking on pavement surface;
- **Potholes (FP2):** Bituminous loss and exposure of underneath layers;
- **Rutting (FP3):** Depression on road surface, especially under the wheel path

FP1. Surface cracking (alligator cracking)

FP2. Potholes

FP3. Rutting

# 3. FIRST STEPS AFTER FAILURE

In this section we need to be aware of the importance of those few first steps following a structural collapse, which will be essential in the forensic investigation and subsequent future awareness and remediation strategy.

The chapter presents different activities related to the recollection of site evidence and as-built technical documentation to set the base ground level for all the structural investigation to come. Note that some of these evidence may be of perishable nature (water level, water speed, sediment size, corrosion of steel surfaces, ..) and other such as debris could be removed from the original position due to subsequent human action for freeing the path, which would affect the forensic investigation of the structural failure.

Therefore, the swift action of the forensic engineer to visit the site is of essence as well as to have a clear working protocol to accommodate:

- Site Safety;
- Preservation of Perishable Evidence;
- Reserving Structural Samples;
- Documentation of Conditions;
- Initial Documentation Gathering;
- Preliminary Evaluation;

In that sense a working protocol related to the first steps after failure would allow to LGED's Local Engineering Team/Upazila Level engineers/Designated Failure Analysis Team to work efficiently and consistently across all the collapsed structures and therefore to obtain the largest possible amount of information to sustain a solid and robust investigation case, less prone to subjectiveness and inconclusive investigations.

## Site Safety

LGED Engineers shall be called upon to any partial or complete collapse of a structure and to provide first assistance in the safety and stability of the structure. This first step on site will require a wide range of expertise and standard care of duty to comply with technical, legal, economical and social requirements and/or constraints. The Engineer may be call upon to make decision such as, but not limited to:

- To assist in identifying the safest alternative route;
- To assist in identifying the safety perimeter zone;
- To assist in identifying components that are imminent to fall;
- To define stabilizing method for the upstanding remaining structure;
- To define structural samples;
- To define demolition sequence, with special attention to post- tensioned structures;

## Preservation of Perishable Evidence

After a total collapse, including partial collapse of a structure, the remaining condition of the structure and the surrounding elements indexes, constitutes the collection of "evidences" in determining the most likely cause of the failure and the potential contributing factors. Some of these "evidences" have a durable nature and will remain relatively intact, with minor weather deterioration, during the investigation period. However, other "evidences" are of perishable nature, which without a proper data recollection procedure, could jeopardize the outcome of the investigation.

The data recollection procedure shall be present and swiftly implemented on site. This procedure shall take into account the following items, but not limited to:

- To collect data on the Collapse Configuration;
- To collect data on the Post-tensioning Configuration;
- To collect data on the Structural Steel Configuration;

### Collapse Configuration

The collapse configuration can provide valuable information on the failure mechanism of the structure and to clearly rule out others. While the time is of essence in those first few minutes after collapse, the pressure to access the site for the search of potential human casualties (injuries or fatalities), and to secure the stability of the remaining structure, may lead to "disturb" structural components. It is therefore important that the configuration of the collapse be capture as quick as possible, in the shortest time as possible with the support of the following pre-established techniques:

- **Nomenclature for labeling key components** (i.e.: pre-established nomenclature for roads and bridges: Abutment East/Est, Pier 1, Pier 2, Beam 1, Beam 2, Deck, Bearings,...);

- Any structural piece that would fall in this key component labeling would be categorized as "**Defined Identity**" since its origin and final position as know;
- "**Undefined Identity**": this would correspond to any structural piece whose origin (non-collapse structure) is unknown. For such structural elements a nomenclature based on

serial numbers shall be used, although arbitrary serial number but unique to the nomenclature system;

- **Nomenclature for Match Marking**: Match marking system for structural segments is a very useful technique that constitutes in marking both sides of a given piece-meal segment that would reconstruct the original structural segment. The nomenclature for several piece-meal segment for a given key component could be the same but each segment with its our mar-matching line, say “Match #1, Match #2, …

### Post-Tensioning (PT) Configuration

Post Tensioned structures are structures that use high strength post-tensional steel used to balance a good percentage of the dead load and superimposed dead load. In that sense, the post tensioning system is a very attractive solution to limit the remaining surcharge (remaining dead load, live load and accidental loads) to be resisted by the reinforced concrete section. In the event of a collapsed structure, the information that could be obtained from the post tensioning condition, both at origin and on site, is of essence as often the examination of the cable duct and cable conditions does provide indices for the potential failure origin and failure mechanism.

Often, the loss of the post-tensioning cable section is observed, either originated from cable wire corrosion mechanism (water/chloride ingress for unbonded PT) or cable wire break (low cycle fatigue failure, Accidental overload condition.

Examination of the failure surface of the cable wire can assist in determining the suddenness of the load and the level of the ductility attained prior to its failure.

Special attention shall be given to the demolition works of the remaining structure (un-collapsed structure) in order to a controlled demolition sequence whereby the remaining PT force in the structure is unknown. The demotion strategy of such a structure shall be defined by experienced structural engineers.

### Structural Steel Configuration

Similarly, to the PT Cable wire, the structural steel surface of a fracture member can provide crucial information about the structural collapse. The examination of the failure surface could indicate the failure mechanism, either fragile or ductile, and whether the failure plane has been the structural steel connection (bolted or welded connection), and whether a crack induced failure mechanism was the origin of the failure. This later will have to be further verified and validated at the microscopic level through laboratory observation and numerical analysis of crack propagation theory (energy concentration at the crack front).

## Reserving Structural Samples

During the removal of structural debris, it is important to set aside a limited number of structural samples that could potentially be used for further verification or, alternatively, to rule-out failure hypothesis during the Forensic Investigation period. While the entire structure cannot be set aside due to its large scale, the presence of a Forensic Engineer during the debris removal is important in order to identify those sampling structural components to be reserved.

There are two (2) type of Structural Samples, Failed and Unfailed Components:

### Failed Components

Failed components are obviously components that will provide a large amount of information and therefore clues to the potential cause, or causes, of the structural failure. While at the initial stage of the investigation it is not possible to clearly identify the failed components that are the main "triggering effect" compared to those that failed as a "consequence", it is important to save most of the debris, within the Authority limit and capability.

### Unfailed Components

Unfailed components are also of interest for the following reasons, but not limited to:

- To rule-out failed components hypothesis, on the basis of clear evidence of unfailed components;
- To confirm the good performance of specific key structural component for best practice/resilience strategies;
- To develop material testing programs: composition, strength, porosity,...;
- To develop construction quality assurance investigation;

Structural samples shall follow a chain of custody in the event of a court trial, and therefore custody protocols, both surveillance, handling and storage requirements, shall be available or developed on the basis of the Authority space, equipment and human resource capabilities.

## Documentation of Conditions

High quality documentation of the existing collapse structures is of essence and provides solid ground for future developing failure analysis assumptions, as well for ruling them out. The most likely failure mechanism and origin of the cause of collapse, will be the assumption that would meet and validate most of the obtained evidence site data. Here after is a list of documentation of the condition that cat be developed, but not limited to:

### Field Notes

Field notes remains the most preferred data recollection option in Failure Analysis as it provides a quick reporting strategy prior to any removal of structural elements on site. This task shall be performed by an experienced engineer in order to record precisely the element position, orientation, and any other information relative to site condition/site debris, including a log of time when the event occurred.

Field notes can also include: Sketches, measurements, interviews, log of site visiting persons, ...

### High Quality (HQ) Pictures

Pictures are valuable data that is typically used to validate assumptions and conclusions, and very often a picture-from-a-picture is generated, hence the need for high quality pictures (larger than 1MB each). It is of essence that each picture is rapidly labeled using the Nomenclature for labeling key components amended with the orientation information (i.e.: North-South, East-West, ..).

Aerial pictures are highly recommended as it provided the overall site condition at the time of the collapse. This information becomes of relevance when the triggering effect is caused by adjacent structures or conditioned by the topographical/hydrological conditions.

### High Quality (HQ) Video

Similarly, to high quality pictures, HQ videos are of value and allows to validate potential contradicting information, to reassess some of the preliminary assumptions and/or conclusions, to validate structural element segment position, relative position and orientation. Consideration shall be given to having the HQ video be done a professional entity;

### Drones and Topographical Survey (3D Cloud)

Latest technology has allowed Forensic Engineering to rapidly obtain a numerical surface model of the collapse structure that is used to demonstrate the sequence of mechanisms that lead to the collapse structure. This constitutes the state of the art in Forensic Engineering as this method relies on stage-by-stage failure and dis-association of segments of a given structural elements/component.

## Initial Documentation Gathering

Gathering of the project documentation, both from the design and construction stage, are of essence. Typically, the following documents shall be obtained, but not limited:

### Planning Stage

- Geotechnical and Geological Site Investigation Report;
- Geotechnical and Geological Site Log (Boring, Pit, Water Table height and chemical composition, …);
- Geotechnical Interpretative Report;
- Topographical Site Investigation Report;
- Hydrological Site Investigation Report;

### Design Stage

- Design Brief;
- Set of Calculations;
- Specifications;
- Set of Drawings;
- Construction Sequence;
- Inspection and Test Plan;
- Independent Check Report;

### Construction Stage

- As-built Drawings;
- Construction Method Statement;
- Inspection and Testing Results;
- Material Certificates;
- Inspection Reports;

### Inspection and Maintenance Stage

- Inspection and Maintenance Investment Plan;
- Inspection and Maintenance Manual;
- Inspection and Maintenance Records;
- Maintenance Projects;

All the above mentioned list shall be amended with contractual documentation for a clear assessment and understanding of the scope of work and responsibilities of each stake-holders involved.

## Preliminary Evaluation

After having secured the site scene, defined and obtained the necessary site sampling and requested and gathered all possible technical documentation related to the infrastructure that have failed to perform as designed, it is time to set the forensic investigation approach.

Two (2) complimentary forensic investigation approaches are presented here after, whereby each of them are very well suited for specific failure analysis scenarios that will depend on the severity (extent versus intensity) of the observed damage/pathology. Both approaches use the same set of predefined pathologies but the first approach being the end result of the forensic investigation while the second approach would set the starting point of the investigation.

### 1st Forensic Investigation Approach: Top-Down Approach

The Top-Down approach is based on a rigorous and systematic engineering investigation, which sets to trace back the structure´s lifetime through the gathering of technical information across the different design stages of the structure, from Planning to Operational Stage, covering Design, Construction and Inspection Stages as part of the Design Life of the failed structure.

The most suited failure analysis technique for such forensic engineering investigation is the Fault Tree Analysis method (FTA).

The FTA allows to model key engineering processes (decisions, reviews, certifications,...) for each of the stages of the Design Life of the structure as a sequence of events that branches out to subsequent stages that would lead to modeling the full journey/pathway of decision making acts in order to identify the potential cause or causes of the observed failure.
While this approach is time consuming, it is very well suited for damages and failures that are:

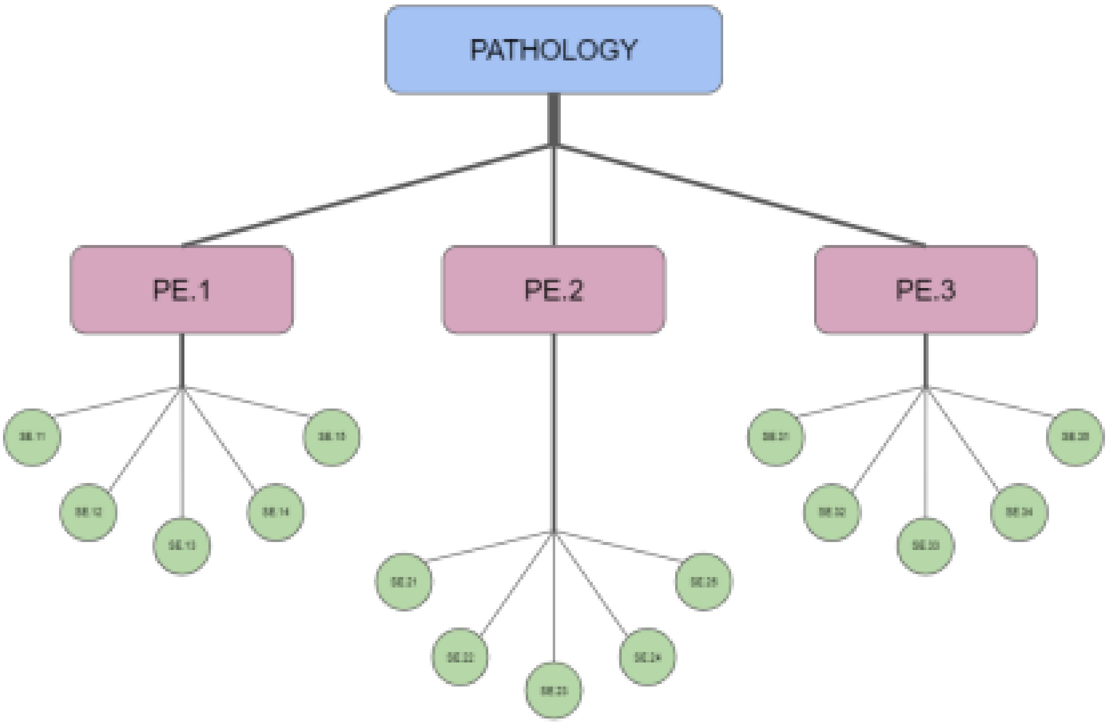
- Extensive (damages that are present over significant part of the structure), or;
- Significant partial or total collapse of the structure under no Exceptional Accidental Load condition (flood, vehicle impact, human terrorist attack…);

## 2nd Forensic Investigation Approach: Bottom-Up Approach

The Bottom-up approach is based on a rigorous but less systematic engineering investigation as the Top-Down approach discussed previously, which sets the investigation strategy from the observed damage/failure and lays down a series of hypotheses, correlated and uncorrelated, that shall be validated. While the number of hypotheses could be unlimited, an experienced engineer with local practice knowledge is of essence to set the first few credible potential root causes of the failure.

An hypothesis, in other words the potential cause of failure, will only be valid and retained should all the gathered data corroborate (damage location, orientation, color, testing…) such hypothesis. Any deviation of the investigated hypothesis in relation to the gathered data will lead to the possibility that other hypotheses will also be the potential cause of the failure to a certain degree.

This degree of involvement in the failure of different hypotheses (potential failure causes) lead to the Adjusted Analytical-Hierarchical Process (AAHP) as the failure analysis technique that is most suited for such forensic engineering investigation.




This approach is very suitable for:

- ○ Localized Damages;
- ○ Failure Modes which preliminary potential hypothesis could be laid out with some certainty (experienced engineer);

In parallel, the effort shall be maintained, but not limited to:

- To continue requesting and chasing Missing Information;
- To develop a Structural Numerical Model;
- To define a Material Test Program
    - Soil, Asphalt, Concrete, Reinforced Concrete, Steel Plates...;
        - Descriptions and objectives;
        - Strength and Ductility Test;
        - Fatigue Test;
        - Chemical Composition and/or Infiltration Test;

# 4. GOVERNANCE AND LEGAL FRAMEWORK

For infrastructure development work the institutional and regulatory framework plays an important role. The codes and standards guide the construction quality, whereas, the responsibilities are shared with several key stakeholders.

This section´s objective is to confirm that a) it exists a well-structured governance and legal framework, b) key stakeholders´ role and responsibilities are clearly defined and well understood by all professionals, c) a competitive and robust market of engineering consultant firms and contractors do exist (capacity and capability), and d) the range of construction material (accessibility and quality assurance).

## Governance and Legal Framework

Bangladesh is the eighth-most populous country in the world, with a population exceeding 161 million people and with an area of 147,570 square kilometers, making it one of the most densely-populated countries in the world. The country is run by a unitary government – no state or provincial government.

The administrative system is highly centralized, and most of the decisions come from the central government. Ministries' functions are governed by the Rules of Business and Allocation of Business as issued and amended by the government from time to time. Under each of the ministries there are a number of implementing agencies that implement the decisions of their respective ministries. The implementing agencies operate their businesses through their subordinate offices at district and sub-district levels.

The field offices are the deconcentrated offices of their headquarters with limited power and authority. The LGED is one of the implementing agencies under the ministry of Local Government, Rural Development & Cooperatives which also operates through its divisional, regional, district, and sub-district offices.

LGED's roles and responsibilities are driven by the Government's Allocation of Business and guided by several sectoral policies, strategies, guidelines and manuals but not limited to the following:

- Rural Development Strategy 1984;
- Rural Infrastructure Strategy Study 1996;
- National Rural Development Policy 2001;
- National Land Transport Policy 2004;
- Urban Management Policy Statement 1999;
- National Water Policy 1999;
- Rural Roads and Structures Maintenance Policy 2013;
- Poverty Reduction Strategies;
- Five Year Plans;
- Perspective Plans;
- Bangladesh Delta Plan 2100;
- Environmental Laws; and

- Bangladesh Climate Change Strategy and Action Plan 2009.

LGED also follows a number of the international conventions and treaties to which Bangladesh is a signatory - for example, Millennium Development Goals (MDGs), Sustainable Development Goals (SDGs), Paris Agreement 2015 and the Sendai Framework 2015-2030.

Bangladesh Climate Change Strategy and Action Plan (BCCSAP) 2009, Seventh Five Year Plan (2016 to 2020), Perspective Plan, SDGs, Paris Agreement, and Sendai Framework particular strategies/documents that guide LGED to consider climate change adaptation and mitigation measures as well as resilient actions in their infrastructure projects/programmes.

In general, there is no further approval required during construction of roads and bridges once it is approved by the ECNEC unless relocation of utilities is needed. But the following cases, permission from other public sector organizations may be required while design the project:

- Permission from the Railway authority is needed in case of construction of flyover and level crossing if the road crosses the railway track.

- 'No objection' for navigational clearance- both horizontal and vertical - from Bangladesh Inland Water Transport Authority (BIWTA) have to be obtained for construction of bridges.

- Permission from Bangladesh Water Development Authority (BWDA) and Water Resources Planning Organisation (WARPO) is needed in case of construction of a new bridge either upstream or downstream at the proximity of existing barrage or dam.

- Permission is needed from the Department of Environment.

- 'No objection' is needed from the Department of Bangladesh Haor and Wetlands Development if the project is located in some specified areas.

- 'No objection' is needed from the Forest Department as the project is located in some specified areas.

Note: The key public authorities in case of bridge construction are:

- Bangladesh Bridge Authority (BBA): responsible for bridges if the total length is equal to or larger than 1500 m irrespective of national or rural road network.

- Roads and Highways Department (RHD): responsible for bridges of length less than 1500 meter on national road network;

- LGED: responsible for bridges of length is less than 1500m on rural road networks.

In addition to the above Public Authorities, Local Government Institutions such as City Corporation and Municipalities also build bridges within their jurisdiction, however, those are largely small and simple bridges.

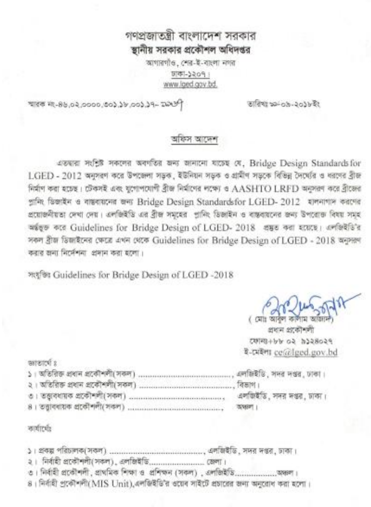
## Codes and Standards

The following Codes, Standards, and Manuals/Guidelines are used in the design of roads and bridges of LGED:

- **Codes**:
    - AASHTO LRFD12 Bridge Design Specifications, Sixth Edition (2012);
    - Guidelines for Bridge Design of Local Government Engineering Department - September 2018;
- **Standards**:
    - Road Design Standard (2004) by the Planning Commission of Bangladesh;
- **Manual and Guidelines**:
    - Pavement Design Catalogue (2003) by
    - Road Structure Manual (2008) by Design Planning & Management Consultants Ltd.;
        - Part A: Design criteria, guidelines and design methods for RC/PC Bridges, Box culverts and Slope Protection Works;
        - Part B: Standard Drawings (Single Lane Bridges);
        - Part C: Design examples of Bridges, Box culverts and Slope Protection Works;
        - Part D: Standard Drawings (Double Lane Bridges);
        - Part E: Design Examples for Bridges;
- **Specifications**:
    - ASTM 14 C 494 Standard Specification for Chemical Admixtures for Concrete;

In summary, LGED is currently using "**AASHTO LRFD Bridge Design Specifications, sixth Edition (2012)**" for design and evaluation of rural bridges.

The bridge loading considers AASHTO-LRFD and **Bangladesh National Building Code (BNBC). "Building Code Requirements for Structural Concrete (ACI 318-14)"** and "ASTM 14 C 494 Standard Specification for Chemical Admixtures for Concrete".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অফিস আদেশ

এতদ্বারা সংশ্লিষ্ট সকলের অবগতির জন্য জানানো যাচ্ছে যে, Bridge Design Standards for LGED - 2012 অনুসরণ করে উপজেলা সড়ক, ইউনিয়ন সড়ক ও গ্রামীণ সড়কে বিভিন্ন দৈর্ঘ্যের ও ধরণের ব্রীজ নির্মাণ করা হচ্ছে। টেকসই এবং যুগোপযোগী ব্রীজ নির্মাণের লক্ষ্যে ও AASHTO LRFD অনুসরণ করে ব্রীজের প্লানিং ডিজাইন ও বাস্তবায়নের জন্য Bridge Design Standards for LGED- 2012 হালনাগাদ করণের প্রয়োজনীয়তা দেখা দেয়। এলজিইডি এর ব্রীজ সমূহের প্লানিং ডিজাইন ও বাস্তবায়নের জন্য উপরোক্ত বিষয় সমূহ অর্ন্তভূক্ত করে Guidelines for Bridge Design of LGED- 2018 প্রস্তুত করা হয়েছে। এলজিইডি'র সকল ব্রীজ ডিজাইনের ক্ষেত্রে এখন থেকে Guidelines for Bridge Design of LGED - 2018 অনুসরণ করার জন্য নির্দেশনা প্রদান করা হলো।

সংযুক্তিঃ Guidelines for Bridge Design of LGED -2018

( মোঃ আবুল কালাম আজাদ )
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৩। নির্বাহী প্রকৌশলী, প্রাথমিক শিক্ষা ও প্রশিক্ষণ (সকল) , এলজিইডি................অঞ্চল।
৪। নির্বাহী প্রকৌশলী(MIS Unit),এলজিইডি'র ওয়েব সাইটে প্রচারের জন্য অনুরোধ করা হলো।


Local Government Engineering Department

PAVEMENT DESIGN CATALOGUE

JULY 2003

## Key Stakeholders Definition

There lies a highly systematic coordination between the actors and stakeholders in the government infrastructure sector.

For any infrastructure proposal, either for new projects or amendments/retrofit of existing ones, shall pass through the **Planning Commission**.

The Planning Commission invites key stakeholders like the Ministry of Finance, Ministry of Environment, Forest, and Climate Change, Ministry of Women and Children Affairs, and Implementation Monitoring and Evaluation Division (IMED) to take part in the discussion. Once the Planning Commission agrees to a project then it goes to the Executive Committee of the National Economic Council (ECNEC) chaired by the Hon'ble Prime Minister where key ministers are members for final approval of the project.

However, it has been identified that there is no regulation and enforcement for overloaded trucks.

The stakeholders of LGED can be broadly divided into two categories: **Internal Stakeholders** and **External Stakeholders**. The **External Stakeholders** are again classified into two subcategories- a) **State Agencies** and b) **Private Entities**.

In the development work, **LGED internal staff officers** are involved throughout the project cycle and along with them external stakeholders from different ministries, Planning Commission or IMED are associated in varying levels of roles and responsibilities. For example, the responsibilities of LGED under the Ministry of Local Government Rural Development, and Cooperatives lie in the operation oversight; whereas the role of the Planning commission is in operational appraisal and approval; on the other hand, Ministry of Finance (MoF) will look into operation budget allocations and fund release.

The **Internal Stakeholders** are essentially the departments within LGED itself. It consists of essentially seven different units namely:

- Planning Unit: Responsible for the formulation and approval of development projects/programs and to ensure they are coordinated and facilitated.
- Design Unit: Provides structural design support as well as verification of design submitted by different projects.
- Project Monitoring and Evaluation Unit: Remains deeply involved in the budgetary allocation for various projects and programmes undertaken by LGED in a financial year. reviews the physical and financial progress of the projects through holding monthly regular meetings at the LGED headquarters chaired by the Chief Engineer, LGED and attended by all Project Directors and other senior officials.
- Road Maintenance and Road Safety Unit: Responsible for accomplishing cost-effective maintenance management and implementation of rural road and culvert maintenance programs.

- Procurement Unit: Responsible for all the activities related to procurement and support procurement professional development.

- Quality Control Unit: Monitors required standards of construction materials, performs laboratory tests whenever necessary and also ensures capacity development in this regard.

- Audit Unit: Primarily provides support to the project director offices in drafting the reply to the queries raised by the external auditors. However, Audit unit usually does not carry out any internal audit.

The private entities under the **External Stakeholder** are essentially the contractors, engineering consulting firms, quality assurance firms and operations maintenance firms. However, currently, quality assurance or operations and maintenance firms are not present in the country. Under the current practice, the engineering consulting firms provide engineering technical advice and in developing engineering documentation ("Project") for approval, bidding, construction and operation and maintenance processes. On the other hand, the contractors undertake the construction of the "Project" under the technical requirements stated in the engineering documentation by means of construction equipment, labour and material. Public Procurement Act 2006, Public Procurement Rules 2008 and Standard Bidding Documents among others provide a clear description of the duties and professional liabilities of the contractors and consultants.

The roles and responsibilities of key **External Stakeholders** is presented below:

| External Stakeholder (State Agencies) | Roles and Responsibilities |
|---|---|
| **LGD, Ministry of Local Government Rural Development, and Cooperatives** | Operation oversight being the LGED's parent ministry |
| **Planning Commission** | Operation appraisal and approval |
| **IMED** | Monitoring and Evaluation |
| **Central Procurement Technical Unit** | Oversight function of application of procurement legislations and management of e-GP portal |
| **Ministry of Finance (MoF)** | Operation budget allocations and fund release |
| **Economic Relations Division, in case of Multilateral Development Bank financing project** | Liaison with the World Bank, Asian Development Bank, JICA, KfW, IFAD, etc. |
| **Comptroller and Auditor General (C&AG)** | External audit of the operation |
| **Anticorruption Commission** | Corruption prevention and investigation and prosecution |
| **Institution of Engineers of Bangladesh** | Facilitate arbitration |
| **Police Department (Traffic Control and Over)** | Traffic Control |

| External Stakeholder (Private Agencies) | Roles and Responsibilities |
|---|---|
| **Engineering Consulting Firms** | Assist in providing engineering technical advice and in developing engineering documentation ("Project") for approval, bidding, construction and operation and maintenance processes. |
| **Contractors** | Undertake the construction of the "Project" under the technical requirements stated in the engineering documentation by means of construction equipment, labour and material. |
| **Quality Assurance / Quality Control Laboratories Not present at this stage in Bangladesh. This role is performed by LGED Quality Control Unit (refer here below) -** | Independent firms responsible for auditing the construction process (material purchase, handling, storage, mixing, assembly, …) and to perform material tests, both destructive and non-destructive testing. |
| **Operation and Maintenance Firms**<br><br>**Not present at this stage in Bangladesh. This role is performed by LGED Road Maintenance and Road Safety Unit (refer here below) -** | Undertake the Inspection and Maintenance function during the operational stage of the "Project". Duties are related to Inspection, Repairs, Replacement of parts of the "Project" to preserve the asset desired operational and service level to the Public. |
| **Public** | Users |

## Standard of Care

Standard of Care requires the compliance of the following two conditions:

i. what skills/degrees should have the professional to perform the design/construction/operation of a Road-Bridge Infrastructure, and
ii. capacity to manage uncertainties (unknown and uncontrolled factors) by providing a judgement based from experience.

The Standard of Care is not what a professional should have done but rather what a competent professional actually did in similar conditions.

# 5. PLANNING

## Pre-feasibility Studies

The preliminary evaluation of complex interventions in the public domain, such as the construction of roads and bridges, is of essence and are frequently neglected by an urgent need, either from society or politicians. As public infrastructures, tax payers' money shall be wisely invested (secured through-out state budget and appropriate procurement process) for an efficient, resilient and robust infrastructure.

Under this framework, the Planning stage of any project, either short term (less than 2 years) or long term projects (5-10 years), becomes crucial as it shall address the project from its holistic and multidisciplinary view, and to mitigate potential financial and technical risks. While the concept of "Risks" seems detrimental to the development of a project, it sets the required mitigation measures (mitigation actions) as soon as possible for the development of a solid and viable design and construction infrastructure.

Exploratory studies, often termed feasibility studies, are a key step in the Planning stage. Such studies shall:

- confirm assumptions, both technical and financial;
- confirm potential procurement process;
- identify new potentials risks and assign risk' owners;
- provide recommendations for new studies;

to support a more robust, resilient design/construction, thereby reducing costs and minimizing potential unknowns that would harm the implementation of the project.

The scope of work for these pre-feasibility studies shall not be onerous, but just enough to validate essential assumptions that have an important impact on the development, either technical or financial, to the project. In summary, these studies shall allow to eliminate or mitigate any potential "show stopper" that would invalidate the project.

Here is a list of the pre-feasibilities studies typically undertaken on large projects, but not limited to:

### Business Case

A business case provides justification for undertaking a project, estimated programme and cost. It evaluates the benefit of several alternative routes, and sets the risks. A business case tends to lead to the definition of a preferred option, when several alternatives are studied. Typically, the Business Case is developed using the following key sections, but not limited to:

1. **Strategic context**: The compelling case for infrastructure development;

2. **Technical alternatives**: Scenarios of infrastructure technical solutions, both land use and structural typologies;

3. **Economic analysis**: Return on investment based on investment options (Publically funded, or Private-Public Partnership -PPP-);

4. **Financial approach**: Derived from state/region sourcing strategy and/or design/construction procurement process strategy for a given time frame;

5. **Management approach**: Project stages, Procurement Process, Roles and Responsibilities (Governances Structure) , life cycle choice, Concession periods, Payment mechanisms, etc;

The Business Case shall cover the whole life cycle of the infrastructure, from Planning to Inspection and Maintenance and, eventually also including Demolition stage;

Through this approach, the business case document becomes a record of the recommended option with rationale and evidence to support the decision.


## Preliminary Technical Studies for Road and Bridge Infrastructure

### Topographical and Bathymetry Study

Topography studies describe the physical geometry of a defined area of land. Topography information typically includes i) the geometry of natural formations such as mountains, rivers, lakes, and valleys, and ii) man-made characteristics such as roads, tunnels, bridges, dams, and residences.

Topography maps record these geometry definitions by means and elevation referenced to the sea level (the surface of the ocean) using isolines (line connecting points in the space of same Altitude).

For a specific giving position on the map, Latitude information is also provided on Topographical maps. Latitude is related to the north/south position of a given location in reference from the Equator, while the Longitude provides the East/West position related to the Greenwich line (Prime Meridian).

A topographical map could show a bridge location (scale 10 cm for 100 m or 1: 1 000) or a region of a country (scale 1 cm for 1 000 m or 1: 100 000).

### Geotechnical Investigation Campaign and Interpretative Report

Geotechnical Investigation Report and the corresponding Interpretative Report can be defined as a comprehensive geological and geotechnical assessment of the soil condition at a particular area where a project will take place.

In addition to a geotechnical desk study of the future project area, the geotechnical Investigation Report includes soil sampling tests in accordance with the geotechnical specifications that are typically discussed, adjusted and agreed with the geotechnical contractor due to their way and means.

Special attention shall be taken in the definition of the soil sampling depth as these shall be as close as possible to the future road/bridge foundation level, in order to obtain the closest exact soil parameters for the design, and therefore limit the risk of uncertainties and overdesign, with both would result on an extra construction cost.

A **Site Investigation Campaign (sampling)** is defined by, but not limited to:

- List of technical standards to be applied;
- Number, mapping / location, depth of boreholes;
- Soil/Rock drilling & sampling methods (Soil Investigations);
- Number and location of standard penetration tests (SPT);
- Number and location of cone penetration tests (CPT);
- Number and location of field vane shear tests;
- Number and location of disturbed and undisturbed soil/rock samples;
- Groundwater sampling and water level measurement;
- ...

Followed by a **Laboratory Testing Programme**, similar to the following, but not limited to:
**Soil Material Properties**

- Moisture content test;
- Atterberg limits tests;
- Specific gravity of soil;
- Dry density of soil;
- Particle size distribution;
- Compaction test;
- ....

**Groundwater Properties**

- Ground water level measurement;
- Results on chemical ground water analysis and evaluation of level of aggressiveness to future concrete/steel structures (pH value, sulphate content and chloride content tests, …);
- ...

**Soil Capacity**

- Unconfined compression strength;
- Consolidation test (one-dimensional consolidation properties);
- Consolidated undrained triaxial compression test;
- Point load test (for Rock Only);
- Uniaxial compressive strength test (for Rock Only);
- Direct Shear (Field vane shear test - On site test);
- SPT (Standard Penetration Test - On site test);
- CPT (Cone Penetration Test - On site test);
- ...

The Geotechnical Interpretation Report shall indicate to the Road and Bridge Engineer:

- The site conditions (soil parameters for every soil layer encountered during the geotechnical investigation);
- The foundation typology and foundation level, and;
- Health and safety related issues to Earthworks;

### Regional and River Flow Hydrology

The regional and River Flow Hydrology should be completed as part of the preliminary plan. The detail of the study shall be commensurate with the importance of and risks associated with the structure. Hydrologic, hydraulic, scour and stability studies are concerned with the prediction of flows and frequencies and with the complex physical processes involving the interactions and actions of water and soil during the occurrence of the predicted flood flows.

The following flood flows should be investigated, as appropriate, in the hydrologic studies:

- The 100-year flood, for assessing flood hazards and meeting floodplain management requirements.
- The overtopping flood and/or the design flood for bridge scour, for assessing risks to highway users and damage to the structure and its roadway approaches.
- Check flood, for the evaluation of catastrophic flood damage at high risks sites.
- Check flood for bridge scour, for investigating the adequacy of bridge foundations to resist scour
- Historical floods to calibrate water surface profiles.

### Road and Bridge Alignment - General Arrangement - Study

Potential for additional alternatives (bridge length, typology, …)
Road and Bridge plan view (1:1000 - 1:500) scale;

### Environmental Impact Assessment

The United Nations Environmental Program (UNEP) defines Environmental Impact Assessment as a tool used to identify the environmental, social and economic impacts of a project prior to decision-making.

Therefore, the EIA aims to predict environmental impact along all the stages of a project development, to define environmental threshold values to be met and its measurement frequency and to some extent present options to decision-makers.

By using EIA procedures, projects are better integrated in its environment and account for a sustainable performance of the infrastructure, resulting in a reduction of Environmental cost. Although legislation and practice vary from country to country, the EIA has a clear objective and framework, which can be summarized as follows, but not limited to: :

a. Screening: To determine which projects require a full or partial EIA study;

b. Scoping: To identify which potential environmental impacts are relevant to assess (Fauna, Flora, Cultural, Heritage, …) based on local legislative requirements, international conventions, expert knowledge and public involvement. To identify threshold values for acceptance/rejection and list of possible alternative solutions that would avoid , mitigate or compensate adverse impacts;

c. Assessment and evaluation of impacts: To predict and identify the likely environmental impacts of a proposed project and finally to derive terms of reference for the impact assessment;

d. Decision-making on whether to approve the project or not, and under what conditions; and

e. Monitoring compliance, and environmental auditing throughout the different stages of the project development.

### Public Utility Plan

Public Utility Plan (PUP) refers to a wide range of Utilities Drawings, above and below ground, that includes trenches, conduits, manholes, service rooms, cabinets, tower/poles, stations, substations,... reference to a local or national grid line. These utilities are typically, but not limited to the following:

- Potable water network;
- Surface/Surface run-off water drainage network;
- Sewage network;
- Gas network;
- Fire protection network;
- Low and Medium voltage electrical network;
- High voltage network;
- Telecommunication network (voice and data);
- Public lighting network;

Other PUP that could be of interest are:
- Flora;
- Road Signaling;
- Street Furniture:
- ...

It is good practice to visit the project construction site in order to validate the PUP documentation. Most of the PUP can be easily checked and contrasted against visible objects such as towers/poles, cabinets, manholes, …), which would give a good sense of the exactitude of the provided documentation.

All utility networks present at the construction site shall be protected at all times in order to maintain the continuity of the utility service, with special attention to those underground, which shall be labeled and marked accordingly.

### Property Plan

Property Plan is also referred to as Cadastral Plan that provides information on the land i) use, ii) boundaries and iii) reference number.

Property Plan is a detailed plan meaning from a Master Plan of a sector/municipality, which shall guarantee that the future road or bridge is in public land.

Should the future infrastructure cross some of the private properties a process of expropriation shall be undertaken, and shall be managed with confidentiality due to the potential economic impact to private owners and state/regional agencies.

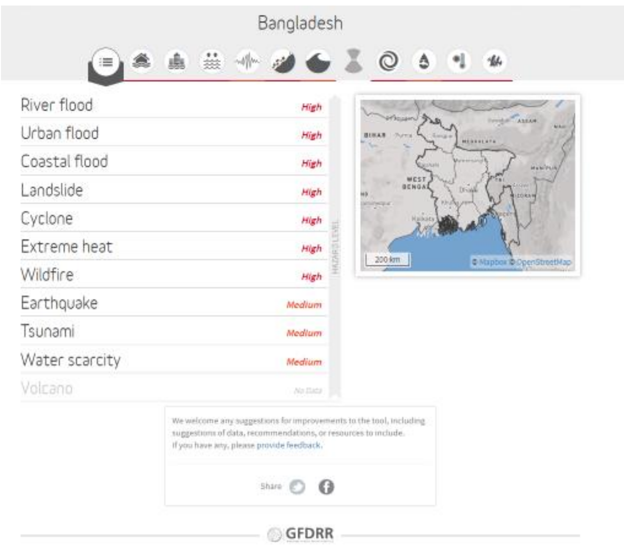
### Region/District/Municipality Limit Plan

Similarly, to Property Plan, Region/District/Municipality Land use plans shall be obtained with the same objective as indicated previously, in order to guarantee that all future roads or bridges are within the public limit.

## Natural Hazard Studies

Bangladesh is exposed to multiple natural hazards due to its geographical position in the Bay of Bengal, its physio-topographic and climatic profile.

The average level for all the key potential natural hazards is medium to high, driven to the high end of the scale (according to the *'ThinkHazard'* methodology, tool developed by the Global Facility for Disaster Reduction and Recovery (GFDRR) and similar compared to other countries in the region, their recurrence and intensity cause concerns in design, construction and operation of road and bridge infrastructures, especially because of the unexpected and sudden change of the hazard profile, leading to the vulnerability of the infrastructure and population.




The most important hazards are floods (river and coastal flood), landslides, cyclones, extreme heat, wildfire, and to a certain degree earthquakes and tsunamis. Significant coastal erosion phenomena are also observed, with special attention to the Ganges river delta. Note that wildfire has the least impact on roads and bridges infrastructure compared to the remaining listed key hazards.

The above classification is consistent with the risk classification given by INFORM (Category: High), ranked 26 out 191 countries, INFORM is a collaboration of the Inter-Agency Standing Committee Reference Group on Risk, Early Warning and Preparedness and the European Commission.

In addition, there is a lack of readily accessible studies, such as an atlas of natural hazards or zoning, for use by political and technical decision-makers responsible for road and bridge design.

Likewise, apart from some of the technical staff - and particularly in associations and professional orders - there is insufficient awareness of the risks posed by natural hazards in the infrastructure design and construction sector.

There is also an insufficient capitalization and dissemination of the achievements of the various projects which could help improve construction.

So, if the hazards are taken into account at the national level by the agency dedicated to disaster management, and there is a database and guidelines on this subject, it is important to disseminate and create awareness of all stakeholders in the infrastructure sector, considering the risk at every stage of the project/construction/operation, during the life cycle of the infrastructure.

Figures: ThinkHazard Bangladesh, GFDRR (https://thinkhazard.org/)

Wild Fire

Extreme Heat

Cyclone

Urban Flood

River Flood

Coastal Flood

Tsunami

Landslide

Earthquakes

## Successful Completion of the Planning Stage

Following the description made above in this Chapter, it is considered that a minimum of technical documents be developed and made available prior starting the early stages (Concept Stage, Scheme Design Stage) of the Design Stage, but not limited to:

Collateral Technical Documents:

- Region/District/Municipality Limit Plan;
- Property Plan;
- Public Utilities Plan;
- Environmental Impact Assessment Study;
- ...

Technical Documents:

- Geotechnical Site Investigation and Interpretative Report;
- Hydrological Studies - Regional and River Flow Hydrology - ;
- Natural Site Hazard Studies;
- Road and Bridge General Arrangements;
- Traffic Demand;
- Special Technical Specification Requirements;
- …

# 6. ROAD BASE AND SURFACE PAVEMENT MATERIAL TECHNOLOGY

In this section, the different composing parts of the road are going to be discussed, from the top layers, the bituminous carpeting or asphalt, to the main contact with the soil, the embankments.

This summary of the road components shall not override the prescriptions of the existing and future Codes and Standards applicable to a particular project, since its intention is to give insight in the technology of use, materials and good practices for properly executing the described component.

## Bituminous Carpeting (BC)

Bituminous mixes are designed to provide a surface course or carpet as the upper layer of the pavement section. This surface is in contact with traffic loads. It provides a continuous and smooth surface to vehicles, in order to make transit both safe and comfortable.

It has a major function as a structural portion of the pavement and it is also designed to resist the abrasive forces of traffic, and to provide a skid resistance surface.

This item consists of one course of pre-mixed bituminous mixtures constructed on a prepared and accepted base course or other road bed in accordance with the Road Design Standards and Pavement Design Catalogue. It also should be in conformity with the required lines, levels, grades, dimensions and typical cross sections.

The **materials** for bituminous mixes shall be composed basically of coarse mineral aggregate, fine mineral aggregate, filler and bituminous binder. The several mineral constituents shall be sized, uniformly graded and combined in such proportions that the resulting blend meets the grading requirements for the specific type of mix. To such composite blended aggregate shall be added bitumen within the percentage limits set in the specifications for the specific type. The resultant density of the compacted bituminous mix shall be between 2250 and 2400 $Kg/m^3$.

Grading of coarse aggregate and bitumen content shall conform Table 9.1. of the Pavement Design Catalogue:

| Serve size (mm) | For 25 mm B.C. | For 40 mm B.C. |
|---|---|---|
| | % by weight passing | % by weight passing |
| **25** | 100 | 100 |
| **20** | 100 | 75-100 |
| **16** | 100 | - |
| **12.5** | 75-100 | 60-80 |
| **10** | 60-80 | - |

| Serve size (mm) | For 25 mm B.C. | For 40 mm B.C. |
|---|---|---|
| | % by weight passing | % by weight passing |
| **6.3** | - | - |
| **4.75** | 35-55 | 35-55 |
| **2.4** | 20-35 | 20-33 |
| **0.6** | 10-20 | 6-18 |
| **0.075** | 2-8 | 2-8 |
| **Bitumen content % by weight of total mix** | 5.2% to 5.8% | 4.9% to 5.5% |

The coarse aggregate is the material fully retained on a 4.75 mm sieve and consists of clean crushed rock or crushed gravel or a combination of both, free from decomposed stone, organic matter, shale, clay or any other detrimental substances. It should present:

- Aggregate Crushing Value (AIV) not greater than 30 or LAA of 40

- Bulk Specific gravity not less than 2.5

The fine aggregate is the portion of the aggregate passing a 4.75 mm sieve and shall consist of natural sand, stone screenings or a combination of both, composed of clean, hard, durable particles rough surfaced and angular, free from vegetable matter, soft particles or other detrimental material.

Bituminous material shall be 60/70 or 80/100 penetration grade straight run bitumen complying with the requirements of ASTM/AASHTO.

Bituminous mixtures **process** must start ONLY when the surface is dry, the weather is not rainy and the prepared roadbed is in a satisfactory condition. In order to achieve this condition a prime coat is to be applied and cured to the surface of the granular base material. In case of an existing bituminous surface (two course carpeting) a tack coat shall be applied.

The process of obtaining a bituminous mix initiate by mixing the aggregates together to give a stockpile of the required grading. The bitumen and aggregates will then be separately heated to a temperature between 140º C to 155ºC for bitumen, and 150ºC to 170ºC for the aggregates. These two components are to be combined in the amount of each fraction of aggregate required to meet the mix formula for a particular mixture. The proper amount of bituminous material shall be distributed over the mineral aggregate and the whole thoroughly mixed to produce a homogeneous mixture in which all particles of mineral aggregates are coated uniformly.

The laying temperature of the mixture shall not be less than 130ºC. The mixture shall be laid to a uniform thickness to the grade, elevation and cross-section shape intended.

Immediately after laying, the material needs to be compacted using a power-driven road roller. All rollers must be self-propelled, using an approved roller (preferably a pneumatic type roller) and a minimum of five passes shall be made. When the temperature falls below 90ºC compaction is not permitted.

Both longitudinal and transverse joints in successive courses shall be staggered so as not to be one above the other.

## Seal coat

A seal coat or slurry seal consists of a thin bituminous mixture to provide surface intended properties to the pavement surface as anti-skid properties, smoothness or regularity which would be more complicated with regular bituminous carpeting.

Bituminous **material** has to be 60/70 or 80/100 penetration grade complying with the requirements of ASTM/AASHTO.

The aggregates shall consist of 6.3 mm downgraded stone. the aggregate may be mixed with natural sand in order to achieve a specified grading requirement. Sand should not present plasticity, must be clean and free from deleterious substances. The mix of aggregates shall meet the following grading:

| Sieve (mm) | % By weight passing sieve |
|---|---|
| **6.3** | 100 |
| **4.75** | 80-100 |
| **2.4** | 70-95 |
| **0.6** | 20-50 |
| **0.075** | 5-15 |

The **Process** is similar to that explained for bituminous carpeting. The aggregate mixed with bitumen is to be laid over the bituminous carpeting to a uniform thickness at least 25% greater than the compacted thickness and immediately compacted fully with a power-driven road roller.

## Tack coat

A tack coat is a bituminous slurry intended for binding together two asphalt courses. It should be only applied between two bituminous surfaces.

Bituminous tack coat **material** is 60/70 or 80/100 penetration grade bitumen complying with the requirements of ASTM/AASHTO.

In order to properly execute the tack coat, the **process** shall be: Immediately before applying a tack coat all loose stone dirt and other objectionable material should be removed from the surface with a broom or blower.

Tack coat shall be applied by mechanical distributor or manually at a rate of 0.5 litre/$m^2$ and at a temperature between 135ºC and 155ºC.

## Prime coat

A prime coat is a bituminous slurry intended for binding together a bituminous course on top of a granular base material.

Bituminous prime coat **material** is cut back bitumen complying with the requirements of ASTM/AASHTO. Bitumen is cut back by adding kerosene/diesel in the ratio of 100 parts by volume of bitumen to 40-60 parts by volume of kerosene/diesel depending on the porosity of the surface.

It may be necessary to use a blotting material to absorb the excess of prime coat material. This material is a free-flowing sand, clean, not containing any cohesive material or organic matter. Not more than 10% shall be finer than 0.075 mm sieve.

As well as the previous coat, the **process** is: Immediately before applying a prime coat all loose stone dirt and other objectionable material should be removed from the surface with a broom or blower.

Prime coat shall be applied by mechanical distributor or manually at a rate between 1.0-1.20 litre/$m^2$ and at a temperature between 100ºC to 120ºC.

## Base course (WBC)

A water bound macadam (WBC) base course is a granular course placed immediately beneath the bituminous carpeting, intended to provide structural support to the overlaying asphalt courses.

The base course **material** shall consist of crushed aggregates well-graded and of desired strength.

Grading requirements are explained in the table below:

| Sieve (mm) | % By weight passing sieve |
|---|---|
| **38** | 100 |
| **20** | 60-80 |
| **10** | 40-60 |
| **4.8** | 25-45 |
| **2.4** | 15-32 |
| **0.60** | 10-20 |
| **0.075** | 0-15 |

Other typical requirements for the aggregates:
- LAA test < 40
- Water absorption not exceeding 16%
- Flakiness index <15%
- AIV test < 32%

The terminated layer should show a soaked CBR not lower than 40% for the first layer (not more than 100mm compacted thickness) and not less than 80% for second and third layers (same maximum thickness). From the *Road Design Standards* by the Planning Commission, surfacing for road types 3 to 8 consist of a bituminous carpeting, mixture of bitumen and aggregates, mixed hot before spreading and rolling.

On top of the carpeting, a seal coat, mixture of bitumen and sand/pea gravels will be placed.

In order to correctly place the WBC, the **process** must be: Materials shall be spread in layers of compacted thickness not exceeding 100 mm. A power rolling of 8 to 10 tons should be used for compaction. Water addition may be necessary. it should be simultaneous with the spreading action or in the initial stages of compaction to prevent an excessively close surface.

## Improved subgrade

The improved subgrade is a layer of compacted soil material presenting a higher support capacity than the natural roadbed material and being less deformable and more stable to moisture variations.

**Materials** for the improved subgrade should be made of natural sand free from vegetable matter, soft particles or excessive clay. It must be free draining. Plasticity index of fines are to be lower than 6 and CBR after compaction at 100% of maximum dry density shall be over 10.

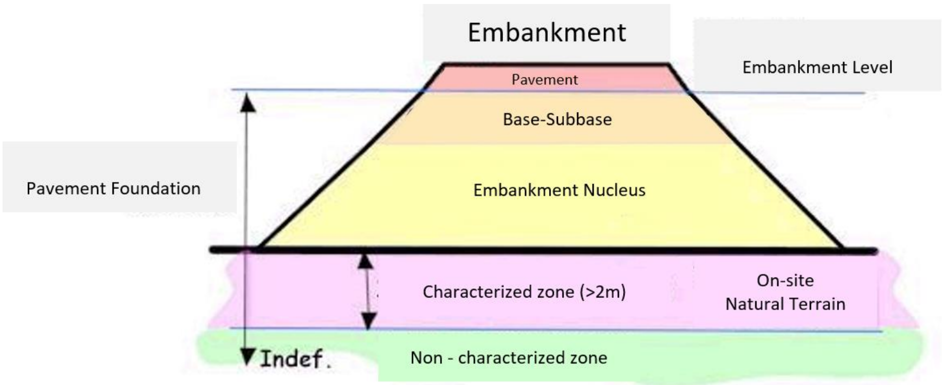
If an Improved subgrade needs to be executed, the **process** should be the following: materials shall be spread in layers with a compacted thickness up to 150 mm being all the layers nearly equal in thickness. It shall be thoroughly compacted with mechanical compaction equipment (to see more information regarding the compaction technology, please refer to Section 8 of this document). The moisture content at the time of compaction shall be the optimum obtained in the laboratory tests with a maximum deviation of 3%. Compaction should reach 100% of the maximum dry density and a soaked CBR of 10. improved subgrade material containing an excess or deficiency of moisture shall be reworked and dried or watered and recompacted.

## Subgrade

Subgrade is the terminated surface of the roadbed. It must provide support, resistance to deformation and to moisture variations.

All subgrade **materials** shall be free from vegetable matter or other deleterious materials. Limit liquid of fine particles should be lower than 50 and plasticity index lower than 20. Dry density must be not less than 95 % of the maximum dry density. Soaked CBR greater than 4% at 95% MDD. The moisture content during compaction is to be the optimum with a maximum deviation of 5%.

To properly **execute** the subgrade, when compaction of subgrade is found to be less than 95% MDD it should be excavated to a depth of 150 mm and stockpiled and a further 150 mm scarified and compacted. The excavated top layer material shall be then spread and compacted. Subgrade may be allowed to dry or be watered so as to bring the moisture content next to the optimum making possible its compaction. The material shall be worked to present an uniform moisture content through the entire layer. The compaction shall be done in a longitudinal direction along the embankment.



## Embankment

An embankment is needed if the material fill is needed to achieve the grade, dimensions and cross sections shown in the drawings.

The **material** used to conform the embankments are the same as subgrade material, unless subgrade is improved.

Prior to **placing** materials for the embankment all clearing and grubbing operations shall be completed. The original ground surface must be scarified, watered, aerated and compacted to at least 90% MDD. Undercuts may be needed in case of soft soils like swamps. The undercut shall be backfilled with suitable material. Embankment is to be constructed in layers not more than 150 mm thick after compaction. The material should present an uniform moisture content through the entire layer. Each layer shall be compacted uniformly using adequate mechanical compaction equipment. Compaction will be carried out in the longitudinal direction of the road alignment.

# 7. REINFORCED CONCRETE MATERIAL TECH.

In previous sections, actions after failure have been discussed and developed. The *leitmotif* for this and the following ones will be to present the requirements to guarantee failures will not occur any longer.

## Definition and use

Reinforced and prestressed concrete are composite material consisting of:

- Cement
- Water
- Aggregates
- Admixtures
- Steel reinforcement
    - Passive reinforcement (Present both in reinforced and prestressed concrete)
    - Active reinforcement (Present just in prestressed concrete)

After its setting (exothermic chemical process, also known as curing, that produces the hardening of the initially liquid mix), concrete becomes similar to a rock.

Due to its material properties, the concrete is generally used to resist compression efforts. Its resistance to traction efforts is rather small (around 10% of its resistance to compression), so when traction efforts need to be resisted, the concrete is reinforced with special steel reinforcement. Concrete is also reinforced with steel to resist shear efforts, and occasionally compression efforts too.

Steel reinforcement is cast in two variants: passive reinforcement consisting of steel reinforcement bars (rebars); and active reinforcement consisting of pre-tensioned or post-tensioned high-tensile steel wires, bars and strands (tendons).

According to the Guidelines for Bridge Design of Local Government Engineering Department, designed concrete must have a Minimum Concrete Strength of:

- 40 MPa for PC girder bridges with a span above 32m
- 35 MPa for PC girder bridges with a span up to 32m
- 30 MPa for RC elements, Pile Projected Pier and Pier System
- 25 MPa  for RC piles

## Materials

### Cement

Cement is a fine binding powder. It's artificially produced out of different minerals, and nowadays it's more commonly seen under the 'Portland' variety. Portland cement is an 'hydraulic' cement; thus, it needs water to set and harden, in a process called 'curing'. The curing of the mix is an exothermic reaction, so some measures will be needed to protect both the operators and the material against the heat effects.

Normally, the designation of the cement will indicate the resistance it will achieve after the curing process; the resistance of the concrete will never be higher than the resistance of the hardened cement. It is common to replace a portion of the cement in the concrete mix with other hydraulic materials, like blast furnace slag or silica fume. When used as cement substitutes, those materials cannot be considered admixtures and must be indicated in the cement designation.

## Water

Water is the catalyst of the curing reaction. When mixed with the cement, it produces the hardening of the mix. Besides, the concrete mixed will need to be watered regularly during the first days of the curing to avoid the heat effects of it (over-drying of concrete surface and cracking).

There are different chemical exigences over the water used in concrete production (specially over organic presence, dissolved salts and sulfates). An easy way to fulfill all these exigencies is using potable water (not flavored, not smelly and not coloured water).

## Aggregates

The aggregates consist of mineral particles and constitute the core of the concrete that will resist the efforts. There are two kinds of aggregates:

- **Coarse aggregate (Gravel):** The coarse aggregate endows the concrete with resistance against the fracture. Coarse aggregate particles in regular concrete are larger than 4mm.
- **Fine aggregate (Sand):** The fine aggregate endows the mix with higher plasticity and collaborates to make a more resistant mix. Fine aggregate particles in regular concrete are smaller than 4mm.

To guarantee the resistance in the concrete mix, the aggregates need to be of a spherical shape and different sizes so they can accommodate in the holes left by bigger particles and produce a compact mineral structure. Normally, fine particles will be between 0.06 and 4 mm large, while coarse particles will be between 4 and 25 mm large.

The mechanical characteristic of the aggregates can only be reached by using aggregates specifically produced in specialized factories to be used in concrete mixes.
Besides, the aggregate particles must be clean before use, with no stains, powder or organic elements which might prevent a proper curing and adhesion between the aggregate and the grout mix.

## Admixtures

Occasionally, some other components might be added to concrete to endow it with new or improved properties (higher resistance, more fluid behavior when placing it in the formwork, etc.). These components are known as admixtures, and they can be:

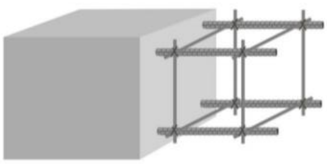
- **Plasticizers:** Concrete containing plasticizers need less water to reach a required slump than untreated concrete. Thus, treated concrete strength rises when compared with untreated concrete with the same water-cement ratio. They are also known as water-reducing admixtures.
- **Retarding admixtures:** Retarders keep concrete workable during placement and delay the initial set of concrete. They are usually used to counteract the accelerating effect of hot weather on concrete setting. Most retarders also function as water reducers.
- **Accelerating admixtures:** Accelerating admixtures are especially useful for modifying the properties of concrete in cold weather, so the setting develops faster.
- **Specialty admixtures:** Specialty admixtures group a wide range of admixtures used for specific cases, such as inhibiting corrosion, alkali-silica reactivity or reducing shrinkage, among others.

| Common admixture | Plasticizers | Retarders | Accelerators | Specialty |
|---|---|---|---|---|
| **Fly ash** | x | x | | |
| **Limestone filler** | x | x | | |
| **Blast furnace slag** | | | | x |
| **Pozzolan** | x | x | | x |
| **Silica fume** | x | | | x |
| **Calcium chloride** | | | x | |

## Reinforcing Steel

Reinforcing steel, commonly seen as rebar, consists of steel bars embedded in the concrete element to supply resistance mainly against traction efforts. Historically, smooth surface rebars have been used; however, corrugated rebars have proven to be superior due to its adherence with the concrete, and smooth rebars are nor seen anymore. Reinforcing steel constitutes the passive reinforcement present both in reinforced and prestressed concrete structures.

Rebars



Reinforced concrete schema

Rebars are characterized after two standardized qualities:

- **Grade:** Rebar's yield strength. Conforming the Guidelines for Bridge Design of Local Government Engineering Department, rebars' design grade will be 400, 420, 500 and 550 MPa (only grade 400 and 420 MPa to be used in seismic zones 3 and 4 as per BNBC 2017 for seismic force resisting elements).

- **Diameter:** Nominal diameter of the bar section. According to the country, rebars' diameter goes from 6 mm to 50 mm.

Additionally, in order to calculate the resistance of a reinforced concrete element, it's important to note that steel's elastic modulus is E=210 000 MPa.

There are some points to take in mind when executing the reinforcement of a concrete element:

- A reinforcement sketch or plan is mandatory. It has to clearly indicate:
  - Exact position, longitude and number of rebars
  - Grade and diameter of the rebars
  - Structural details such as anchorage, relative position of rebars in the crossings or any other with a relevant structural role.

- The rebars must be anchored (normally, to other transversal rebars) to avoid their slippage inside the concrete element. Unions between crossing rebars will be made by tying them with iron wire.

- Rebars must be clean and not present signs of rust in the moment of commissioning.

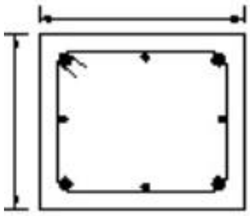
- When possible, the reinforcement structure will be precast in the factory or workshop, and then transferred to the worksite; making the inspection of the process easier.

- During the commissioning, rebars must be kept at a constant distance from the formworks. In order to get this point, standardized rebar spacers made out of plastic or concrete will be used alongside with more iron tie wires.

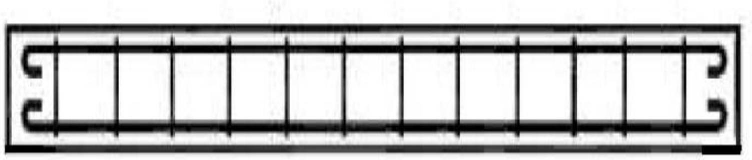
- Conforming the Guidelines for Bridge Design of Local Government Engineering Department, at coastal zone (Bagerhat, Borguna, Barisal, Bhola, Chittagong, Cox's Bazar, Khulna, Noakhali, Patuakhali, Pirojpour, Jhalokathi and Satkhira) as well as in saline prone area, epoxy coated reinforcement will be used conforming ASTM A775/BDS ISO 14654:2013. The lap length and anchorage lengths shall be increased by 25%.

- If by chance any rebar is kept waiting in an unfinished structure, they will have to be protected from any deformation. Besides, safety protrudes will have to be placed on their tops to prevent any accidental harm.

- Doubtful points about reinforcement steel not treated in this document will be solved conforming BDS ISO 6935-2:2006/2016 or ASTM A706M-16.



Cross-section sketch



Longitudinal sketch

Rebars spacer (chair)

By CMMNA - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=33438692

Rebars safety protrudes (caps)

By Paul Goyette - https://www.flickr.com/photos/pgoyette/156364587/, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=1043011

## Prestressing Steel

Prestressing steel, used in prestressed concrete elements, consists of high-tensile steel wires, bars and strands. Prestressing steel is the active reinforcement that can be used for both pre-tensioned and post-tensioned concrete pieces.

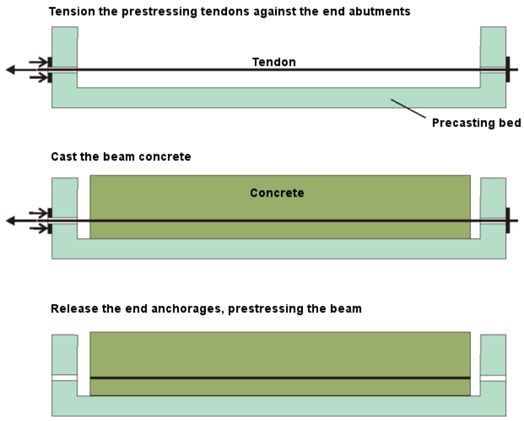
When compared with reinforcing steel bars, the prestressing steel has a higher yield strength due to some alterations in its chemical composition. Design ultimate tensile strength will be assumed as 1860 MPa while elastic modulus is usually assumed as E=200 000 MPa.

Pre-tensioned concrete is made by submitting the steel strands to a high tension in an empty formwork and pouring then the mix of concrete to cover the steel. After the curing of the concrete, the steel is released, letting it to recover its natural length; however, the curated concrete will not allow the steel to totally recover its previous length, producing a combined system where the steel is elongated and under traction efforts, while the concrete is shortened and under compression efforts.

Post-tensioned concrete follows the same physical principle where the steel is under traction efforts and the concrete under compression efforts. The main difference with pre-tensioned concrete relies on the tension process. While in pre-tensioned concrete the steel is prestressed before the pouring of the concrete, in the post-tensioned case the concrete is poured over empty sheaths, and after the curing of the concrete the steel strands will be introduced in the sheaths, tensioned, and released.

Post-tensioned anchorage

By Störfix - Self-photographed, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=296999




Pre-tensioning system

By https://de.wikipedia.org/wiki/User:St%C3%B6rfix - https://en.wikipedia.org/wiki/File:Sofortiger-Verbund.png, CC0, https://commons.wikimedia.org/w/index.php?curid=50998370

Conforming the Guidelines for Bridge Design of Local Government Engineering Department, in new prestressed elements to be designed, the assumed prestressing system will consist of helicoidal strands of 7 wires with an equivalent diameter of 15.24 mm. Cables will have 19 strands maximum, unless specific approval. Furthermore, designer must be aware that pre-tensioned and post-tensioned concrete are normally used in precast concrete pieces, and rarely they will be made on site. Stressing will not be done before 14 days unless special approval from the design unit.

Strands and anchorage will meet the requirements in and PTI - M50.1-98

The execution of prestressed concrete elements is complex and must meet some requirements:

- The process will be done by experienced operators
- The tension process will follow a tension process developed by the design unit
- Conforming the Guidelines for Bridge Design of Local Government Engineering Department, following standards and tests will be followed:
    - ASTM A 416M/AASHTO M203 for strands. Prior to its use in PC girders, strands will have to perform the following tests:
        - Ultimate Tensile Strength
        - Yield Strength
        - Unit Weight/Cross sectional area
        - Modulus of Elasticity
        - Percentage of Elongation and Rupture
    - PTI - M50.1-98 for anchorages

- PTI - M55.1-12, ASTM C938 and ASTM C939 for grouting in the case of post-tensioned systems.

## Formworks

Formworks are not strictly part of the concrete elements. However, they are of capital importance in order to get proper structures, as they are the structures that serve as cast for the fresh mix of concrete, allowing it to be shaped according to the designer prescriptions and resisting its weight until the setting evolves to endow the concrete with strength enough to resist its own weight.

Formworks can be:

- Lost formworks: They cannot be reused after the curation of the concrete, either because of remaining in place or because of not having the mechanical or geometric qualities it would need to be reused.
- Reusable formwork: After finishing the commissioning and hardening of the current concrete element, the formwork can be reused in another piece.

Formworks can be made in steel, aluminum, timber or plastic. Metallic and plastic formworks are standardized and usually are reusable. On the other hand, timber formworks used to be made *ad hoc* and are lost formworks.

Modular steel frame formwork for a foundation



Traditional timber formwork



Formworks need to be prepared before the shuttering of the concrete. The preparation of the formwork includes:

Adjustment and fixation of the formwork according to the desired geometry of the final piece. Normally, steel or timber props are used to fix the position of the formwork and resist the vertical forces. These props must be spaced at a distance not higher than 1m.

As a small deflection of horizontal elements is unavoidable, it's recommended to give and upward camber to counteract this effect. 4mm per meter span might suffice for pinned slabs and beams. Cantilevered elements should have a camber of 1/50 L (where L stands for the length of the element) at their free end.

Surface treatment of the formwork. Formwork must be clean, and in case of timber formwork, surfaces that are to be in contact with concrete must be watered so they are wet enough not to absorb water from the concrete. Formworks should be at environmental temperature in order to not produce thermal gradients during the setting.

All formwork surfaces to be in contact with concrete must be coated with an oil or soap solution to facilitate an easy removal of the shuttering.

When the setting of the concrete is done, the formwork must be removed smoothly. It's of great importance to remove the props. Those must not be removed at once, but after concrete has reached a minimum resistance. Thus, a props removal plan must be developed and followed in order to avoid unexpected or sudden efforts in the structure.

# 8. ROAD INFRASTRUCTURES DESIGN APPROACH

In this section we need to verify that the design is correct and code compliant. Note that this section has no intention to replace any of the codes and standards but to briefly explain the structure, insight in the design and calculations and general rules to understand what is deeply explained in the codes among quick tools and formulation to foresee and know the range of results the structure should be before entering the formulations explained in the codes, being intrinsically connected to the pathologies a flaw in the design can deliver to the structures during its use.

## Codes, Standards and Guidelines

The codes, standards and guidelines of mandatory use are:

- Road Design Standard (2004) by the Planning Commission of Bangladesh;
- Pavement Design Catalogue (2003)
- AASHTO Design of Pavement Structures.
- Road Structure Manual (2008) by Design Planning & Management Consultants Ltd.;

## Technical Design Documentation

The design technical documents that compose the road design can be summarized in the next, but not limited to:

### Road Design Brief

The Road Design Brief sets the design criteria/recommendations that englobes from the roads preliminary data collection to the geometric design and road normalized sections to use. The following items can be outlined:

- Road Traffic Data collection;
- Road Design Life;
- Verification of the compliance between road section and Road Design Standards class type catalogue;
- Geometric design. Drawings showing dimensions of carriageway, hard shoulder, verge and crest width;
- Special constraints:
    - Design Flood elevation + Free Board. Height of embankment.
    - Slope inclination in relation with embankment height. Compliance with Road Design Standards
    - Options considered for soft soils in subgrade (CBR<2): drains, geotextiles, etc.

### Road Detail Drawings

The Road Detail Drawings explains the geometry of the numerous sections the road may have during its path. It contains the longitudinal path of the road, numeration of the sections, geometric approach, etc., and the information within the document has to be clear and unrepeated, in order to avoid repetition mistakes. The components of a complete set of Pavement Drawings are, but not limited to:

- Sketch of the pavement section showing the following elements:
  - Embankment
  - Subgrade and/or improved subgrade
  - Sub-base course
  - Base course
  - Bituminous carpeting and seal coat

- Verification of the compliance between pavement section and Road Design Standards section catalogue.

- Additional verifications pavement section related:
  - Thickness of improved subgrade based on subgrade CBR values under 8
  - Slope inclination of the embankment
  - Slope protection details and compliance with Road Design Standard drawings

## Road Technical Specification Document

The Road Technical Specification Document defines the specification on the materials needed to build the embankment, road and subbase of the road according to the design and standards have to be fully described. To outline the set of specifications that can appear in a Quality Requirement of Pavement layers' document are:

- Embankment soils
  - Grain size distribution
  - Water content
  - Compaction requirement (% Mod. Proctor)
  - Minimum soaked CBR

- Subgrade layer
  - Minimum thickness
  - Grain size distribution
  - Water content
  - Compaction requirement (% Mod. Proctor)
  - Minimum soaked CBR

- Improved Subgrade layer
  - Minimum thickness
  - Grain size distribution before improvement
  - Nature of improvement material and content in the mixture
  - Water content
  - Compaction requirement (% Mod. Proctor)
  - Minimum soaked CBR

- Granular layers: Base and Subbase
  - Thickness
  - Grain size distribution
  - Compaction (% Modified Proctor)

        - Soaked CBR

    - Bituminous layers
        - Contents of bitumen binder, aggregates (coarse and fine) and filler
        - Aggregates grain size distribution
        - Thickness
        - Minimum density

The Road Specification Document also includes material prescriptions of the materials needed to build the asphalt mixture, which have to be described. To outline the set of specifications that can appear it can be summarized (but not limited to):

- Material prescriptions on bitumen
    - Penetration grade

- Material prescriptions on aggregates for bituminous mixes
    - Maximum aggregate crushing value (ACV)
    - Minimum bulk specific gravity
    - Maximum flakiness index
    - Maximum weight loss when subjected to AASHTO T-104 test

- Material prescriptions on filler material for bituminous mixes
    - Demulsibility test

- Material prescriptions on aggregates for granular courses
    - Grain size distribution
    - Maximum Los Angeles Abrasion (LAA) coefficient
    - Maximum Aggregate impact value (AIV) coefficient
    - Sand equivalent index

- Material prescriptions on subgrade soils
    - Grain size distribution
    - Maximum Liquid Limit and Plasticity Index
    - Maximum content of organic matter

- Material prescriptions on embankment soils
    - Maximum size
    - Maximum Liquid Limit and Plasticity Index
    - Maximum content of organic matter

## Set of Calculations: Integrity and Stability calculation

The Set of Calculation of the slope of the embankment has its own section further on this document due to its importance on the road and the risks it may induce in the trafficability of the road. The minimum content of a Stability Calculation Note have to be:

- Calculation of safety factor of the embankment in order to define:
    - Side slope
    - Overall embankment width

- Determination of phreatic line for hydraulic statical conditions
- Seepage analysis for steady-state flow condition created by the construction of the embankment

## Construction plan

The construction plan document shall include, on its minimum development:

- Identification of borrow areas for embankment material and testing plan

- Study of quantities considering shrinkage or swelling coefficient from borrow to embankment

- Study of hauling equipment and equipment for extension. Productivity and Schedule

- Compaction process (embankment soil, subgrade, base and subbase):
    - Lab test to define clearly the curve soil density vs water content for a compaction effort (generally Proctor Modified)
    - Testing area to define number of passes, thickness of layer and compaction equipment to be used
    - Watering equipment to provide the required water content

- Quality control plan of the terminated unit (number of samples, frequency, etc)

- Bituminous layers
    - Fabrication plan in asphalt plant: Production rate
    - Hauling equipment to deal with the required production
    - Temperature of the mix at the construction site
    - Extension and compaction equipment plan
    - Quality control plan of the terminated unit (number of samples, frequency, etc)

## Operation and Maintenance Plan

The Operation and Maintenance Plan has a major importance in roads. In comparison with concrete structures, the roads are more exposed to degradation and to the loss of the correct properties of the asphalt, being easier to appear deficiencies or pathologies. The Operation and Maintenance Plan is the unique manner to ensure the correct functioning, trafficability of the roads and to ensure a correct aging until the lifespan of the road has been reached. The following points have at least to be described on this document:

- Performance assessment. Condition (distress) survey plan indicating periodic visual evaluations

- Maintenance plan. Periodic thin asphalt overlays, periodic pavement patching, pothole repair or crack sealing

- In case of major distresses: over the scope of the maintenance plan. Promotion of a pavement rehabilitation project.

# Design Variables / Design Loads

This subsection refers to the criteria that must be considered for every road that is being defined and calculated and the variables that affect the design. Within these criteria, the variables of design are:

## Time Constraints

The selection of the performance and analysis period inputs which affect the pavement design from the dimension of time are required for all the roads, including the low volume and rural roads.

The performance period refers to the time that an initial pavement structure will last before a rehabilitation is needed, also, the time span between the rehabilitations. The Designer must select minimum and maximum bounds that are established by LGED.

In practice, the performance period can be significantly affected by the type and level of maintenance. It is desirable that at least the initial pavement structure lasts 10 years before some major rehabilitation occurs. The analysis period refers to the length of time that any design strategy must cover, and it is often called the 'Design Life' of the road. It comprehends the strategies from construction to rehabilitation in order to achieve the expected lifespan of the road.

| | Existing Design | | | Recommended Design | | |
|---|---|---|---|---|---|---|
| Road Class | Cumulative Million ESA's | Typical Expected Design Life (years) | New Class | Design Type | Design Life (Million ESA's) | Expected Design Life** (years) |
| Rural Road / Union Road | 0.5 | 10 | Uion | 8 | 1.0 | 10 |
| | | | | 7 | 1.0 | 10 |
| Feeder Road B / Upazila Road | 1.0 | 10 | Upazila | 6 | 1.0 | 10 |
| | | | | 5 | 1.6 | 10 |
| | | | | 4* | 2.0 | 10 |
| Feeder Road A / Zila Road | 1.0 | 10 | Zila | 5 | 1.6 | 10 |
| | | | | 4 | 5.0 | 20 |
| | | | | 3 | 6.5 | 20 |

*** Overlaying of 25-40mm BC will be required after every 7-8 yrs. * Special type to be used under special circumstances*

## Traffic Loads

For any design situation, the traffic load over the analysis period is needed. The usual way to evaluate the traffic load is based on the cumulative expected heavy vehicles single axle loads during the analysis period. In AASHTO, these heavy vehicles are expected to weigh more than 8 tons of equivalent axle loads.

Therefore, the traffic has to be predicted. In order to do that, a previous study has to be conducted, using methods like the Origin-Destination matrix of the area of study, previous knowledge of traffic in surrounding areas, and extrapolation methods to expect the growth of the traffic during the design lifespan of the road. Normally, the methods to expect the traffic growth are linear, but there are some more complex methods, such as evaluating the expected inflation of the country using its Gross Domestic Product.

The AASHTO proposes the following equation to determine the 8tons equivalent axle load of the road:

$$w_{18} = D_D \, x \, D_L \, x \, w^*{}_{18}$$

Where $D_D$ is a directional distribution factor, expressed as a ratio, $D_L$ is a lane distribution factor, that accounts for distribution of traffic when two or more lanes are available in one direction, and $w^*{}_{18}$ is the cumulative two directional 8tons (18kip) axle predicted for a specific section of road during the analysis.

Usually, $D_D$is 0.5, if the studies show that the two main directions of the roads are equally used by the public, but often this factor has to be evaluated further, due to the transit of heavyweight trucks that go full capacity from factories or rural areas to the destination points and come back empty using the same road.

For the $D_L$ lane, the following table proposed by AASHTO can be used as a guide:

| Number of Lanes in Each Direction | Percent of 18-kip ESAL in Design Lane |
|---|---|
| 1 | 100 |
| 2 | 80–100 |
| 3 | 60–80 |
| 4 | 50–75 |

# Integrity and Stability Design

## Soil Compaction

Compaction is defined as the process of increasing soil density by removing air voids. It is done by mechanical means. Compaction should not be confused with consolidation, which is the increase in soil density because of exploitation of moisture content of the soil. It is a time dependent process controlled by the permeability of the soil. Skipping the compaction on sites, where it is essentially required can cause serious problems.

Over time soil may settle down under the load due to reduced bearing capacity. Soil may also slide down allowing the water to pass underneath the surface of foundation.

This movement, of course, can cause damage to roads, an improper compaction can result in settlements of pavements and cracking in the pipes underneath the road.

### Soil properties

Before explaining the relationship between compaction and moisture content, it is important to understand what moisture content really is. To define it in a single sentence, moisture content is the amount of water contained in soil.

When dry soil is compacted, the soil particles start to come close to each other and the soil becomes stiff and cracks and gaps are formed. These cracks are due to improper contact of dry soil particles.

If we add water to soil, the water will form a thin layer around the soil particles, which helps the particles to get in contact with each other properly. Hence soil becomes denser under compaction.

At a certain point, the volumes of air in soil become minimum and dry density would become maximum. This is called the maximum dry density point. No more water should be added beyond this point and the moisture content of soil at this stage would be the optimum moisture content.

### 95% Compaction

On construction projects, you also test small soil samples in the laboratory taken from the site. From the test you get a value of maximum dry density. Let's call it D.

Then you go to the construction sites and measure the compaction there. You also obtain a value of maximum dry density at site. It should not be less than the 90-95 % of the maximum dry density computed in laboratory (D).

Therefore 95% compaction means that soil is compacted up to 95% of the maximum dry weight possible (computed in the laboratory as maximum dry density).

### Compaction technology

Four different techniques are used to achieve compaction: Vibration, impact, kneading and applying pressure. These four techniques can use either static or vibratory force. Static force uses the weight of the machine while vibratory force uses the mechanically driven force. For topsoil layers, static techniques like kneading and pressure are well suited.

Deeper soils need dynamic techniques like vibratory and impact methods.

### Compaction machinery

The type of machines we can use for compaction depends on the types of soils, we are compacting and the site conditions. Soils are categorized into different types based on their grain sizes. As a result, these soils have different densities and moisture contents.

Following types of compaction equipment are available:

- Plate compactors;
- Taming rammer;
- Sheepsfoot compactors;
- Smooth wheel rollers;
- Vibratory rollers;
- Pneumatic tyre rollers;
- Trench rollers;
- Reversible plate compactors;
- Tow behind compactors;
- Forward plate compactors;
- Grid rollers.

## Slope Stability

The study of slope stability deals with ultimate state phenomena or the rupture of soil masses. The external "agent" responsible for instability is a mass force: weight and possibly seepage effects to which must be added, generally as a secondary factor, to possible external loads.

The quantitative determination of risk or safety indices requires the use of techniques and models specific to Soil or Rock Mechanics.

### Stability calculations theories

Those are the "limit equilibrium" methods (less rigorous than the strict application of the theory of plasticity), which have historically been used since the 1920s to deal with slope stability. Over time, these methods acquired power and flexibility to adapt to the complex conditions of internal geometry and hydraulic regime that often arise in the study of slopes and are therefore mostly used, especially in two dimensions (plane deformation).
Among these methods, the most used are:

- Global Equilibrium Method (Hoek & Bray)
- Slicing Methods. Bishop method, Janbu method, etc

However, with the rise of numerical modeling, nowadays the best option is to evaluate using finite element method the Slope Stability.

### Natural Stabilizations

From several studies across the globe, vegetation has been found as one of the most effective natural stabilization of slopes. Vegetation protects the slope from the runoff, controls the erosion of the slope and reduces the water infiltration in the embankments. As per LGED, the grass implementation in the sides of the slope is mandatory.

### Slope Protections

In order to stabilize and increase slope safety by controlling the presence of water, it is important to consider that water will always seek the path of least resistance, where it can convert its potential energy into maximum kinetic energy.

- Increases the weight of the slope.
- Increases the interstitial pressure in pores and fractures, generating destabilizing forces.
- Increases the thrust on the containment elements.
- Runoff produces erosion and dragging of materials.

Thus, the slope protection and water system have an important role, as a passive measure impeding the water filtration in the embankment and an active measure evacuating the filtered water.

Among the slope protection systems, there are:

- Breakwater walls. Breakwater walls and gabions are active means of defense for the protection of unstable slopes, aiming to contain the land. Breakwater walls are made up of large loose stones that are placed one on top of the other. Therefore, the support of the slope is provided by the weight of the rockfill itself, which must therefore be sufficient to counteract the strong thrust of the earth that forms the slope. They are used on unstable slopes, especially earth slopes, where significant movements can occur.

- Dynamic screens for slope protection. Dynamic screens are means of passive protection against the instability of slopes and natural gradients. They are placed transversely to the path of stones that may fall, in order to slow down their trajectory and thus prevent them from affecting traffic. It is a structure that absorbs the impact by means of a significant deformation capacity, and is made up of vertical posts anchored to the ground that support a double metal mesh, one of which is denser and with a finer wire, and the other made up of thicker cables. The energy dissipating elements can operate by friction or by shear stress.
- Etc.

## Pavement Design

Following the standards for rural road design, the 'Pavement Design Catalogue' by LGED is the document that contains all the information needed to design the pavement using a catalogue of cross sections of the road, depending on the number of commercial vehicles and the zone the road is projected; Upazila, Zila and Union.

Once the designer has evaluated the traffic load the road is subjected to, the categories of the pavement design can be selected. Depending on the area where the road is constructed, the categories are:

| Category | Upazila Road (Commercial Vehicles/Day) | Union Road (Commercial Vehicles/Day) |
|---|---|---|
| **I** | 500 | 300 |
| **II** | 300 | 200 |
| **III** | 200 | 100 |

The base-subbase and asphalt/bituminous carpeting common properties of these roads areas are:

| Properties | Upazila and Union Roads |
|---|---|
| **Axle Loading** | 10.2 ton |
| **Growth Rate** | 8% |
| **Design Life** | 10 years |
| **Side Slope of the embankment** | 1:1.5 clayey and 1:2 Sandy or silty soil |
| **Embankment compaction** | 95% STD Compaction |
| **Subgrade CBR** | Min 4% (Soaked) |
| **Improved Subgrade CBR** | Min 10% |

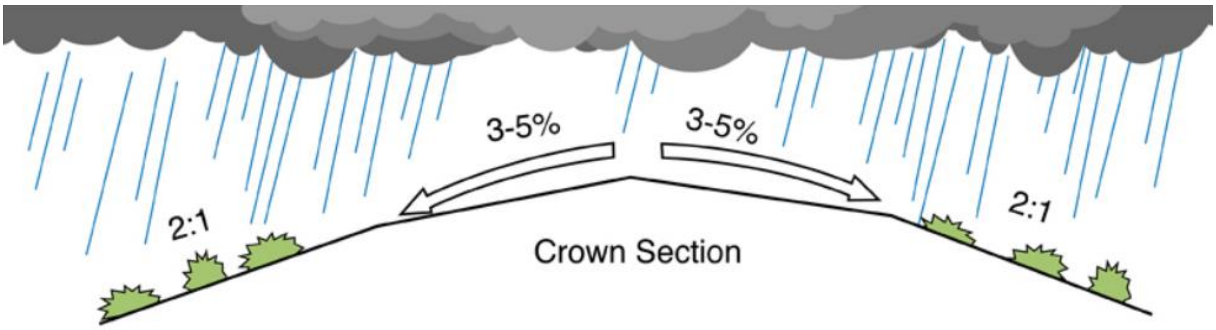
| Properties | Upazila and Union Roads |
|---|---|
| **Base Course 1st layer CBR** | Min 40% |
| **Base Course 2nd & 3rd layer CBR** | Min 80% |
| **Bituminous Carpeting depth** | 40mm plus 7mm seal coat |

Depending on the environment of the road section, the designer has to choose between the Plain Lands Cross Sections and Hilly Lands Cross sections, each of them of unique characteristics that can be seen in the Pavement Design Catalogue by LGED.

## Water Drainage Systems

Among water drainage systems, the following list englobe the principal ones, but it is not limited to:

- Transverse slopes.
- Culverts. The most common form of water drainage, the water is collected and transported before runoff on top of the slope.
- Vertical wells. They should be located so as to intercept the flow of water into the slope, usually at the crest of the slope. They can be constructed before excavation of the slope begins, which makes excavation easier and safer. and safe, and can also be used as reconnaissance boreholes.
- Etc.



# 9. BRIDGE INFRASTRUCTURES DESIGN APPROACH

In this section we need to verify that the design is correct and code compliant. Note that this section has no intention to replace any of the codes and standards but to briefly explain the structure, insight in the design and calculations and general rules to understand what is deeply explained in the codes among quick tools and formulation to foresee and know the range of results the structure should be before entering the formulations explained in the codes, being intrinsically connected to the pathologies a flaw in the design can deliver to the structures during its use.

## Codes, Standards and Guidelines

The following codes and standards are of mandatory use:

- AASHTO LRFD12 Bridge Design Specifications, Sixth Edition (2012). In the AASHTO Code, material definitions, properties, design calculations, specifications, design loads, etc.
- Guidelines for Bridge Design of Local Government Engineering Department - September 2018;

## Bridge Design Technical Documents

The design is composed by several documents, one of each of unique and unrepeated content and information, which can be resumed in the followings:

### Preliminary Technical Documents (Planning Stage)

The Preliminary Design Technical Documents develop the information the designer has to consider when calculating and designing the concrete structure.

In this planning stage, the hydrological, geotechnical, topographical, climate and traffic studies (if applicable) have to be complete and sufficiently extensive to retrieve relevant information for the project. With those reports, the preliminary decision making on the design approach can be done.

### Bridge Design Brief

The Design Brief content is related to the approach of the project, its intended use and motivation, as well as a summary of the important information to take in account in the set of calculations, which are based on the Preliminary Technical Documents, such as seismic maps, geological-geotechnical information for the project location, etc.

As corollary of the document, the first insight of the materials the structure is going to be using and basic geometric definitions should be included, likewise the first set of pre-calculations of the structure using 'thick numbers'.

### Set of Calculations

The Set of Calculations is the main core of the structural project, as it composes the background calculations, refinements and decision making of the structure. It starts from the definition of the numerical model (if any) or the simplifications the calculations of the structure are going to be using in order to properly resist the loads it is going to be subjected to.

The next part usually is the description of the loads, where the Preliminary Design Technical Documents take an important role, as it gives the accidental loading; such as seismic load, flooding load, and quasi-permanent loadings; wind, amount of traffic load or at least the order of traffic load to search in the codes the equivalent 'truck convoy models' and other variable 'usual' loads. In the end of the load description, it has to appear the estimation of the permanent weight of the structure, including all the elements of it, railing, asphalt, the structure itself, etc.

The next subsection of the set of calculations are the load combinations. Using the codes, the loads of the last subsection described have to be combined with ponderation factors, creating a set of 'Load Cases', in three categories: accidental load cases, permanent load cases and quasi-permanent load cases, corresponding the first two of the Ultimate Limit State Calculations and the last one of the Serviceability Limit State.

Once describing the set of load cases, the incoming subsections are the shear, moment, punching and torsion calculations for every component of the bridge.

The incoming section is the calculation of the reinforcement and final geometry of the elements of the bridge, comparing the efforts (shear, moment, torsion, punching) the element is subjected to, to the resistance capacity of the element. It starts with an approximation of the expected reinforcement/geometry and iteratively adjusting the reinforcement and geometry to augment the element capacity.

## Technical Specifications

The Technical Specifications are the minimum technical characteristics to be met by the products, equipment and systems to be permanently incorporated into the projected structure, as well as their supply conditions, quality guarantees and the reception control to be carried out. This information can be found in the section corresponding to the Prescriptions on materials in these Specifications.

Also, the technical characteristics of each unit of work, with an indication of the conditions for its execution and the verifications and controls to be carried out to check its conformity with what is indicated in the project.

The measures to be adopted during the execution of the works and in the use and maintenance of the structure, to ensure compatibility between the different products, elements and construction systems, shall be specified. This information can be found in the section corresponding to the Prescriptions regarding the execution by work units of the present Specifications.

Ultimately, the verifications and service tests, where appropriate, must be carried out to check the final performance of the building. This information is to be found in the section corresponding to the Requirements for verifications in the finished building, of these Specifications.

## Detail Drawings

The Drawings section of the project is usually the most conflictive part of the project. It has to include, without repetition, all the geometric information to place every element of the project, from a beam, to the reinforcement geometrical cover. Any lack of definition in this part leaves the execution of the structure undefined and it is a source of ulterior pathologies. The characteristics of a proper drawing set are clarity in the drawings, proper scaling of the elements, unrepeated information in the drawings and clear structure; commencing with position of the structure in the world (Coordinates and topographic interaction), followed by geometric views from the top and lateral, and then the structural indications using sections, zooms of the elements, etc.

## Operation and Maintenance Plan

The Operation and Maintenance Plan shall contain all the information necessary to ensure that the structure is used in accordance with the assumptions made in the design bases.

Of all the information accumulated on a structure, the instructions for use shall include those that are of interest to the owner and users, which shall be at least: permanent actions; overloads of use; admissible deformations, including those of the ground, where appropriate; particular conditions of use, such as respect for overload limitation signs, or the maintenance of markings or bollards defining areas with special requirements in this respect; where appropriate, the measures adopted to reduce structural risks.

The maintenance plan, as far as structural elements are concerned, shall be established in accordance with the calculation bases and any information acquired during the execution of the work which may be of interest, and shall identify: the type of maintenance work to be carried out; a list of the points requiring particular maintenance; the scope, performance and frequency of maintenance work and a schedule of checks.

## Bill of Quantities/Surveyance and Cost Estimate

The budget is the document that reflects the cost of executing the project, i.e. the investment necessary to carry it out, but it does not include, in any case, the operating costs that the new industry will generate once it is built.

In order to obtain the budget for a project, the following stages must be carried out:

1. Identification of the units of work that make up the project, understanding that a unit of work is an elementary part of the work, which involves a certain action (use of labour and/or machinery), generally for the application on site of certain elements that will have the character of materials. The work units must be identifiable and measurable in order to be able to make a correct calculation. Each unit of work will have a different price, so when defining it, a series of differential factors must be taken into account. For example, an excavation of 1m3 is not the same for clay soil as for rocky soil, with manual or mechanical means, etc.

2. Carry out the Measurements of the Work Units. They must be done trying to take into account all of them; in reality it is a question of determining the quantity of Unit of Work that there is in the Project. In the Project phase there are Units of Work that are difficult to measure, as in the case of trenches or trenches that will have to be opened for the work of electricians,

plumbers, gas fitters, etc. The budget is then budgeted for in order to estimate these costs and thus take them into account in the final budget.

3. Calculate the unit cost of the Unit of Work. It is important that there is a clear correspondence between the description of the Units of Work in the Price Schedule and those in the Measurement Schedule in order to avoid errors and discussions. It should be emphasised that the price schedule is contractual in nature, as are the plans and the specifications. The Price Schedules can be presented broken down including the breakdown of all the components or Totals with a single value in letter and number that reflects the previous sum.

4. Calculate the total cost of the Units of Work by multiplying their measurement by the unit cost. This is summarised in a Budget Table.

5. Adding up the total cost of all the Units of Work gives the Total Budget.

## Key Structural Elements

The intention of this subsection is to describe the key components of the structure. Centering in concrete bridges, the following components can be outlined, but not limited to:

### Deck Slab

The main part of the superstructure. It is the first element to be in contact with the vehicular loads and its mission is to transmit and distribute the load and efforts to the next structural element. Depending on the span of the bridge, the slab itself can compose the entire superstructure, supported by the abutments.

### Longitudinal and Transverse Beams

The beams are elements used in longer spans of the bridges, as they contribute and are capable of resisting more effectively the shear and the moment the loads are transmitted to the bridge. The longitudinal beams are supported by the abutment and the intermediate piles (if necessary) and carry the load to the supports, while the mission of transverse beams is to provide rigidity to the structure as a whole, limit the deformation of the slab and reduce the torsion of the longitudinal beams.

### Abutments

The abutments are elements that interact both with the superstructure and the soil. Its role is to transmit the loads from the deck slab or the beams to the ground, ensuring the proper distribution and stability of the structure depending on the properties of the soil of the Geotechnical Study. If close to the water stream or foreseen its interaction with water, the abutments must have water protection elements to prevent water scour and erosion of the structural element.

### Piles

The piles are vertical intermediate concrete elements which principally are used to reduce the span of the bridge. If there is so much span to cover between abutments, an intermediate support (pile) can be added to the structure to reduce the amount of flexural moment the longitudinal beams have to resist. It is important to highlight that introducing an intermediate pile in the middle of a water stream has to be carefully studied and checked with the hydrological studies, to foresee and ensure the feasibility of the pile subjected to the water loading and further hydraulic analysis the designer must perform.

## Shallow Foundations

These are foundations that are supported on the superficial or shallow layers of the soil, because the soil has sufficient bearing capacity. In this type of foundation, the load is distributed over a horizontal bearing plane. In bridges, foundations are supported deep enough to ensure that no damage will occur. The supporting elements that connect the supports to the ground are called footings. When the foundation design provides for many footings in close proximity to each other, they are replaced by a continuous element called a foundation slab.

## Deep Foundations

When the poor quality of the ground makes it necessary to use deep foundations. They are based on the vertical friction effort between the foundation and the ground to support the loads, so they need to be located deeper, in order to be able to distribute over a large area a sufficiently large effort to support the load. Some methods used in deep foundations are piles and screens.These foundations when used in a water stream are called 'Piers', and they must be protected against water scour and erosion using massive concrete elements or using a different and/or heavy-weight soils, like breakwater/riprap in the river bed.

## Mechanical Devices

### Bearings

Bearings are elements consisting of a block of elastomer containing within it a series of steel sheets which by adhesion and vulcanisation form a single body. The main objective of the bearings is to adapt to and resist all multiple movements and deformations caused by temperature changes, the action of the structure's self-weight and the overloads to which it is exposed, and to transmit these efforts to the infrastructure elements, such as the piles or the abutments. They come with a unique description depending on the type of support they are intended to model and a set of calculations to limit the deformation and choose the right bearing.

### Movement Joints

Expansion joints are deformable devices capable of ensuring the transit of vehicles across discontinuities between the different structural sections of a bridge, allowing relative movements of the deck. The joints are deformed to absorb the movements to which the structure is subjected, and are sized according to these movements, including movements due to concrete shrinkage and creep, movements due to temperature and movements due to braking.

# Design Load Definition

In this subsection of the design a list of the most usual loads the concrete structure is subjected to is described. Note that this list probably is going to content the common load cases for every project, but is not limited to, and every particular project shall study all the loads and particularities it may have:

## Permanent Loads

- Self-Weight. The weight of the structure itself. It is important to have in mind that the Self-Weight of the structure changes if any geometric change of the structure is done in the 'Capacity of the elements calculation section', and also the expected deformation calculations are affected afterwards.

- Dead loads. All the weights that are permanently gravitating over the structure, such as railing, the asphalt, etc.

## Variable Loads

- Vehicular Live Loads/Traffic Loads. The most common variable load the structure is subjected to. It is important to characterize this load using AASHTO in order to define the envelope of all types of vehicles. It should include Special Vehicle Loading when applicable in the project if it is expected.

  Also, if the bridge is expected to have a pedestrian use, this load should also be considered and combined with the vehicular load case.

- Wind. Depending on the bridge length, altitude and exposure the wind loading is more relevant. It is based on the fastest-mile wind speed measurements of the area.

## Accidental/Extreme Loads

- Collision/Impact of vehicle load. On exposed piles to the traffic, i.e. an elevated intersection between roads, an impact load case has to be considered on the piles of the bridge.

- Seismic Load. Load related to earthquakes, depending on the seismicity of the area in which the structure is going to be placed, the seismic loading is an important factor and if not calculated it can put at risk the integrity of the structure or its components.

- Flood Load. Certain hydraulic events such as flooding must be taken into account in several flood loading cases, from normal water thrust on the piles and foundations of the bridge, to extreme flooding which can move the superstructure of the structure. If the hydraulic studies are accurate, the expected water height of the flood should also influence the anchorages and interaction between the slab and abutments/piles in order to calculate the traction component a flood load case can induce in those elements, preventing structural collapse.

# Design Limit State Analysis (Load Combinations)

## Serviceability Limit State

A Serviceability Limit State is a type of limit state which, if exceeded, results in a loss of functionality or deterioration of the structure, but not an imminent risk in the short term. In general, serviceability refers to situations that are resolvable, repairable or allow for mitigating measures or non-severe inconvenience to users. Among the serviceability limits it can be differentiated:

- Stress restrictions,
- Deformation restrictions.
- Crack width restrictions

## Strength Limit State

Strength Limit States are those which ensure the strength and stability, both local and global of the structure. Provided to resist statistically significant load combinations that the bridge is expected to experience in its design life.

Among the strength limits it can be differentiated:

- Ultimate moment capacity
- Ultimate shear effort capacity
- Punching resistance
- …

## Fatigue and Fracture Limit State

The fatigue and fracture limits are related to stress control and range, as a result of a single truck occurring at the number of expected stress cycles. Its intention is to limit crack growth under repetitive loads during the design life of the bridge.

## Extreme Event Limit State

This Limit State is calculated to ensure the survival of the structure under seismic events, flood, collision, etc. Extreme events are considered to be unique occurrences during the life of the structure, that may have severe impact on the structure.

# Rule of Thumb for Bridge Structural Design

In order to fit the first approach of the design of the concrete bridge without requiring hours of iterations with negative results from the Strength Limit States or Service Limit States, some generalist numbers can be taken into account. Those numbers are often called 'rule of thumb' or 'thick numbers', which can be used to do the first geometric approach on the widths of the slab, height of the beams, estimate the efforts, etc.

The intention of this section is to explore and give some general overview of the 'dance' of numbers and requirements the designer may encounter during the process.

## Geometric Definition for the Deck Slab

To estimate what thickness the concrete slab should have, the span or length of the bridge shall be taken into account. As a general rule:

$$\textbf{Deck Slab Thickness}/\textbf{Bridge Span} > \mathbf{1/30}$$

For concrete structures with non-embedded beams (non prestressed):

$$\textbf{Deck Slab Thickness}/\textbf{Bridge Span} = \mathbf{1/16}$$

So for a 5m span bridge with no intermediate support, the slab should be around 30cm of depth in the first design approach. Later on the design this value can be reduced if the reinforcement of the slab is near the minimum reinforcement for flexural moments.

## Live load estimations

The first requirements in order to use these equations/relationships hereby presented in this subsection are to have previously estimated the live loads the bridge is subjected to.
First, to define '$q_{ll}$', the linear live load expressed in kN/m, the width of the bridge must have been defined and the vehicular load as well as per AASHTO code. Depending on the use of the bridge, AASHTO proposes a design lane load, a design truck and a design tandem, but here we take the short path. Use the sum of all the expected live loads in the bridge and make them uniform per meter of the span.

$$\boldsymbol{q_{ll}}(\textbf{estimated}) = (\textbf{Truck} + \textbf{Maximum Axles} + \sum \textbf{Surface Lane Loads x Lane Widths})/\textbf{Bridge Width}$$

## Longitudinal Beams and Positioning

For this stage of design, the loads the bridge is subjected to must have been already defined, as this 'thick number' uses the load to be calculated. Having the geometric dimension of the slab, the self-weight is easily calculated. For normal width of bridges from 3-5m, two longitudinal beams should be sufficient to resist all the loads. The best position of the longitudinal beams is under the wheel path in single lane roads, as the efforts the wheel transmit to the slab are directly gathered by the beam.

The depth of the longitudinal beams should be:

$$\textbf{Beam height} = \textbf{Span}/\mathbf{15}\ \textbf{to}\ \textbf{Span}/\mathbf{20}$$

The moment capacity of the beams in bridges supported by the abutments should be at least
.

$$\boldsymbol{M_{capacity}} > \boldsymbol{M_d} = [(\boldsymbol{q_{ll}} + \boldsymbol{q_{sw}})/\textbf{number of beams}] * \textbf{Length of Span}^{\mathbf{2}}/\mathbf{8}$$

## Locations of Transverse Beams

In general, the proportions of the deck slab should be maintained under 1.5 coefficient. That coefficient is the result of A/B, being A the length of the slab without interruptions (abutment or transverse beams) and B the spacing between the longitudinal beams.

$$\boldsymbol{A/B} < \mathbf{1.5}$$

For shorter bridges, this relationship can increase the weight of the structure, as it may place a unique transverse beam in the middle. This can lead to a premature serviceability limit state violation of deformations. If this happens, please consider removing the intermediate beam and check again the torsion effort in combination with the shear effort in the longitudinal beam for the compliance of this strength limit.

### Shear Capacity of the deck slab and beams

In order to estimate the concrete contribution to resist the shear efforts transmitted to the elements in the concrete structure without shear reinforcement, the following simplified formulae can be taken:

$$\boldsymbol{V_{capacity} = Vcu = 0.5 * b * d}$$

Being 'b' the width of the beam/girder or 1m for the deck slab (remember the deck slabs calculations are per meter of length) and 'd' the depth of the element.

The shear capacity of the elements should be at least and has to be verified in two (2) directions:

$$\boldsymbol{V_{capacity} = 0.5 * b * d > V_d = (q_{ll} + q_{sw}) * Span/2}$$

Note that the length of the span can be the distance between beams in X and Y directions, or the main length of the bridge if we are analyzing the shear in the longitudinal beams.

## Numerical Modeling

This subsection is the summary of the decision making on the tools the designer shall use when calculating a structure. One of the most common ways to improve calculations and increase material harnessing is to use numerical modeling. Note that numerical modeling by no means is a replacement of the background knowledge in structural calculations, it is only a tool to improve design.

Once the structure is already pre-calculated using the guidelines of the last subsection and having an expected maximum moment and shear efforts, it is time to do the Strength, Service and Extreme Limit States calculations. To do a numerical model of a bridge, the following steps are vital to avoid mistakes:

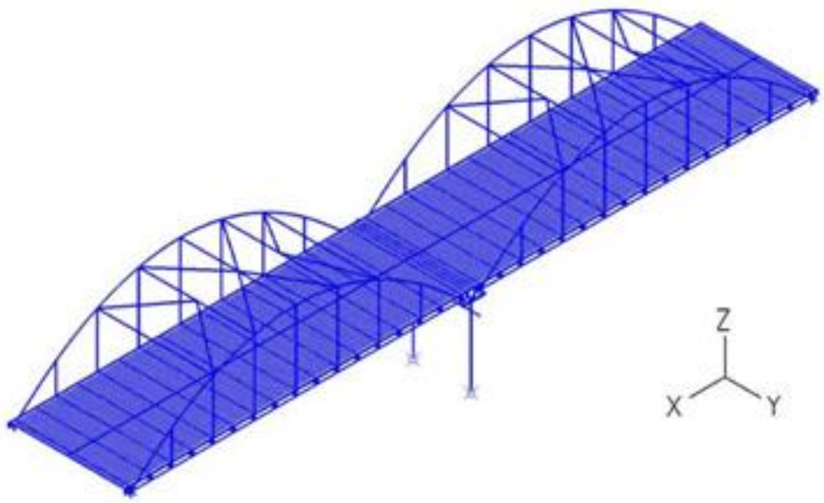
### Selection of the software

There is an extensive number of software which help to model numerically a concrete structure, using Finite Element Modeling, or other numerical methods. Because of that, the designer should select a specific bridge calculation software, not a generalistic software, as specific bridge design software usually helps the designer to introduce the elements of the bridge easily, as well as load combination, vehicular tandems and extreme event loading.

The minimum content a numerical software must have to be selected for the calculations are, at least:

- 1D/2D Geometry Selection
- Concrete Material Pre-created in the base of materials
- Variety of beam sections to choose for the bridge design
- Load Combinations
- Live load (wind, vehicular)

- Meshing controls
- Clear Post-processing to retrieve the results




## Watch-out when developing Numerical Models

As it has been explained earlier, numerical modeling is used to facilitate and reduce calculation time. The point of calculating using numerical software is to iterate 3-5 times the geometry of the structure and compare the best suitable geometry balanced with a not excessive reinforcement.

It is NOT recommended to extract the rebar calculation directly from the program without checking externally the reinforcement needed in the section. Instead, if the software used gives a reinforcement amount/ratio, this shall be taken as the first 'shot' at calculating the reinforcement.

## Numerical Modeling Inside

A numerical model of a structure is an idealization of reality and a simplification of it. Thus, the proper assumptions should be made:

- 1D Elements (Beams): This modelization is used when the height of the section of the element is drastically smaller than the longitude. I.e. Beams, which have a b/L<<1. The main characteristic of beam elements is that a section has to be assigned to complete the information needed for the model to calculate its inertia and other properties;

- 2D Elements: For elements in which the above ratio is not fulfilled. I.e. Deck Slabs. In this case, the information needed is the width of the slab, to calculate the rest of the properties;

- 3D Elements: For global modeling these elements should not be used, as they get a stress-based result and it is complicated to evaluate our goal, which are moment and shear efforts. Most of the concrete structures, like slabs/beams and abutments can be calculated using 1D and 2D elements.

In order to know perfectly what the program is doing, a separated numerical model is recommended to be done for the superstructure (deck-slab + beams), and the infrastructure (abutments and piles). The input in the second numerical model should be the results of the superstructure's reaction in the boundary conditions applied.

Most of the bridges will be modeled as a combination of slab-beam elements. The key to achieve a good numerical modeling of both 1D-2D is to manually implement the interaction between the elements. In reality, in the space the beam is occupying there is no deck slab, but in the numerical model the beams are represented as 1D, so they coexist in the same space, adding an numerical (unreal) rigidity/capacity. To solve this discrepancy, a lateral offset to the slab of the half the width dimension of the beam has to be introduced. If the program does not allow this option, another solution is to subtract the height of the slab to the height of the beam.

## Boundary Conditions

The boundary conditions have a vital role, both in the reactions and behavior of the model. From the pre-calculation phase of the design the type of bridge should be clear; simple supported in the abutment, one embedded support and other sliding, etc. It should depend on the soil conditions and typology of the bridge. For now on, the most common type of support for short bridges is going to be discussed. As designers, the intention will always be to calculate and design isostatic structures, only when a specific case needs a hyperstatic (embedded) boundary condition, will be chosen.

The normal boundary conditions for simple supports are:

- Restricted displacements support, on one end, limiting XYZ movements, but having the rotational movements free. They are often represented as a triangle with linear marks emulating the contact with the ground

- Sliding support. The predominant direction of deformation/movement (X) is liberated and free to move, while the other two are restricted (Y&Z). Normally, the bridge span is oriented in the X-axis, the reason why X in the sliding support is free.

## Meshing

The meshing process is normally overlooked in most bridge numerical software, hidden in the calculation tab or non-existing at all. The meshing is key to retrieve good and accurate results where the designer needs. The mesh element's size should be at least 100 times smaller than the length of the bridge, allowing to capture the peaks of efforts and obtaining more accurate results. This will increase computing time and it must be refined in a second iteration to verify that the solution obtained in the first place is mesh-independent.

## Load Application

In the pre-calculation section, the list of loads which have to be applied according to the codes and guidelines has to be followed during the load creation and application to the model. In this phase of the modeling, the designer must check or verify the manner the software calculates the self-weight of the structure, as it normally is introduced automatically.

Live loads should be introduced as 'moving loads' as softwares normally call vehicular loads, selecting the path the vehicule/tandem will be driving. The truck/tandem creation must follow the codes.

Seismic acceleration calculations usually carry other kinds of complications, such as the Spectrum definition. Use the software help guide to properly identify the parameters of the codes and understand what type of seismic calculation does.

### Load Combinations

Using the coefficients of the AASHTO, manually combine the introduced loads. The designer is obliged to create as many load combinations as Limit States are, for every live load combination. Normally visually the designer can skip load combinations with concomitance factors that have less load applied to the model.

### Result Output

Once the numerical model has been solved, the designer has to extract the results of the model. Those results have to be contrasted with the preliminary results in the pre-calculation of the bridge to check if any effort is out of range.

Note the importance of not believing at first sight what the numerical model is returning. For every action and click the designer has made to create the numerical model, there is a potential error.

After validating the order of magnitude of the results and if they are in the expected range, the effort results are interpreted. For every beam and the deck the following results have to be extracted:

- For Strength/Extreme Limit States:
  - Maximum moment
  - Minimum moment
  - Maximum absolute shear effort
  - Maximum torsional effort
  - Maximum punching effort (slab only)

- For Service Limit States
  - Maximum deformation

With these results, the capacity of every element has to be manually checked and the design of the reinforcement is done to withstand the efforts the bridge is subjected to. Normally, this process results in an adjustment in the geometry and a recalculation. It is an iterative solving process.

## Bearing Design

Any structure when it enters into service is subject to multiple movements and deformations caused by temperature changes, the action of the structure's own weight and the overloads to which it is exposed. In order to adapt to and resist all these changes, it requires support elements that make all these movements possible without being damaged. Elastomeric bearings allow:

- Simultaneous movements in two different directions.
- Simultaneous rotation in three different axes.
- Absorption of vertical loads.
- Absorption of short-term horizontal loads.

Without being exhaustive, for the general case of a straight span bridge, the origin of the three components of the forces in the most common cases are as follows:

● Fz Component: Originated by the vertical loads transmitted by the deck due to:
- Permanent loads, overloads and prestressing where applicable.
- Foundation dips
- Seismic forces of vertical components.

● Fx Component: Caused by longitudinal horizontal loads transmitted by the deck due to:
- Braking and starting effects of vehicles.
- Elastic shortening in the case of pre-stressed panels.
- Thermo-Hygrometric deformations of the deck (temperature, shrinkage, creep).
- Seismic effects of X component.

● Fy Component: Originated by the transverse horizontal loads transmitted by the deck due to:
- Wind effects
- Thermo-Hygrometric movements in the case of bridges of appreciable width.
- Centrifugal force in the case of bridges with a curved plan.
- Seismic effects of transverse components.

## Set of Calculations

The calculations of the bearing dimensions and types have to follow Section 5.8.4.3.6. of the AASHTO. In most cases, the bearing specifications and calculations are done by the manufacturer. However, these minimum requirements the bearings must have to be checked:

- Maximum allowable displacement. This has to be contrasted with the movement obtained in the sliding support boundary condition of the numerical model.

- Maximum lateral force. Again, this value can be easily retrieved from the 'displacement restricted boundary condition', where the lateral reaction force in the support is the value of the reaction transmitted to the bearings,

- Maximum vertical force. In most cases, bearings have a limited amount of allowable settlement, compared using the vertical reaction value from the boundary conditions and the manufacturer's data.

- Maximum pressure on the bearing device. This value is obtained by dividing the maximum vertical reaction force by the area of the bearing. Using this simple equation, the bearing area needed to resist the vertical reaction can be calculated.

### Bearing Detail Drawings - Proprietary Details -

The bearing and support specifications must be clearly and legibly represented in the drawings. The minimum specification they must content, but they are not limited to:

- Bearing type
- Bearing dimensions
- Bearing positioning in the abutment/pile
- Bearing anchoring bolts/devices to the abutment/pile

### Additional Information

In the design it must be considered and specified the expected lifespan of the bearing, as well as the periodical inspection and maintenance plan, in the corresponding document.

## Movement Joint Design

Movement joints are deformable devices capable of ensuring the transit of vehicles across discontinuities between the different structural sections of a bridge, allowing relative movements of the deck.

There is a wide variety of types of joints, depending on the structure on which they will be placed and the movements they will have to absorb. Some of these are:

- Gasket sealed with elastic material
- Folded rubber strip
- Joints with sliding plates
- Modular seals
- Comb seals
- External sliding plate seals

### Set of Calculations

Similarly, to the bearings, the manufacturer's specifications of the joints must be clear, and often the manufacturer will advise of the best option regarding the structure. However, the following requirements have to be checked by the designer:

- Maximum temperature expected deformation. This calculation must be performed prior to the selection of the joint, in order to calibrate the width of the opening.

- Maximum load. The maximum load which the joint is going to be subjected to. This value can be obtained from the design truck of the AASHTO, majoring the value by 1.5, as a dynamic coefficient for the 'bump' the truck is subjected to and therefore the dynamic effects it applies over the joint.

- Maximum lateral displacements due to seismic events. This value should be obtained by evaluating the displacement in the Extreme Limit State of earthquake, it also rules the spacing needed between the plates of the joint.

- Maximum lateral displacements due to braking. This effort has been taken into account in the Serviceability Limit State, and it should also be considered when dimensioning the spacing of the joint.

### Movement Joint Detail Drawings - Proprietary Details -

The movement joint specifications must be clearly and legibly represented in the drawings. The minimum specification they must content, but they are not limited to:

- Joint type
- Joint length and width dimensions
- Joint spacing between plates
- Joint positioning in the deck

### Additional Information

In the design it must be considered and specified the expected lifespan of the movement joint, as well as the periodical inspection and maintenance plan, in the corresponding document.

## Bridge Drainage Design

A very high percentage of the durability problems of bridges can be attributed to the harmful effects of water on them. Indeed, although concrete is a material with a good resistance to attack by the most normal external agents, this is not the case for the reinforcing steel or weaker sports like the movement joints or bearings, occurring pathologies like corrosion in the rebars, degradation or malfunction of the joints or premature aging of the bearings.
To prevent water damage in the bridge, the following aspects have to be avoided:

### Entrance of water FROM the adjacent road.

Providing the necessary preliminary collection and drainage facilities, as well as surface slope protection systems to ensure that run-off from adjacent ditches does not erode the backfill of abutments.

### Accumulation of water ON the deck slab

To prevent the water accumulation on the concrete slab, the bridge has to be provided from slopes in both directions; longitudinal and transverse.

In the **longitudinal direction** of the bridge, it is recommended at least to have **1% longitudinal surface slope** from one abutment to another, to ensure water won't stagnate in the bridge. If the running surface of the deck slab is intended to be rougher than normal concrete, to prevent traffic slip, the surface slope has to be steeper, up to **2% longitudinal surface slope.**

In the **transverse direction**, the slope of the running surface has to match the slope from the road section **specified in LGED Standards**. As it is a concrete structure, the water conveyed to the sides of the bridge has to be collected and transported to the drainage system in the abutments or via downpipes in the piles, If the height difference between the deck slab and the river height is not expected to be more than 2-3m, weep holes can be used to directly expulse the water to the water stream from the water collection system of the bridge itself.

Some systems have been developed to ensure water collection and transportation in bridges. Among these options, the designer can detail in the drawings:

- Surface culverts between the road and the pedestrian zone of the bridge (if any) and always before the wheel protection. It stands out for its ease of execution, maintenance and repair, its durability and its low risk of clogging, with the disadvantage of reduced traffic safety.

- Installation next to the kerb of a prefabricated longitudinal drain with top groove, embedded in the paving and flush with the wearing course. This must be thicker next to the drain to store the infiltrated water until it is evacuated. It stands out for its drainage capacity and its difficult clogging. This type of prefabricated longitudinal drains can also be placed under a draining pavement. They are more difficult to install, maintain and repair but present less risk of clogging and greater safety in use (as they are not visible from the outside).

- Installation of shaped kerbs with a channel inside and a lateral opening towards the pavement, which must be installed below the draining wearing course to collect all the transversal water. It stands out for its ease of maintenance, durability, drainage capacity and low risk of clogging.

-

## Infiltration of water IN the joints

When the presence of joints in the abutments and/or piers interrupts the circulation of water through the deck, it is necessary that upstream of all joints a drain must be installed to collect the water that runs on the surface and has not been previously carried to the drainage systems.

The lack of a watertight joint or the absence of a drainage system causes runoff to fall on the piers, abutments or support devices, leading to degradation of the concrete, reinforcement and premature aging of the bearings.

# 10. CONSTRUCTIONS

## Construction Documentation (Input)

The purpose of this Procedures Manual is to:

- Describe the scope of the works and the responsibilities of the parties during the construction of the works.

- Establish the different methods and procedures for the activities to be developed during the construction of the works.

All parties should sign an acknowledgement register to confirm their adherence to the administrative and technical procedures for a clear and transparent construction process.

A Construction Organizational Chart shall be developed with clear role, responsibilities, contact person, email address, phone/fax number, and address, with alternative points of contact for any unexpected urgency. The Organizational Chart shall not only include the Technical Site Team but also Health and Safety and Environmental Coordinators as well as Fire and Rescue Brigade numbers.

Note that all new subcontractors shall adhere automatically to Procedure Manual once approved by the Main Contractor and detailed information about role, responsibilities, contact person, deliverables, working programm, … shall be made available.

### Construction Documentation

Construction Documentation is composed of the following Contractual Documents:

- Volume 1: Civil Works Contract dated xxxx
- Volume 2: Specification dated xxxx
- Volume 3: Drawings dated xxxx
- Volume 4 Site Data dated xxxx
- Volume 5: Environmental Study dated xxxx
- Volume 6: Health and Safety Study dated xxxx

Note that any other Construction Documentation not listed above shall not be considered appropriate for construction purposes.

The following copy of the above mentioned documents shall be made available on Site:

- Volume 3: Drawings:
    - On its original size, drawings to scale (A1 format)
    - ½ size (A3 format)
- Rest of Volumes: On its original size (A4 format)

### Language

Communication language shall be English and/or and all Site Documents shall be produced in English.

### Numbering System for Documents

Refer to Asset Management document.

## Construction Materials

We need to verify that the construction is correct and code compliant. In the review of the construction documentation, the following aspects should be checked in the next subsection:

### Material Requirements

- Concrete Structures
    - Concrete
        - Specification and Certification;
        - Storage and Handling;
        - Water/Cement Ratio;
        - Maximum Aggregate Size and percentage of sand and fine material;
        - Shape of aggregates;
        - Workmanship;
    - Steel Rebars
        - Specification and Certification;
        - Storage and Handling;
        - Workmanship;
- Road Structures
    - Specification and Certification;
    - Storage and Handling;
    - Workmanship;
- Temporary Structures;

#### Material Certification

The material provenance shall be clearly identified and identifiable, and from an authorized supplier. Record of provenance includes, but limited to:

- Date of freight;
- Supplier;
- Quantity of material supplied;

- Characteristic of material supplied;
- Price;
- Incidences, if any;

The material mechanical and chemical characteristics shall match those sets in the Material Specification document, part of the Design documentation Package;

### Material storage and handling

Cement and any occasional admixture will be kept locked in a fresh and dry environment, under the person in charge.

Water from the potable water network will be used. If not possible, the person in charge will determine the reliability, according to chemical and biological characteristics, of any other source.

Fine and coarse aggregate will be kept outdoors, protected from environmental events such as wind, rain, flood, or hail.

Rebars will be kept outdoors, protected from environmental events such as wind, rain, flood, or hail.

Similarly, to above, the material storage and handling characteristics shall match those sets in the Material Specification document, part of the Design documentation Package;

## Material Testing Requirements

The following construction materials are subjected to testing. Listed below there are some examples of the testing that is needed, but not limited to:

**Soil, Asphalt, Concrete, Reinforced Concrete, Steel Plates, etc.**

- Descriptions and objectives:
    - Strength and Ductility Test;
    - Fatigue Test;
    - Chemical Composition and/or Infiltration Test;

## Construction Quality Management Plan

The Contractor shall prepare and submit the following technical Documents for Client´s review, but not limited to. Note that these documents constitute collectively the Construction Quality Management Plan.

- Document management system (refer to LGED Asset Management Quality Plan);
- Construction procedure;
    - Method Statement - MS - (Erection procedure, Temporary works, Safety and Environmental considerations…);
    - Inspection and Test Plan -ITP -;
- Construction safety audits;
- Field measurements and surveys;
- Material identifications, certification and traceability;
- Procurement monitoring and Subcontractor's quality assessment;
- Control of non-compliant product (record, actions and mitigation measures);;
- Corrective actions and preventive measures;

Method Statement (MS) shall be developed for all construction activities related to the constructions of engineering structures (excavation, foundations, retaining walls, piers/abutments, decks, embankment, pavement, …). These MS(s) include a detailed description of each stage of the construction, identification of the contractor´s equipment and material to be used, definition of temporary works (if needed), and construction safety and environmental considerations with their corresponding contingency/mitigation measures. In other words, the MS demonstrates how the proposed works ensure construction safety (structural and human), and limit the impact into the Environment.

The Inspection and Test Plan (ITP) identifies by means of a check list (typically) the required hold points, witness points and identifies the testing programme for key structural elements (position and number). Upon inspection points and material testing, reports are developed for quality assurance of the construction procedure.

## Construction Reports at Completion of the Works

It is a good practice that at completion of each of the key structural works, a construction report including the following information be submitted to the Client for record and future use, shall it be not already stated in the Construction Contractual arrangement, but not limited to:

- Records of the laboratory and field tests;
- Records of the remedy actions undertaken;
- Summary of the issues encountered during the construction of the structural element;
- Records of the temporary works left on-site;
- Compliance with structural design drawings and specifications documents;
- Records of non-compliance and corresponding review/approval process;
- As-built drawings;

# 11. OPERATION, INSPECTION AND MAINTENANCE

As indicated in the Design Stage for Roads and Bridges, the Operation and Maintenance Plan is an essential document to be produced and passed-on to the Infrastructure Owner's and Infrastructure's Operation and Maintenance's Organization (Private Entity or Public Agency). The **O&M Plan** includes all the information necessary to ensure that the structure is used (operates) in accordance with the assumptions made during the Design phase.

This O&M Plan is a **live document** that shall be developing itself as the project and construction site progresses, and as new team members/stakeholders participate actively in the construction of the infrastructure.

In this section we will present the necessary steps and developments that shall be made to the O&M Plan to become an **O&M Manual**, that sets out as detailed as possible the requirements in terms of materials, inspection, maintenance, accessibility, Health and Safety and Environmental as to be a practical manual and reference document to the future Inspection and Maintenance organization.

The O&M Documentation shall consist of the following documents/reports, but not limited to:

**O&M Documentation**

- Infrastructure Design Brief (Design Team);
- Project Structural (and non-structural) Element Decomposition (Design Team);
- Long Term Planning Activities and Cost Planning (Design Team and O&M Organization);
- O&M Drawings (O&M Organization);
- O&M Monitoring (O&M Organization);
- Blank Report (By Contractor);
- Inspection Report #0 (By Contractor);
- Deformation Report #0 (By Contractor);
- **Operation and Maintenance Manual** (O&M Organization, validated by Infrastructure's Owner);
    - Health and Safety Plan;
    - Environmental Management;
    - Quality Assurance and Quality Control;
    - Inspection and Maintenance Plan – IMP – (O&M Organization);
    - Inspection Procedure – IP – (O&M Organization);
    - ...

## Codes, Standards and Guidelines

- Refer to the planning stage.

# Operation and Maintenance Documentation

## Infrastructure Design Brief (Design Team)

This document has the objective “to identify and translate into inspection and maintenance requirements the design, constraints and assumptions criteria set during the Design Stage of the project”.

## Project Structural (and non-structural) Element Decomposition

This document has the objective “to decompose (break down) the structure into object elements so that to clearly address an inspection and maintenance plan for each or group of these object elements”.

This decomposition shall be captured and coordinated with the “Bridge Reference System” (refer to Asset Management procedure).

## Long Term Planning Activities and Cost Planning

This document has the objective “to capture the long term planning activities and forecast the inspection and maintenance costs on the long run. These costs are purely indicative”.

## Blank Report

This document has the objective:

- To gather the available data related to the project (Design Basis, Design Report, Drawings, Specifications, Bill of Quantities, etc.…);
- To record any previous inspection works performed, if applicable, and its correlation to the drawings, and;
- To gather measurement instructions / protocols.

## Inspection Report #0

This document has the objective “to define a baseline of values and conditions for future inspection and maintenance measurements / evolution and potential claims”.

## Deformation Report #0

This document has the objective “to capture the specific deformation profile at several key points in order to produce a stage 0 – recorded 0 position) in order to determine any long-term deformation”.

## Inspection and Maintenance Manual

This document has per objective “to set the instructions for the inspection regime (frequency, type of inspection, % of inspection, etc...)”.

# Operation and Maintenance Manual

## Health and Safety Plan

The Inspection and Maintenance organization will be required to operate under an independent Health and Safety Plan (H&S Plan).

All inspection and maintenance work shall be planned and carried out in accordance with the Health and Safety law and regulations and shall take into account the practices, procedures and site rules of the Inspection and Maintenance Organization from LGED.

For each activity, a method statement shall be prepared in conjunction with a risk assessment addressing all relevant hazards, risks and mitigation measures. Account shall also be taken of access requirements and of the equipment to carry out the work.

Special attention shall be made for the work performed over traffic/movement areas such as the canal and land side (roads) as the clearance may be compromised. Proper coordination with local authorities shall be taken into account and the program detailed.

### Environmental Management

The Inspection and Maintenance organization will be required to operate under an independent Environmental Management Plan.

Similarly, to the H&S Plan, the Environmental Management Plan shall be referenced and adopted for any activity developed in conjunction with Inspection and Maintenance work.

## Inspection

### General

The aim of the inspection is the timely identification of all significant defects and deterioration of the bridge to enable the structure to be maintained in a sound and safe condition and to allow traffic to be carried safely in accordance with RWS requirements. This is achieved by the means of the planned implementation of appropriate inspection procedures.

Any Inspection regime shall cover the following aspects:

- Nature
- Category
- Frequency
- Scope


The requirements for each of these aspects of inspection are described hereafter.

These aspects shall form the basis of the Inspection and Maintenance Plan (IMP) and Inspection Procedures (IP).

### Nature of Inspections

The nature of an inspection is the approach taken to carry out the work required.

Approaches relevant to the inspections would be:

- Visual Inspection
- Close Visual Inspection
- Detailed Visual Inspection
- Non-Destructive Testing
- Destructive Testing

The use of these approaches in each Inspection Category is described hereafter.

### Visual Inspection (VI)

Visual Inspection is used to determine the basic structural condition of all structural components and relevant facilities, members, attachments and corrosion protection systems and to identify any missing parts, obvious damage, deterioration, matters presenting a danger to bridge users or others, or matters requiring more detailed investigation.

Adequate natural or artificial light is required for Visual Inspection. Binoculars should be used when direct access is not available. Pre-cleaning and the provision of special access arrangements are not required.

### Close Visual Inspection (CVI)

Close Visual Inspection is used to determine the basic structural condition by visually accounting for all structural components and relevant facilities, members, attachments and corrosion protection systems and to identify any missing parts, obvious damage, deterioration, matters presenting a danger to bridge users or others, or matters requiring more detailed investigation.

Close Visual Inspections are to be carried out from <u>within touching distance</u> of the surface being inspected. Adequate natural or artificial light is required. Pre-cleaning is not required but the provision of special access arrangements will be necessary for some elements. Protective covers and shrouds will have to be removed.

Inspections for deviations from flatness and straightness may be carried out by sighting along the members or parts to judge the magnitude of any deformation. Where the magnitude appears to constitute a defect the deviation shall be determined accurately by measurement and recorded for future reference.

### Detailed Visual Inspection (DVI)

Detailed Visual Inspection is used to detect by visual means, using magnification or endoscope where appropriate, any significant surface defects, deterioration or areas which may require further examination.

Detailed Visual Inspections are to be carried out from <u>within 300mm of the surface being inspected</u>. Adequate natural or artificial light is required. Pre-cleaning to bare metal will normally be required. Special access provision will be required in most cases. Protective covers and shrouds will have to be removed.

Detailed Visual Inspection is only used as part of a Special Inspection for the detailed investigation of a particular problem (e.g. formation of cracking in a weld).

#### Non-Destructive Testing (NDT)

Visual Inspection may be supplemented, if required, by basic non-destructive testing techniques, e.g. tapping of concrete or steel surfaces with a light hammer to detect by the sound generated whether lamination has taken place or whether bolts have lost tightness.

For Special Inspections, the non-destructive use of ultrasonic, magnetic particle, radiographic and other appropriate test methods may be used where relevant in order to determine the nature and extent of a defect.

#### Destructive Testing (DT)

Destructive Testing may require the removal of any part of the structure to determine the cause of a defect. No such testing shall be undertaken without prior review by RWS in each case. A detailed written method statement shall be provided in advance to RWS.

### Inspections Categories

The Inspection Categories are as defined as:

- Safety Inspection
- General Inspection
- Principal Inspection
- Special Inspection
- Inspection for Assessment

#### Safety Inspection

The purpose of a **Safety Inspection** is defined as **"to identify obvious deficiencies which represent, or might lead to, a danger to the public and, therefore, require immediate or urgent attention."**

Safety Inspections shall take the form of a Visual Inspection carried out by trained bridge inspection staff. They may be made from a slow moving vehicle passing over the bridge, or where circumstances dictate, inspection staff may need to proceed on foot.

The scope of Safety Inspections shall be in accordance with the requirements set in section "Scope of Work" of this report and shall be defined in the Inspection & Maintenance Plan.

Safety Inspections shall include, but not be limited to:

- carriageway surfacing
- road markings
- vehicle restraint systems, parapets and safety fences
- wind shields
- noise/environmental barriers
- signs & VMS
- marine navigation lights
- aviation warning lights

Any defects, damage or debris which may present a hazard to bridge users or others shall be recorded and reported for immediate remedial action. Any instances of structural deterioration or damage likely to indicate reduced load capacity or safety shall be reported to the Operating Authority.

### General Inspection

The purpose of a **General Inspection** is defined as **"to provide information on the physical condition of all visible elements of a highway structure."**

General Inspections shall comprise a Close Visual Inspection carried out by trained bridge inspection staff from within touching distance of all visible parts of the structure that can be inspected without the need for extensive traffic management arrangements. Special access arrangements (bridge deck gantries, mobile under bridge gantries, cable inspection gantries) will be required to allow close inspection of the structure.

The scope of Safety Inspections shall be in accordance with the requirements set in section "Scope of Work" of this report and shall be defined in the Inspection & Maintenance Plan.

General Inspections shall examine the functional, durability and safety aspects of components of the structure by visible means, aided by basic inspection equipment (e.g. tapping hammer, endoscope, feeler gauges, etc). <u>Testing is not required for General Inspections</u>.

General Inspections shall include earthworks and marine works where these are relevant to the behaviour or stability of the structure.

Before undertaking a General Inspection the bridge inspection staff should review the structure records in order to become familiar with the characteristics of the structure and of the condition of the bridge at the last inspection, including any significant maintenance and modifications.

Any damage, defects affecting long-term durability, deterioration affecting proper functioning of the structure or any matter which may cause potential hazards to bridge users or others shall be quantified, recorded and reported for remedial action.

Any instances of structural deterioration or damage likely to indicate reduced load capacity or safety shall be reported to the Operating Authority. A General Inspection may give rise to the need for a Special Inspection to investigate a particular defect.

### Principal Inspection

The purpose of a **Principal Inspection** is defined as **"to provide information on the physical condition of all inspectable parts of a highway structure. A Principal Inspection is more comprehensive and provides more detailed information than a General Inspection."**

Principal Inspections shall comprise a Close Visual Inspection carried out by trained bridge inspection staff from within touching distance of all inspectable parts of the structure. Special access arrangements (bridge deck gantries, mobile underbridge units, stay cable inspection gantries) will be required to allow close inspection of the structure. Traffic management arrangements may also be required.

The scope of Safety Inspections shall be in accordance with the requirements set in section "Scope of Work" of this report and shall be defined in the Inspection & Maintenance Plan.

Principal Inspections shall examine in detail the functional, durability and safety aspects of all inspectable components of the structure. Suitable inspection techniques should be considered (e.g. tapping hammer, endoscope, feeler gauges, etc.). Testing is not generally required for Principal Inspections.

A Principal Inspection shall include earthworks and marine works where these are relevant to the behavior or stability of the structure.

Before undertaking a Principal Inspection the bridge inspection staff should review the structure records in order to become familiar with the characteristics of the structure and of the condition of the bridge at the last inspection, including any significant maintenance and modifications.

Any damage, defects affecting long-term durability, deterioration affecting proper functioning of the structure or any matter which may cause potential hazards to bridge users or others shall be quantified, recorded and reported for remedial action.

Any instances of structural deterioration or damage likely to indicate reduced load capacity or safety shall be reported to the Operating Authority.

A Principal Inspection may give rise to the need for a Special Inspection or Scheme of Monitoring to investigate a particular defect.

For areas of difficult or dangerous access (e.g. obscured parts, confined spaces, working at height, etc.) alternatives to Close Visual Inspection may be used such as CCTV.

### Special Inspections

**(a) Special Inspections (General)**

The purpose of a **Special Inspection** is defined as **"to provide detailed information on a particular part, area or defect that is causing concern, or inspection of which is beyond the requirements of the General/Principal inspection regime."**

Special Inspections are carried out when a need is identified and are tailored to meet specific needs and circumstances. A special Inspection may comprise a single inspection, a series of inspections or an ongoing programme of inspections.

Special Inspections may comprise Close Visual Inspection, Detailed Visual Inspection, Non-Destructive Testing, Destructive Testing or Scheme of Monitoring.

The scopes of all Special Inspections shall be agreed in advance with RWS.

Circumstances in which a Special Inspection may be required include:

- Exposure to an extreme environmental condition (e.g. very high wind);
- After a lightning strike;

- After a major incident or accident (fire / impact) on, in or adjacent to the structural components;
- Following the discovery of a significant defect which is potentially of a repetitive nature;
- Structural defects or anomalies (including indications of weld cracks) arising from accidental damage or found during routine inspections or other inspections and which require more detailed investigation or inspection;
- The accumulated or sudden settlement of part of the structure by more than 10mm;
- After the passage of an abnormal load across the bridge without prior notification and approval and /or the necessary escort and clear carriageway arrangements in front and behind the vehicle;
- After a ship / barge impact to the deck, towers or piers;
- Following the discovery of elements of a structure with a severe defect;
- If any of the following events found during routine inspections / maintenance:
    - Bearings: tilted, protruding PTFE, steel component cracked /fractured / loose;
    - Movement joints: cracking / deformation of structural member, cracks on welded joints, damage to control buffers, restricted movement,'spring effect' on movement joint;
    - External prestressing tendons: severe damage (fire attack / chisel impact), loss of prestress, abnormal vibration;
    - Deck girder: cracking of an erection weld;
    - Deformation / deviation / lamination found to main structural elements i.e. webs, bottom flange, deck plate, etc.;
    - Abnormal movement to the structure: propagation of cracks in prestressing anchorages / deviators;
    - ...

**(b) Underwater Inspection**

An Underwater Inspection is a specific type of Special Inspection, concerned with parts of a structure below water level.

The condition of the structure below water level shall be recorded, together with any signs of scour, navigation damage and any other relevant deterioration.

Requirements for Underwater Inspections shall be included in the relevant Inspection & Maintenance Plan.

## Frequency of Inspections

The frequency of the various Categories of Inspection is set out here below:

| Inspection Type | Minimum Frequency |
|---|---|
| **Safety Inspection** | 6 months, but dependent on Inspection Results<br>Carriage way to be inspected daily. |
| **General Inspection** | 24 months but dependent on Inspection Results |
| **Principal Inspection** | 6 years |
| **Special Inspections** | As required |

Note: For certain elements the frequency of Safety and General Inspections is modified. Please refer to the Inspection and Maintenance Plan.

The MC and Contractor will be required to prepare a programme of inspections, which shall be agreed with RWS. The Inspection & Maintenance Organization will then adopt this programme for their work.

## Scope of Inspections

The Inspection & Maintenance Organization will be required to define the scope of inspections in the Inspection & Maintenance Plans, taking into account the requirements of the relevant Inspection Category defined above together with the appropriate Inspection Coverage Rate.

### Inspection Coverage Class & Coverage Rate

Each section or component (Special Items) shall be assigned an Inspection Coverage Class depending on the structural and material characteristics and behavior of that section or component.

Coverage Class defines the number of Inspection Units to be included in an inspection and the Coverage Rate of inspection to be applied to those units, as follows:

Inspection Coverage Class, Number of Inspection Units and Coverage Rate

- Class 1: < 10 units 100%;
- Class 2: 10 < units < 20 - 50%;
- Class 3: 20 < units < 100 - 20%;
- Class 4: > 100 units 10%;

The inspection Coverage Class is derived to provide an initial objective guideline on inspection frequency in the early lifetime of the bridge. The interval shall be reviewed based on the Inspection Rating System described below.

The Coverage Rate for **Safety Inspections** shall be 100%. The Coverage Rate for **General Inspections** shall be determined based on the coverage area or the quantity of an individual component.

### Defects

At all times, all personnel engaged with any aspect of the Road and Bridge inspection should be vigilant and report promptly anything that appears to need attention, including all aspects of structural behavior and especially all unusual vibrations and deflections.

The extent of each defect shall be rated. Rating of the severity of a defect is based on the risk of loss of structural integrity.

The general rating of severity is as follows:

- Rating 1 No significant defect;
- Rating 2 Recognisable defect but of minor, non-urgent nature;
- Rating 3 To be included for attention/repair in the current maintenance programme;
- Rating 4 Severe – requires urgent remedial work;

## Inspection and Maintenance Plan – IMP

The Inspection and Maintenance Plan for typical elements such as Concrete and Steel Elements shall be developed as per the indications described in the Inspection Chapter of this report.

Please note that the structure of the I&M Plan allows at any time to expand and insert any new IMP. IMP are self-contained documents.

IMP typical elements shall be consistent with the structural element breakdown as described in the **Asset Management Manuel** corresponding to **Level 5 Components**.

Elements requiring inspection and maintenance are associated with the Structural Decomposition of key infrastructure elements as described previously.

| **1** | **IMP-xxx** | **Longitudinal Cracks – Welding Process -** |
|---|---|---|
| **2** | IMP-xxx | Cross Beams |
| **3** | IMP-xxx | Wearing Course - Pavement - |
| **4** | IMP-xxx | Bearings (An example is presented) |
| **5** | IMP-xxx | Movement Joints |
| **6** | IMP-xxx | Tie Downs |
| **7** | IMP-xxx | |
| **8** | IMP-xxx | |

Inspection and Maintenance Plans for each of these following Structural Elements are typically developed:

An example of Inspection and Maintenance Plan for bridge bearings is presented on Annex 2;

## Inspection Procedure – IP –

In general, inspections are grouped by generic type and sub-divided according to the constituent materials (please refer to **Asset Management Manuel** corresponding to **Level 5 Components)**.

| | | |
|---|---|---|
| **1** | **IP-xxx** | **Longitudinal Cracks – Welding Process -** |
| **2** | IP-xxx | Cross Beams |
| **3** | IP-xxx | Wearing Course - Pavement - |
| **4** | IP-xxx | Bearings (An example is presented) |
| **5** | IP-xxx | Movement Joints |
| **6** | IP-xxx | Tie Downs |
| **7** | IP-xxx | |
| **8** | IP-xxx | |

An example of Inspection Plan for bridge bearings is presented on Annex 3;

## Roadway Surface

### Scope and strategy

Maintenance of the roadway is the primary way in which the goal of providing a safe and efficient transportation utility is achieved.

Safety means to provide a non-skidding surface. Efficiency means to provide a good regular surface, to prevent time or fuel wasting, and achieve good serviceability and comfort.

Maintenance strategy should be based on two different items which are complementary: preventive maintenance and repairing activities.

One of the most important items in maintenance strategy is the scheduling and budgeting. Routine maintenance and periodic preventive activities are to be anticipated and planned. If traffic loads increase or weather conditions are extreme, the needs for repairs and resurfacing may occur sooner than predicted.

## Preventive maintenance of flexible pavements

Preventive actions are those intended to extend the life of the pavement sufficiently to more than justify the cost of applying the treatment.

One of the most typical preventive maintenance activities is the **crack sealing** and filling which prevent the pavement from future more severe deterioration. When cracking is not excessively extended into the pavement section, the use of **slurry seal** spread evenly on to the bituminous pavement surface provides the fill of the cracks, repair incipient raveling and achieve a skid-resistant surface.

**Micro surfacing**, slurry seal using a polymer-modified emulsion, is effective for treating irregularities that are larger than those normally treated with regular slurry seals.

A more comprehensive preventive treatment is the sand and aggregate seals, in which a light application of asphalt emulsion is followed by a sharp, clean sand or uniformly graded aggregate for cover. This type of treatment has proved very efficient in increasing the life of the pavement in countries like France, South Africa or Australia.

## Maintenance short-term repairs of flexible pavements

Next it is presented a brief description of the most typical action items in relation with short-term repairs in flexible pavement sections. These action items should be distinguished from full depth repairs or reinforcement with overlays which should be considered out of the scope of maintenance activities and into long-term repairs not scheduled regularly.

**Micro surfacing, cold milling** and **leveling with asphalt fills or overlays** are typical actions against rutting distresses, corrugations and shoving. These distresses can be very dangerous when filled with water, creating hydroplaning or splashing.

**Patching** is the action item related to repairing potholes before the distress is too great and a full depth repair is needed. Patching consists of shaping the pothole to be square with the pavement, the bottom and sides of the prepared patch area should be given a light tack coat, and finally a cold premixed patching material should be placed in thin layers. and thoroughly compacted before the area is opened to traffic.

## Preventive maintenance of rigid pavements

When joint materials become inadequate for its purpose by losing its capability to expand and contract with the concrete, the base or subgrade are likely to be damaged as a result of water entering through the joints. The maintenance remedy consists of **joint sealing** or **joint filler replacement**. When joint seals are to be replaced they are usually sawed out taking care not to damage the edge of the concrete. Roadway joints should be periodically checked to ensure that they are properly sealed.

Surface texture failures and cracks are typical distresses in concrete pavement. If they are not properly treated the severity of the distress may increase to the point of needing a hot plant mix surface treatment. **Crack sealing** is the typical preventive action item in maintenance of concrete pavements.

## Maintenance short-term repairs of rigid pavements

**Patching** for Portland cement concrete broken slabs is made by the use of high-early strength cement to open the patched area to traffic as early as possible. When the distress is too sever, alternate methods include replacement or overlays with asphaltic cement concrete to level or strengthen depressed areas

Spalling occurs as chipping or splintering of a localized area of Portland cement concrete. It is commonly found next to joints and caused by poor construction or poor joint maintenance. **Joint cutting and sealing** is the typical repairing action in this case. If the spalled area is to be corrected temporarily, it may be **filled with a bituminous paving mixture**. Larger areas should be repaired with **concrete** to ensure a uniform, long-lasting riding surface.

Blow Ups are localized pavement buckling. Rarely is it to detect the change in pavement surface profile before the rupture, so once a blow up occurs, it becomes an emergency repair to prevent a hazard to the traffic. Usually a **full depth pavement patch** is required along with the creation of an **expansion joint**.

Settlement on the approach slabs to bridges is typically caused by the loss of fine granular material under the slab. Corrective actions include applying a **leveling course of asphaltic concrete** or removing the settled slab and making a **full depth replacement**.

Another way of subsurface repairs include grout pumped under pressure under Portland concrete cement slabs to restore the settled slabs to the original position by **"slab jacking".**

## Maintenance of earth roads and stabilized earth roads

Unpaved or earth-surfaced roadways are roads surfaced with crushed rock or gravel. They are used for low traffic volume roadways.

Preventive maintenance consists mainly in blading the surface to provide a slope outward from the centerline. Good drainage is essential to maintaining unpaved roads. Frequent inspections and regularly scheduled maintenance are more essential to this type of roadway. Stabilized earth roads consist of an unpaved road over which a stabilizing material is incorporated. The usual method is to pulverize the soil to be stabilized and mix it on site with a stabilizing material such asphalt, portland cement, lime, etc.The mix is then shaped and compacted. Stabilized earth roadways offer a firm load-bearing surface that resist raveling and loss of aggregate, reducing the need of maintenance in comparison with earth roads.

When the corrugations and rutting of unpaved roads caused by traffic become important, the only satisfactory method to repair these distresses is to scarify to an appropriate depth, pulverize (in case of stabilization), shape and re-compact.

## Roadway drainage maintenance

Roadway drainage maintenance focuses on retaining the intended design efficiency of the drainage system. Major changes of the drainage system imply a new design and reconstruction project.

Maintenance activities include the following:

Roadside ditches and natural water courses should be monitored regularly and specially after storms, for debris accumulation. Removing these elements is essential to provide a uniform flow line.

When debris accumulates against bridges and culverts it may block water flow, creating the potential of scouring or washing out the structure or the adjoined embankment. Again, removing is the only option.

Correction of minor defects such as sealing cracks in culvert walls, repairing scour around bridge piers and abutments, regrading eroded slopes to their original condition and replacing culvert entrances that have been damaged are some typical corrective maintenance actions in relation with the drainage system.

## Coordination with LGED´s Asset Management Procedures

As mentioned across this document, Operations, Inspection and Maintenance Manual procedure shall be consistent with the Asset Management (AM) Process being in-place. This section aims to provide a clear link/path to the Asset Management Strategy currently been implemented by LGED by means of an additional Level (level 6) on the AM Organigram, summarized here after:

### Road Infrastructures

| Level 1 Asset Class | Level 2 Asset sub-class | Level 3 Asset Type | Level 4 Asset Sub-Type | Level 5 Asset Component | Level 6 Observed Conditions (Pathologies) |
|---|---|---|---|---|---|
| **Rural Road Infrastructure** | Upazila Road<br>Zila Roads<br>Union Road<br>Village Road | Pavement | Flexible<br>Rigid<br>HBB<br>WBM<br>Uni-Block<br>Earthen | Asphalt layers<br>Base<br>Subbase<br>Improved subgrade<br>Subgrade<br>Embankment | Rutting<br>Surface cracking<br>Potholes<br>Scour and Wash-out<br>Excessive deformations |

## Bridge Infrastructures

| Level 1 Asset Class | Level 2 Asset sub-class | Level 3 Asset Type | Level 4 Asset sub-Type | Level 5 Asset Component | Level 6 Observed Conditions (Pathologies) |
|---|---|---|---|---|---|
| **Rural Road Infrastructure** | Structures | Bridges | PC Girder Bridge<br>Steel Structure<br>Bailey Bridge<br>RCC Bridge<br>Box Girder Bridge<br>Arch Bridge<br>Sluice Gate | Wing wall<br>Abutment<br>Girder<br>Slab<br>Railing<br>Rail post<br>Expansion Joint<br>Walkway<br>Wheel Guard<br>Pier & Pier Cap<br>Cross Girder<br>Diaphragm<br>Bearings | Cracking<br>Concrete Spalling<br>Excessive Deformations<br>Structural Failure<br>Honeycombs<br>Scour & Erosion<br>Movement Joint Malfunctioning<br>Bearing Malfunctioning |

# 12. IMPLEMENTATION OF FORENSIC ENGINEERING (ToolKit)

To organize this Failure Analysis Process, Fault Tree, Check List … are often used to aid and to structure the process of Failure Analysis. The following section describe a "ToolKit" option as an aid to fulfill this purpose:

## Failure Analysis Methods

In order to describe the most common standardized methods to perform a Failure Analysis Investigation, the following methods, can be highlighted, while not limited to:

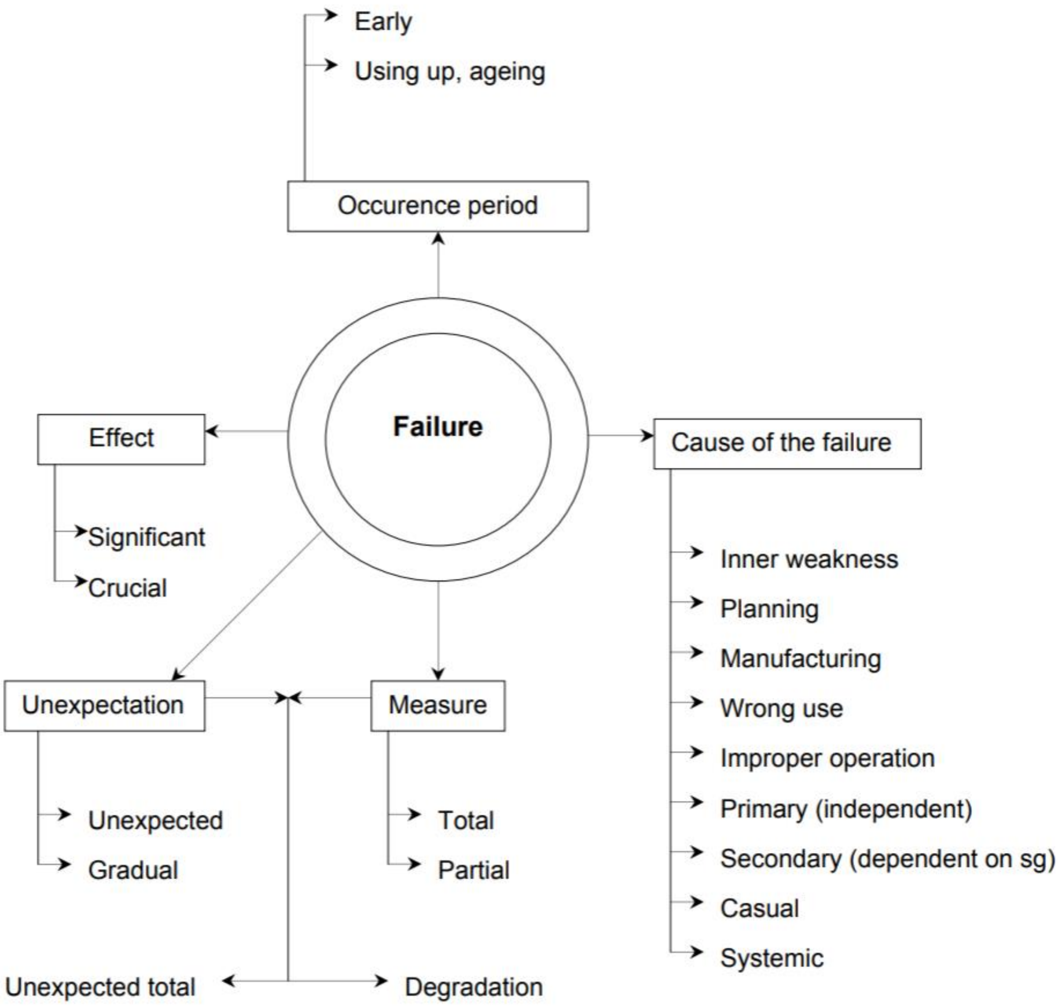
- Karoly Möller´s Analysis Method;

Briefly, the Károly Möller's Analysis categorizes the Failure in terms of cognition, source, importance, repairability and by usual building process. In this aspect, the method falls short when going after the root cause of the problem, being this method suitable for early stages of a forensic investigation:

- Failure Analysis in Quality Assurance;

The Failure Analysis in Quality Assurance serves as a method for receiving feedback of a constructed infrastructure. It is based on the modern management systems, where the feedback of the product provides useful information in order to gradually improve the final item and helps in the decision making of the changes to come.

This method is suitable only for evaluating the deterioration of the structure, not for determining the root cause of the problems, nor the origin of a pathology, because it does not introduce human and economical factors into account.



- Fault Tree Analysis;

The last of the most relevant methods in Forensic Engineering is the Fault Tree Analysis. This method provides reliable and systematic evidence of the root causes of the failure, while providing useful information that can be used as an input for future structures.

It includes a logical diagram that displays the interrelationships of the causes/reasons and the potential pathology that is being observed or potentially being generated in a short-medium term.

Because the scope and deepness of the analysis depends only on the time/effort of the analyst and it provides results that can be proved, new hypothesis to explore and validate, it can be selected as the proper system to develop a full-resilient, upgradeable, scalable and easy to implement ToolKit.

## Fault Tree Approach

The structure of the analysis can be described as a two-way system, where the inputs and outputs can be both ends of the tree. In one part of the tree, all the life-cycles and decisions of the infrastructure, from the first economical analysis to the last inspection procedure on a movement joint; in the other part of the tree, the pathologies of the different infrastructure are described. In between, the algorithm appears, interrelating the two sets of branches of the tree, which has been carefully studied to thoroughly and accurately relate both parts.

Depending on the part of the tree the analyst want to explore, the analysis can be divided in:

- Top Down Approach: Decisions during the Live-cycle of the Infrastructure:
- Bottom-Up Approach: Failure Mode Study

In order to analyze both approaches, the analyst has to define numerical parameters to categorize the potential risk of both occurrence and potential causes.

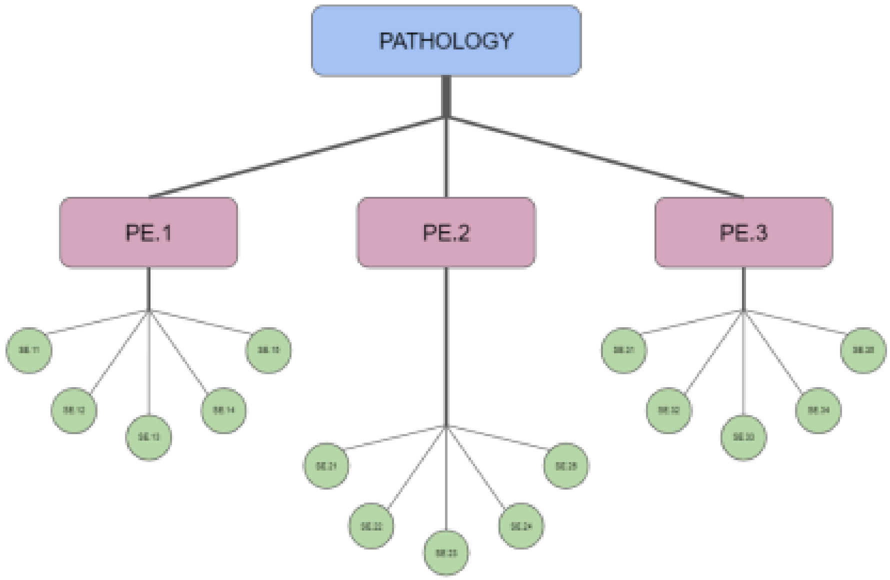
Being this a very subjective task, the only manner to overcome this issue is to define thresholds based on images-related numbers to decouple the subjectivity of the analyst. Therefore, the Guidance Materials are created to serve as a follow-along document that without them, the scoring system of the Toolkit is arbitrary.

## ToolKit (Beta version)

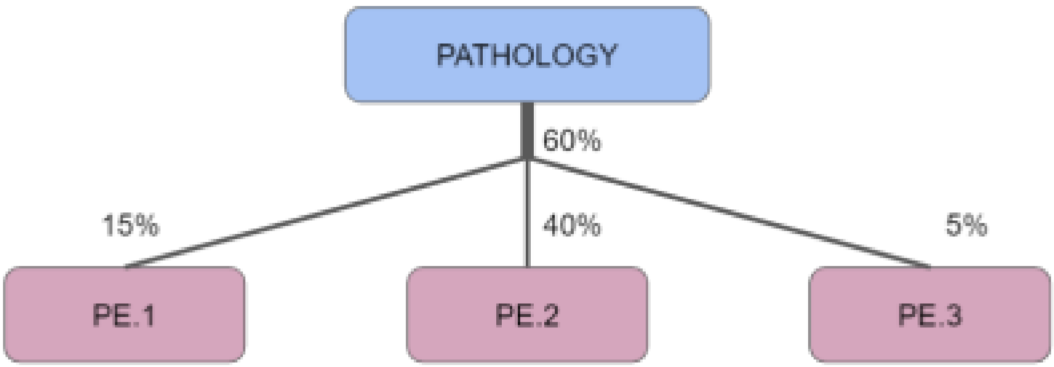
The User Manual is found in the Guidance Material: Toolkit User Manual

The ToolKit pretends to provide a simple but sturdy way to explore the different shallow and deep causes that lead to the apparition of a pathology. It works under the combination of two analysis methods:

- Fault Tree Analysis (FTA) where the answer to some questions leads different paths with some other questions to answer, until reaching a final and satisfactory answer.
- Analytic Hierarchy Process (AHP) where possibilities are assorted according to their perceived relevance.



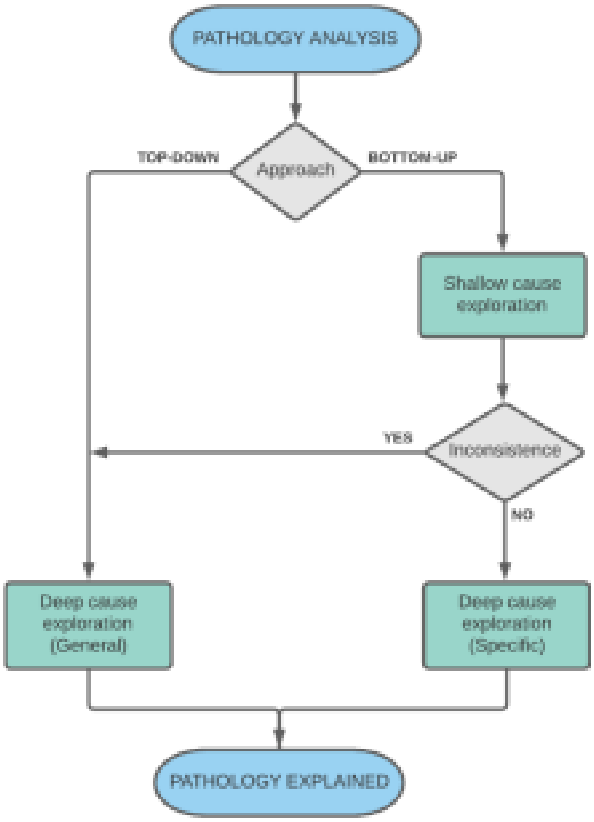

When analyzing a pathology, the operator will be asked a small collection of questions related to the shallow causes. According to his answers (rated from 0% to 100%, in intervals of 25%, and where 100% implies total non-Conformity and 0% total Conformity), the ToolKit will analyze the relevance of each primary explanation in the appearance of the pathology.




Once all shallow causes are weighted, two situations may occur:

- **There is no inconsistency:** In this case the ToolKit will lead the operator to evaluate the secondary explanations that conform to the most relevant primary explanation (Bottom-Up approach).

- **Inconsistency occurs while exploring the shallow causes:** In this case a general approach (Top-Down approach) will be developed. Inconsistencies are:
    - **Multifactor failure:** Non-Conformity Index is above a given threshold.
    - **Lack of evidence:** Conformity Index is above a given threshold.
    - **Lack of data:** Lack of data is above a given threshold.




The toolkit is a spreadsheet with a pyramidal structure, where the operator uses only the Analysis sheet. The programmer works on the deeper layers of the structure.

First, the operator will be asked to determine which is the pathology to study and the approach (Top-Down or Bottom-Up). That selection will feed the data regarding the selected pathology in the 'Pathology Sheet' (there is a Pathology Sheet for each pathology) to the 'Calculation Module', which will likewise offer some questions to the operator in 'Analysis'.

Answers from the operator in the 'Analysis' sheet will be feedback to the 'Calculation Module'. This process will go on until the end of the analysis, where the operator will use the 'Analysis' sheet.

These answers are processed as follow:

- First, the spreadsheet counts the number of questions to be answered by the operator related to shallow causes. Questions answered as NON-APPLICABLE are removed from the counting.
- According to the valid answers (any answer different with NON APPLICABLE), the spreadsheet calculates the different indexes.
- Non-Conformity Index is distributed among the different shallow causes following an Analytic Hierarchy Process, where each answer is compared with the others. On a default basis, every shallow cause is equally relevant (100 points for shallow cause "A" counts as 100 points for shallow cause "B"), hence the Analytic Hierarchy Process is

isomorphous with a proportional distribution of weights among the shallow causes. This can be modified by the programmer.

- Shallow causes get each a portion of the Non-Conformity Index and are ranked. Operator is then offered the possibility of exploring the deep causes related to any of the shallow causes.

- In the deepest level of the pyramid are the 'Impact Matrices' and the 'Auxiliar Sheet', that have no direct role in the calculation. In the 'Impact Matrices' sheet, the programmer determines the interaction between each and every pathology with the shallow causes, and the shallow causes with the deep causes; information that will be fed in each 'Pathology Sheet' to be curated. In the 'Auxiliar Sheet' are collected all the possible answers for both the operator and the programmer, as well as every information related to pathologies, shallow causes and deep causes.

# 13. BUILD BACK BETTER RECOMMENDATIONS

After an extreme event or human error, conclusions shall always be derived for the growth and maturity of our society. The importance of Build-Back-Better is highlighted in Priority 4 of the United Nations' Sendai Framework for Disaster Risk Reduction in 2015. Key considerations to 'build back better' are:

- **Build back "stronger":** to consider how the reconstructed infrastructure so that it could resist more intensive extreme events in the future (**Resiliency** of the Infrastructure);
- **Build back "faster":** to consider how the reconstruction can take place more expeditiously through good planning, contractual and financial arrangements;
- **Build back more "efficiently":** to consider how to include lessons learnt, issued from a Failure Analysis Procedure, are implemented from one project to the other;

## Governance and Legal Framework

- Accessibility to Design Codes and Commentary Section of Design Codes (Electronic version of latest version); Centralized library;
- Clear identification of Codes and Standards hierarchy (Codes, Standards, Manuals, Guidelines, …);

## Planning

**Strategic Context**

- The development of an infrastructure (Road and Bridges) shall respond to a) social and b) economical growth aligned with the Rural Road Infrastructure Strategy Plan;

**Technical Alternatives**

- Hazard Studies shall be investigated;
- Risk Register and Mitigation Measures Plan shall be developed and updated at every stage of the project;
- Extensive hydrogeological site investigation shall take place benefiting the study of road and bridges structural alternatives;

**Economic Analysis**

- Sensitivity analysis standardized prices and also foresee the inflation of the construction prices;

**Financial Approach**

- Financial Scenarios shall be developed and evaluated based on current and future market conditions (Loans, Bons, Private Finance, …);

**Management Approach**

- Organizational Chart with clear role and responsibilities shall be established for the different Financial Scenarios 'type;

## Design

**Road Design**

- The traffic estimation has to be compliant with the traffic studies conducted by LGED. If the road is expected to surpass those values, the designer should take measures in order to foresee a higher capacity design for both embankment materials and pavement sections;

- The aggregates must be compliant with LGED Standards in terms of composition, dosage and mechanical properties;

- The materials used to conform the embankments are the same as subgrade material, unless subgrade material is already an improved subbase;

- No soil base material, for embankments, subbase and grade, shall be placed without proper Soil Mechanical Properties, Method Statements and Inspection Test Plans. Similarly for road pavement;

- Compaction tests of the terminated surface shall be performed before the placement of the road pavement;

**Bridge Structures Design**

- Concrete material and reinforcing steel bars shall be compliant to the project Technical Specification Document and shall not be placed without proper Method Statements and Inspection Test Plans;

- Concrete Pathologies and potential causes are multiple, and therefore special care shall be taken at every decision-making process, which would lead to an adverse performance of the structure, both capacity and performance wise;

- A holistic approach to Bridge Design allows to develop a resilient and robust structure; Take the time to address all potential hazards;

- If close to water stream, or foreseen structural interaction with water, the abutments/piers foundations shall be designed against scour and water erosion mechanisms;

- Numerical modeling by no means is a replacement of the background knowledge of structural calculations and understanding of the flow of forces; it is only a tool to improve design demand under several load combination scenarios;

- The Design shall include the considered and required lifespan of a) bearings and b) movement joints, as well as the recommended periodical inspection and maintenance regimes in the corresponding documents;

## Construction

- It is mandatory to have a clear Construction Organizational Chart (role, responsibilities, …);
- The Construction Quality Management Plan should be clearly developed at the beginning of the construction stage;
- All Construction Activities must have both Method Statement (MS) and Inspection and Test Plan (ITP);
- All the documents must be accessible and numbered according to the standard numbering system, refer to asset management documents;
- All construction material, including mechanical/electrical components, shall be in accordance with the Material Specification Document for material quality, storage and handling characteristics;
- Audit on material quality shall be performed shall be performed in accordance with applicable Codes, Standards and/or Specific Contractual Requirements;

## Operation, Inspection and Maintenance (OI&M)

The minimum documents that conform this OI&M documentation are:

- Infrastructure Design Brief (Design Team);
- Project Structural (and non-structural) Element Decomposition (Design Team);
- Long Term Planning Activities and Cost Planning (Design Team and O&M Organization);
- OI&M Drawings (OI&M Organization);
- OI&M Monitoring (OI&M Organization);
- Blank Report (By Contractor);
- Inspection Report #0 (By Contractor);
- Deformation Report #0 (By Contractor);
- Operation and Maintenance Manual (OI&M Organization, validated by Infrastructure's Owner);

Prior to developing this documentation, it is needed to have a full understanding of the structure.

# 14. RECOMMENDED NEXT STEPS

In view to develop a meaningful recommendations strategy with the corresponding project list, following the mission and workshops, the following recommendations/next steps have been raised, but not limited to:

- To continue providing the support to LGED in the development of the Tool Kit related to other existing failure, other than the Pilot case in view to continue a) validating and b) calibrating the tool;

- To support LGED in the development of repair strategies following the Failure Analysis Assessment of the structure;

- To continue enhancing the understanding of resilient infrastructure in Bangladesh through the study of failed infrastructures;

- To make recommendations to support the LGED advance infrastructure resiliency by highlighting and prioritizing key activities and investment opportunities throughout the implementation process (planning, design, construction and operation and maintenance) of rural transport infrastructure, and policy reforms and steps to ensure that new infrastructure is safe and resilient.

# ANNEX 1 CONCRETE MIX RATIO

| Element | Weight ratio | Density (kg/L) |
| --- | --- | --- |
| C. Cement | 1.00 | 1.51 |
| W. Water | 0.45 | 1.00 |
| F. Fine aggregate (sand) | 1.75 | 1.80 |
| Co. Coarse aggregate (gravel) | 3.50 | 1.80 |

**1m$^3$ concrete example**

| | | |
| --- | --- | --- |
| C. Cement | 250 Kg | (165 L) |
| W. Water | 110 Kg | (110 L) |
| F. Fine aagregate (sand) | 440 Kg | (240 L) |
| Co. Coarse aggregate (gravel) | 880 Kg | (490 L) |

**Wheelbarrow example**

| | |
| --- | --- |
| C. Cement | 2 bags of 50 Kg |
| W. Water | 45 L |
| F. Fine aagregate (sand) | 1 full wheelbarrow |
| Co. Coarse aggregate (gravel) | 2 full wheelbarrow |

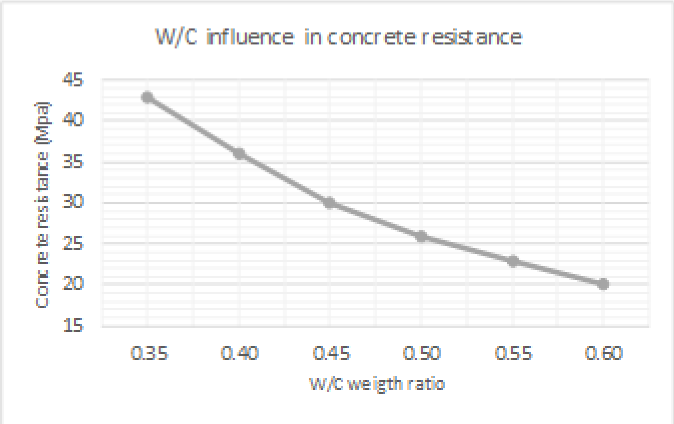
*A full leveled wheelbarrow has a capacity around 100 L*

**Water-Cement ratio (W/C)**

Water-Cement (W/C) ratio is one of the key factors in the concrete strength. In table 1, W/C is set as 0.45, leading to a 30 MPa concrete. Small variances in this ratio lead to other resistances.

| W/C | fck (Mpa) |
| --- | --- |
| 0.35 | 43.00 |
| 0.40 | 36.00 |
| 0.45 | 30.00 |
| 0.50 | 26.00 |
| 0.55 | 23.00 |
| 0.60 | 20.00 |

When changing the W/C ratio, F/C and Co/C ratio shall not be changed unless required by designer or person in charge.



# ANNEX 2: EXAMPLE OF INSPECTION AND MAINTENANCE PLAN FOR BEARINGS

Subject : Bridge – IMP Bearings

Date : xx xx xxxx Job No./Ref: xxxx

## 1. Inspection and Maintenance Requirements

### 1.1 Overall Schedule of Inspection and Maintenance Requirements

| IMP-xxx: Bearings | Safety Inspection (SI) / General Inspection (GI) | | | | |
|---|---|---|---|---|---|
| | SI | | GI | | |
| | Fz | % | Fz | % | Special Inspections (SI)? Inc. Frequency of Inspection |
| Bridge bearings | 6M | 100 | 2Y | 100 | Tilting of the bearing<br>Protruding of the PTFE<br>Fracture of the holding down and anchorage bolts |
| | | | | | |
| | | | | | |
| **Replacement:** Bearing every 25 years cycle. Bearing components every 10 years cycle or as necessary.<br>**Routine Maintenance**: In conjunction with Safety and General Inspection | | | | | |

### 1.2 Routine Inspections

#### 1.2.1 Six (6) monthly cycle: Safety Inspection

1) 100% Visual Inspection of bridge bearings for the viaducts to check for any accumulation of debris and any signs of damage or distress.
2) Procedure Ref.:
    a. Bearings, Visual Inspection; & Bearing O&M Manual by Manufacturer

#### 1.2.2 Two yearly cycle: General Inspection

1. 100% Close Visual Inspection of bridge bearings, including the fixings and bolting to the underside of the deck girder and to the plinths and upstands under the bearings. Close Visual Inspection should extend to cover the concrete below and above the bearings.
2. Procedure Ref.:
    a. General Concrete Structures, Close Visual Inspection
    b. Bearings, Visual Inspection; & Bearing O&M Manual by Manufacturer

### 1.3 Special Inspection

1. Special Inspection shall be carried out if the Routine Inspection reveals damage or defects which require closer investigation or assessment. Such follow-up inspection will generally be the prescribed Close Visual Inspection for the particular item or element concerned.
2. Special Inspection shall also be carried out following abnormal incidents, such as: -
    a. Transit of overweight vehicle(s) or abnormally heavy loads;
    b. Major accidental impact by vehicles;
    c. Outbreak of fire on or within the structures;

After abnormally adverse environmental conditions (exceeding the design limits as shown on the Design Memorandum).

## 1.4 Routine Maintenance

### 1.4.1 Six (6) monthly cycle: General cleaning, Maintenance, and Non-critical Repair

1. General Cleaning, Maintenance, and Non-critical Repair shall be carried out in parallel with or at reasonable time after Routine Safety or General Inspection; including but not be limited to the following:
   a. To repair any surface damage to concrete substrates.
   b. To replace any deteriorated / leakage part of the drainage pipe-works and fire hydrant mains; to tighten up the loose fittings and fixings.

## 1.5 As required Maintenance/Repairs

1. As-required Maintenance / Repairs can arise as a result of Routine Safety or General Inspection, and also from Special Inspections. Any discovered damage or defect which poses a safety hazard to the public or would endanger or diminish the proper functioning of the structure if repair were to be deferred until the next Routine Maintenance, must be programmed for remedial action as soon as practicable after discovery. Non-critical repairs / replacements shall be programmed into the 6-monthly General Cleansing, Maintenance, and Non-critical Repair cycle.

2. Examples of As-required Maintenance / Repairs shall include but not limited to: -
   a. To repair any damage to concrete substrates showing sign of heavy spalling / cracking / flaking, which are usually resulted from severe major accidental impact by vehicles.
   b. To replace any broken / missing part of the drainage pipe-works and fire hydrant mains.

## 1.6 Long Term Maintenance

1. Renewal / Replacement of the bridge bearing components as necessary. Bearings are designed for every 25 years cycle while bearing components with a design life of 10 years.

2. Renewal / replacement of any bearing components can be carried out one by one at any time by jacking up the deck girder by 10mm using temporary jacks, which shall be designed to take up the full dead load and live load to maintain the normal traffic.

3. Any Special Consideration on traffic loading during bearing replacement will be listed here after and confirm with Inspection and Maintenance Organization:
   a. To be Completed

# 2. Special Access Considerations

1. Access to the external concrete surface of the pier is done from the land side via cheery pickers.

2. Access to the abutments bearings is generally through the abutment access doors and hatch to abutment roof where bearings are located.

# ANNEX 3 EXAMPLE OF INSPECTION PLAN FOR BEARINGS

Subject : Bridge – IP Bearings

Date : xx xx xxxx Job No./Ref: xxxx

## 1. Inspection References

1. Code of Practice for Lighting, Signing and Guarding of Roadworks, as applicable per LGED.
2. Inspection Manual for Highway (Structures), Structures Division, as applicable per LGED.

## 2. Safety

The work creates potential hazard to the inspection team and other road users, the Code of Practice for Lighting, Signing and Guarding of Roadworks shall be observed and followed. Safety procedure shall be established with reference to the Code of Practice for Lighting, Signing and Guarding of Roadworks. The procedure shall be briefed to the inspection team before the commencement of work.

## 3. Personnel

The inspection shall be undertaken by LGED Maintenance Inspector under the supervision of LGED Maintenance Engineer. The Inspector shall work with an assistant for the safety implementation.

## 4. Equipment

1. Personal protective equipment;
2. Computerized data logging / capture device / inspection form;
3. Digital camera;
4. Binoculars (x 20 magnification);
5. Feeler gage;
6. Straight edge (1 m);
7. Light tapping rod:
8. Color marker / chalk;
9. Lights / torch;
10. Communication equipment with control room;

## 5. Procedure

### 5.1 Visual Inspection

1. The Visual Inspection can be carried out by using either of the following access alternatives:
    1. Bearings at Piers:
        1. *I&M Path from Abutments to Pier*
        2. *I&M Traveller from Abutment to Pier*
        3. *Cherry picker at Pier location*
    2. Bearings at Abutments
        1. *Access doors and Roof Hatch at the Abutments*
2. The inspection must be carried out under the adequate natural or artificial lighting and preferably in daytime.

3. Bearings shall be given a General Inspection as indicated in the IMP Bearings following installation.

4. Paint or protective coatings must be maintained in good and efficient condition and free from scratches or chips. Any areas of the protective coating showing damage or distress must be rectified appropriately.

5. Areas surrounding the bearings must be kept clean and dry and free from debris or water/salt.

6. The wearing surfaces of the bearings must be checked to ensure that they are continuing to operate efficiently. The degree of wear which has taken place on PTFE surfaces must therefore be measured not less frequently than every two years and the PTFE must be replaced when the PTFE projection above the confining recess falls to 1mm.

7. Fixing bolts must be checked for tightness.

8. Any bedding material showing signs of distress or ineffectiveness must be replaced and the reason for its failure should be investigated.

9. Routine inspections shall include a check that translational and rotational capacities of the bearing show no sign of being likely to exceed the requirements specified on the bearing schedule. Should the performance of the bearing be examined unsatisfactory or the conditions be adversely deteriorated which likely result in affecting the intended function of the viaduct or damaging its structural integrity, replacement of the bearing is required given that malfunction of the bearing or the proper function of the bearing no longer performed is identified. Procedure of replacement of bearing is described hereafter.

10. The associated inspection procedure shall also make reference to the O&M manual, drawings and specifications for the bearings.

11. The visible surfaces of bearings, concrete plinth and shelves shall also be inspected. The following deficiencies shall be reported, if found:
    1. Tilting;
    2. Spalling-off on concrete plinth;
    3. Bolt loosen / missed;
    4. Deflection;
    5. Cracks on steel components;
    6. PTFE sheet protruded;
    7. Scratched, distortion on sliding plate;
    8. Any significant defects.

12. Take photographs of any significant defects and record the exact location.

## 5.2 Close Visual Inspection

All the above description for Visual Inspection (VI) is also valid for Close Visual Inspection (CVI) amended with the following:

**Equipment:**

1. Inspection mirror with telescope (large)

**Procedure:**

1. This inspection shall be done within "touching" distance

2. The visible surfaces of bearings, concrete plinth and shelves shall be inspected. The following deficiencies shall be reported, if found:
    a. Tilting;
    b. Rotational movement;
    c. Spalling-off, delamination, cracks ( 0.25mm) on concrete plinth;
    d. Bolt loosen / missed;
    e. Loose, broken, missing to bearing components;
    f. Deflection on bearing plate;
    g. Cracks on steel components;
    h. PTFE sheet protruded;
    i. Scratched, distortion, grout stain on sliding plate;
    j. Excessive movement;
    k. Restriction on movement;
    l. Corrosion and effectiveness of protection system;
    m. Deterioration on bedding mortar;
    n. Any significant defects.

3. If necessary, a local Special Inspection and movement and tilting monitoring should be carried out on the defective bearings.

## 5.3 Bearing Replacement

To be completed

# Recording & Reporting

1. Record location and details of any potential hazard or damage found.
2. Inform operating and maintenance authorities without delay of any critical hazards requiring urgent further investigation or remedial action.

Log record of inspection (including any nil returns) and any recommended maintenance or further inspection requirements (critical or non)