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Climate Adaptation: Risk Management and Resilience Optimisation for Vulnerable Road Access in Africa

Engineering Adaptation Guidelines

Council for Scientific and Industrial Research (CSIR), Paige-Green Consulting (Pty) Ltd and St Helens Consulting Ltd

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Abstract

The African Development Bank states that Africa is one of the regions in the world that is most vulnerable to the impacts of climate change. The majority of both vulnerability-led and scenario-led studies carried out in the region suggest that damages from climate variability and change, relative to population and Gross Domestic Product, are expected to be higher in Africa than in any other region in the world.

In order to help address this significant threat to Africa's development, the Africa Community Access Partnership (AfCAP) (a research programme funded by UK Aid), commissioned a project that started in April 2016. Its aim was to produce regional guidance and to develop climate-resilient rural access in Africa through research and knowledge sharing within and between participating countries. The output should assist the development of a climate-resilient road network that reaches fully into and between rural communities.

The study addresses the issues of appropriate and economic methodologies for vulnerability and risk assessments; prioritisation of adaptation interventions; and optimisation of asset resilience in the context of rural access low volume roads.

The study focuses on: (a) appropriate engineering and non-engineering adaptation procedures; (b) sustainable enhancement of the capacity of three AfCAP partner countries to deal with the likely impacts of climate change on rural road networks; (c) sustainable enhancement of the capacity of additional AfCAP partner countries; and (d) uptake and embedment of research outputs across AfCAP partner countries.

In this Guideline, engineering adaptation options related to the various climatic stressors are presented. The crucial importance of effective drainage and timely and appropriate maintenance is highlighted.

Adaptation techniques for handling the expected changes in temperature and precipitation, windiness, seal-level rise and more frequent extreme events are identified and discussed. These are specifically related to unpaved roads, paved roads, subgrade materials, earthworks and drainage within and outside the road reserve as well as possible implications for construction activities. The impacts on maintenance practices are also highlighted and guidance given.

Key words

Capacity Building; Change Management; Climate Adaptation; Climate Change; Climate Impact; Climate Resilience; Climate Threat; Climate Variability; Demonstration; Maintenance; Risk; Rural Accessibility; Rural Roads; Vulnerability.

Research for Community Access Partnership (ReCAP)

Safe and sustainable transport for rural communities

ReCAP is a research programme, funded by UK Aid, with the aim of promoting safe and sustainable transport for rural communities in Africa and Asia. ReCAP comprises the Africa Community Access Partnership (AfCAP) and the Asia Community Access Partnership (AsCAP). These partnerships support knowledge sharing between participating countries in order to enhance the uptake of low cost, proven solutions for rural access that maximise the use of local resources. The ReCAP programme is managed by Cardno Emerging Markets (UK) Ltd.

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Glossary (based on the Intergovernmental Panel on Climate Change, IPCC, 2018)

Accessibility	The ease for population groups to reach or participate in service activities using a transport network.
Adaptation	In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities (i.e. actions that reduce hazard, exposure and vulnerability). In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.
Adaptive Capacity	The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.
Adaptation Needs	The circumstances that arise when the anticipated risks or experienced impacts of climate change require action to ensure the safety of populations and the security of assets and resources, including ecosystems and their services.
Adaptation Options	The array of strategies and measures that is available and appropriate for addressing adaptation. They include a wide range of actions that can be categorized as structural, institutional, ecological or behavioural, amongst many others
Build back better	An approach to post-disaster recovery that reduces vulnerability to future disasters and builds community resilience to address physical, social, environmental, and economic vulnerabilities and shocks
Capacity Building	The ability to enhance the strengths and attributes of, as well as the resources available to, an individual community, society or organisation in response to change.
Change Management	A collective term for all approaches to preparing and supporting individuals, teams, and organisations in making organisational or institutional changes in order to equip them to address and resolve new or recurring challenges impacting on them and their stakeholders (e.g., impacts of climate variability and change on their operations).
Climate Change	Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.
Climate Variability	Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system such as ocean-atmosphere coupling (internal variability), or to variations in natural or anthropogenic external forcing such as variations in solar output or changing concentrations of greenhouse gasses (external variability).

Disaster	Severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread and adverse human, material, economic or environmental effects that require immediate emergency responses to satisfy critical human needs and that may require external support for recovery.
Early Warning Systems (EWS)	The set of technical, financial and institutional capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare to act promptly and appropriately to reduce the possibility of harm or loss. Dependent upon context, EWS may draw upon scientific and/or Indigenous knowledge.
Exposure	The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected by hazards.
Extreme Weather Event	An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).
Flood	The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, groundwater floods, and glacial lake outburst floods.
Hazard	The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.
Impacts (Consequences, Outcomes)	The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather and climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and wellbeing, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Impacts may be referred to as consequences or outcomes, and can be adverse or beneficial.
Impact Assessment	The practice of identifying and evaluating, in monetary and/or nonmonetary terms, the effects of [climate] change on natural and human systems.
Likelihood	The chance of a specific outcome occurring, where this might be estimated probabilistically.

Lock-in	The concept of 'lock-in' pertaining to climate change: decisions made now about the location, design and operation of assets will determine their long term resilience to the effects of climate change.
Mobility	The ability to move people and goods efficiently and effectively for socio-economic activities between an origin and destination using a transport network.
Resilience	The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation.
Risk	The potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain. In the context of the assessment of climate impacts, the term risk is often used to refer to the potential for adverse consequences of a climate-related hazard, or of adaptation or mitigation responses to such a hazard, on lives, livelihoods, health and wellbeing, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Risk results from the interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence.
Risk Assessment	The qualitative and/or quantitative scientific estimation of risks.
Risk Management	Plans, actions or policies to reduce the likelihood and/or consequences of risks or to respond to consequences.
Road Criticality	Road criticality refers to the importance of a rural access road to the communities it serves in terms of the community's dependence on a road for accessing markets, goods and services.
Stressors	Events and trends, often not climate-related, that have an important effect on the exposed system and that can increase vulnerability to climate-related risk.
System Sensitivity	The degree to which a system is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g. in response to a change in the mean, range, or variability of temperature) or indirect (e.g. damages caused by an increase in the frequency of coastal flooding due to sea level rise).
Vulnerability	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.
Vulnerability Assessment	Process that attempts to identify the root causes for a system's vulnerability (to climate variability and change).

Acronyms, Units and Currencies

$	United States Dollar
°C	Degrees Celsius
AASHTO	American Association of State Highway and Transportation Officials
ADB	Asian Development Bank
AfCAP	Africa Community Access Partnership
AfDB	African Development Bank
AsCAP	Asia Community Access Partnership
ASTM	American Society for Testing and Materials
BMS	Bridge Management System
BPC	Bipartisan Policy Centre
BS	British Standards
CBR	California Bearing Ratio
CEC	Cation Exchange Capacity
CPT	Cone Penetration Testing
CSIR	Council for Scientific and Industrial Research, South Africa
DFID	Department for International Development, UK
EIA	Environmental Impact Assessment
ESP	Exchangeable Sodium Percentage
GDP	Gross Domestic Product
GFDRR	Global Facility for Disaster Reduction and Recovery
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
LVR	Low-Volume Roads
MESA	Million Equivalent Standard Axles
NCHRP	National Cooperative Highway Research Program
OECD	Organisation for Economic Co-operation and Development
OMC	Optimal Moisture Content
PG	Performance-Grading (bituminous binders)
PI	Plasticity Index
PMS	Pavement Management System
RAMS	Road Asset Management System
ReCAP	Research for Community Access Partnership
SADC	Southern African Development Community
SAR	Sodium Absorption Ratio

SATCC	Southern African Transport and Communication Commission
SMS	Slope Management System
SPT	Standard Penetration Testing
SSA	Sub-Saharan Africa
TRH	Technical Recommendations for Highways
TRL	Transportation Research Laboratory
UK	United Kingdom (of Great Britain and Northern Ireland)
UKAid	United Kingdom Aid (Department for International Development, UK)
UNFCCC	United Nations Framework Convention on Climate Change

Executive Summary

Africa's development is highly dependent on an adequate and reliable roads system that also can withstand the impacts of climate change. To help address the significant threat of climate change to Africa's development, the Africa Community Access Partnership (AfCAP), a research programme funded by UKAid, commissioned a project in April 2016 to produce regional guidance on the adaptation of rural access roads to climate change. The project aims to provide pragmatic, cost-beneficial engineering and non-engineering adaptation procedures and guidance to road sector institutions through research and knowledge sharing within and between participating African countries.

The study covers climate threats and adaptation for both existing and new infrastructure. It addresses the issues of appropriate and economic methodologies for vulnerability and risk assessments; prioritisation of adaptation interventions; and optimisation of asset resilience in the context of low-volume rural access roads. In addition, it provides evidence of cost-, economic- and social-benefit links to rural communities arising from more resilient rural access to support wider policy adoption across Africa.

The study focuses on the following:

a) Demonstration of appropriate engineering and non-engineering adaptation procedures
b) Sustainable enhancement of the capacity of three AfCAP partner countries[1] (i.e. Ethiopia, Ghana and Mozambique) to deal with the likely impacts of climate change on rural road networks - these three countries represent nearly the full range of climatic systems in sub-Saharan Africa
c) Sustainable enhancement of the capacity of additional AfCAP partner countries
d) Uptake and embedment of research outputs across AfCAP partner countries.

The Handbook on Climate Adaptation[2] provides a methodology for carrying out a climate adaptation assessment for rural access to support socio-economic sustainability. It also focuses on those activities and actions that conventional engineering standards and procedures do not necessarily cover. The Handbook is supported by three separate guideline documents that cover the following:

- Change Management
- Climate Risk and Vulnerability Assessment
- Engineering Adaptation

This Guideline on *Engineering Adaptation* discusses the expected effects of different climate change attributes on low volume access roads and highlights possible adaptive solutions. The process to be followed to ensure that as many roads as possible become more climate resilient and can retain their passability after both periodic and extreme climatic events or because of gradually changing climatic conditions is discussed more fully in the *Climate Adaptation Handbook*.

The Guideline targets decision makers, design engineers, construction/maintenance providers in both the public and private sector, and specifically road authorities operating at national, provincial/state and district level. Since this Guideline deals with the impact of the environment of rural road networks, other entities actively involved in the fields of climatology, environment, forestry, hydrology, meteorology, planning and rural settlements, among others, may also have an interest in this Guideline.

[1] The AfCAP Partner Countries currently consist of the Democratic Republic of Congo, Ethiopia, Ghana, Kenya, Liberia, Malawi, Mozambique, Sierra Leone, South Sudan, Tanzania, Uganda and Zambia.

[2] Head, M., Verhaeghe, B., Paige-Green, P., Le Roux, A., Makhanya, S., Arnold, K. (2019). Climate Adaptation: Risk Management and Resilience Optimisation for Vulnerable Road Access in Africa: *Climate Adaptation Handbook, GEN2014C. London: ReCAP for DFID*.

The primary climatic attributes and potential effects of these are firstly introduced, followed by the provision of suggested adaptation measures. These suggested adaptation measures are discussed separately for each infrastructure component. The crucial importance of effective drainage is highlighted and the critical importance of timely and appropriate maintenance, particularly in excluding water from affecting the pavement structure is emphasised.

This Guideline includes a wide range of adaptation measures, some of which will be more appropriate to certain projects and others less appropriate. It is up to the practitioner to decide which of these are appropriate or which combinations of them are most suitable for each individual project, and to reconcile these with the available funding. Many of the adaptation countermeasure concepts can be designed and constructed in a variety of ways and will need to be uniquely implemented.

It should be noted that this guideline only discusses generic adaptations, and each situation needs to be assessed individually and the most appropriate adaptation techniques employed. These are normally based on conventional good engineering principles and must be assessed individually, in an open-minded manner with significant lateral thought. Innovative solutions for specific options may often be necessary, particularly those that will enhance operational, driver safety and infrastructural performance improvements related to low-volume rural roads.

1 Background and Context

1.1 Project background

1.1.1 Aims and Objectives

The overall project aim is to move forward from previous AfCAP research and deliver **sustainable enhancement in the capacity of AfCAP partner countries** to reduce current and future climate impacts on vulnerable rural infrastructure. The study covers threats and adaptation for both existing and new infrastructure. This is to be achieved through the research, and consequent uptake and embedment, at both policy and practical levels, of pragmatic, cost-beneficial engineering and non-engineering procedures based on the recognition of locally-specific current and future climate threats.

The fundamental ***research objective*** is to identify, characterise and demonstrate appropriate engineering and non-engineering adaptation procedures that may be implemented to strengthen long-term resilience of rural access based on a logical sequence of defining:

- Climate threats
- Climate impacts
- Vulnerability to impact (risk)
- Non-engineering adaptations (referred to in this Guideline as Change Management options)
- Engineering adaptations
- Prioritisation

The second objective, which focusses on ***capacity building and knowledge exchange***, is to meaningfully engage with relevant road and transport Ministries, Departments and Agencies/Authorities in a knowledge dissemination and capacity building programme based on the outputs from the research.

The third objective is to ensure that there is focus on ***uptake and subsequent embedment*** of outcomes aimed at a range of levels from informing national policies, through regional and district planning, down to practical guidance on adaptation delivery at rural road level.

1.1.2 Scope

The Climate Adaptation regional programme aims to deliver sustainable enhancement in the capacity of AfCAP partner countries to reduce current and future climate impacts on vulnerable rural road infrastructure. This is achieved through research, and consequent uptake and embedment, at both policy and practical levels, of pragmatic, cost-beneficial engineering and non-engineering procedures based on the recognition of locally-specific current and future climate threats.

In accordance to DFID's Research Business Case for RECAP (DFID, 2014), the three guidelines set out to incorporate climate change and the associated challenges into the rural road planning, design, construction and maintenance phases. The impact that climate change, climate variability and extreme events (such as floods and droughts) may have on rural accessibility is likely to influence choices of design and associated planning decisions for rural roads. The subsequent guideline builds on this principle and supports the generating of scientific evidence for decision makers in rural road planning, design and construction.

The Guideline presented herein accompanies the *Climate Adaptation Handbook* and guides the user through the engineering options available to render rural access roads more climate resilient. It is meant to support and inform decision making and prioritisation when adapting existing and new road infrastructure to the impacts of climate variability and change.

This guideline is supported by investigations in the three AfCAP partner countries of Ghana, Ethiopia and Mozambique. These have been used to verify and test the proposed methodologies on a project level where possible in order to refine the approach and ensure that it will be practical and applicable in nature.

1.1.3 Overview of the Adaptation Handbook

The *Climate Adaptation Handbook* is the overarching document and provides relevant information on climate adaptation procedures for rural road access, along with instructions on an appropriate methodology to address climate threats and asset vulnerability, to increase resilience for the foreseeable future. The Handbook has been produced to provide relevant information on adaptive procedures for both **new** and **existing** rural road access, along with instructions on an appropriate methodology to address climate threats and asset vulnerability and to increase resilience for the foreseeable future. It has been developed to cover a wide range of climatic, geomorphologic and hydrological circumstances, based on application to Mozambique, Ghana and Ethiopia, but equally applicable to any sub-Saharan country and beyond. Although the scope of the Handbook, as per design, is predominantly focusing on *low volume roads,* the principles will also apply to *high volume roads,* although there will be differing priorities and design parameters[3].

The Handbook only illustrates the fundamental principles, processes and steps required for climate resilience. Details regarding actual adaptation measures and vulnerability assessment methodologies are included in the accompanying guidelines documents that cover the following: (1) Climate Risk and Vulnerability Assessment; (2) Change Management; (3) Engineering Adaptation Guidelines, and (4) a Visual Assessment Manual (see Figure 1).

Figure 1 Applications covered in the handbook

1.1.4 The content of the Handbook

The methodology comprises five stages, as per Part B of the table below, with each stage covering several activities as set out. However, it will be applied in a slightly different rigour depending on the scale, application and circumstances of its application. Policy and strategy directives may be in place or be absent. Appropriate data management support systems may or may not be in place and the level of resource availability and skills to implement adaptation options will vary significantly.

[3] Refer to PIARC (2012 & 2015) and TRB (2008) for adaptation options for high volume roads.

Because of this wide range of circumstances, the Handbook is split into two parts; **Part A** covers the *Situational Analysis and Management Process* and **Part B** covers the appropriate *Methodology*.

The scope of this Guideline is shaded in green.

Contents and scope of the Adaptation Methodology

Part A	Situational review and adaptation management
Covers:	Problem identification (including evidence) Identification of probable causes Drivers of change (policy-driven) Change management Approach and delivery Effective data management
Part B	**Methodology**
Stage 1	***Climate risk screening (national/regional)***
B.1.1	Needs determination
B.1.2	Identification and mobilisation of stakeholder/partner involvement
B.1.3	Setting of policy, objectives and scope (network level)
B.1.4	Analysis of observed and projected climate effects
B.1.5	Data gathering and risk analysis
Stage 2	***Impact and vulnerability assessment (project/local level)***
B.2.1	Project-level climate risk screening
B.2.2	Climate-sensitive impact assessments
B.2.3	Data gathering and vulnerability assessment
Stage 3	***Technical and economic evaluation of options***
B.3.1	Identification of strategies and potential adaptation measures
B.3.2	Impact assessment of 'do something' and 'do nothing'
B.3.3	Stakeholder consultations
B.3.4	Prioritisation and selection of adaptation measures
Stage 4	***Project design and implementation***
B.4.1	Development of an implementation plan (including 'Inadequate Budget' scenario)
B.4.2	Design parameters and optimisation
B.4.3	Construction supervision and documentation
Stage 5	***Monitoring and Evaluation***
B.5.1	Development of a monitoring and evaluation plan
B.5.2	Reporting on and sharing of implementation experiences

1.2 Context

1.2.1. Climate vulnerability

The African Development Bank (AfDB) states that Africa is one of the most vulnerable regions in the world to the impacts of climate change. Most studies suggest that damage from climate change, relative to population and Gross Domestic Product (GDP), could be higher in Africa than in any other region in the world (AfDB 2011). These studies also suggest that adaptation costs in Africa could amount to $20-30 billion per annum over the next 10 to 20 years. There is a pressing need to mobilise resources to address the continent's current limitations to deal with climate events, as well as resources to deal with future climate change. Beyond this a series of more targeted adaptation investments are required and it is crucial that African decision-makers factor climate change into all long term strategic decisions.

In the past four decades (1975 to 2015), African countries have experienced more than 1,400 recorded weather related disasters (meteorological, hydrological and climatological). These disasters have had significant impacts on countries' economies and on rural communities and their livelihoods. The high social vulnerability and low adaptive capacity of these communities as well as their high exposure to natural hazards has resulted in the deaths of more than 600,000 people (95 per cent due to droughts), left 7.8 million people homeless (99 per cent due to flooding and storms) and affected an estimated 460 million people (CRED, 2016).

In many African countries, limited or no funds for adaptation and mitigation are challenging these countries to identify the threats that are posed by climate change, develop adaptation approaches to the projected changes, incorporate changes into mid-range and long-term development plans, and secure funding for the proposed and necessary adaptations. Existing studies have attempted to quantify the impact of climate change on infrastructure assets that could be affected by climate change in the coming decades (Hughes et al, 2010; Chinowsky et al., 2011; Chinowsky et al., 2013).

1.2.2. Rural access

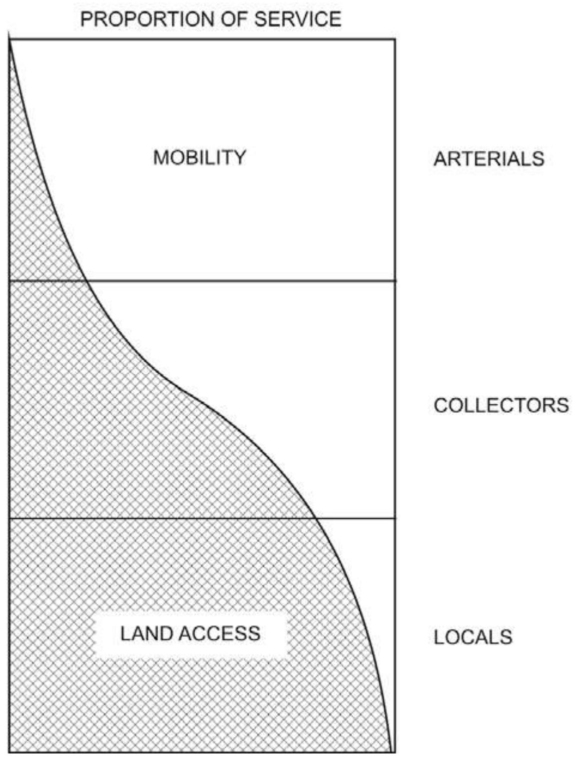
Sub-Saharan Africa (SSA) has one of the lowest rural road densities in the world, which is significantly stifling its potential for agricultural growth and development. In addition, less than 40 per cent of rural Africans live within two kilometres of an all-weather road, making social, medical and educational interventions timely, costly and unreliable. Much of the road network contributing to agricultural and social development in these rural areas can be classified as low volume.

Low-volume rural road networks in these countries vary from simple tracks and un-engineered earth roads to reasonable, high standard paved roads built to "conventional" standards. Irrespective of their quality, these roads are frequently rendered impassable because of periodic extreme weather events, exacerbated by minimal or only intermittent maintenance interventions. Associated with these roads are water crossing structures, ranging from drifts/fords to culverts of varying sizes and larger bridges. High water velocities often damage these structures, rendering road links impassable for extended periods. Flooding leads to similar consequences. Whereas road pavements can usually be reinstated quickly to restore rideability after extreme events, road closures caused by flooding can take several hours to many weeks before water levels subside and accessibility can be restored. However, severe harm to water crossing structures caused by destructive water velocities could take several weeks or even months to reinstate, depending on the emergency response capability and adaptive capacity of the road authority. The projected increase in the number and intensity of extreme events in many countries could contribute to even bigger problems than are currently being experienced, being encountered in future.

Most of the low volume rural road network in Africa is used for accessibility as opposed to mobility as shown in Figure 2, where:

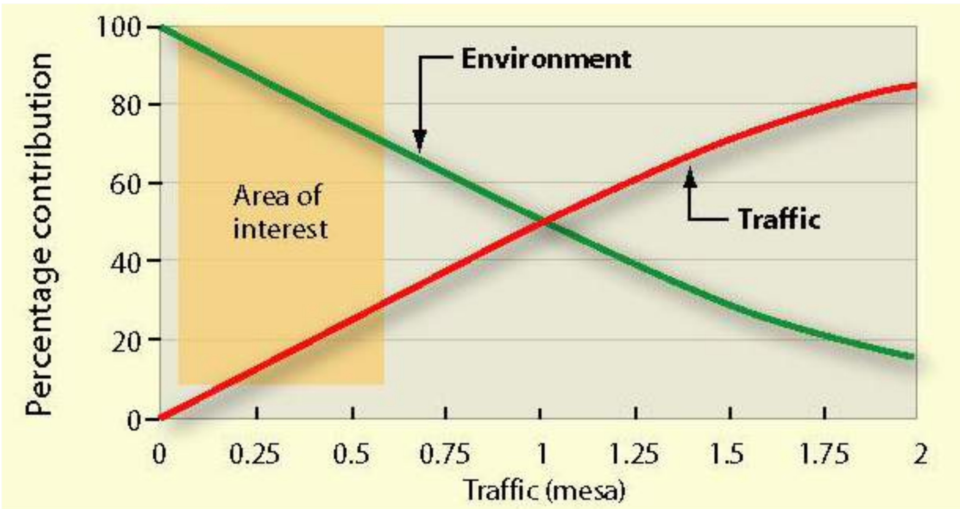
- *Accessibility* refers to the ease for population groups to reach or participate in service activities using a transport network, and
- *Mobility* refers to the ability to move people and goods efficiently and effectively for socio-economic activities between an origin and destination using a transport network.

Figure 2 Use of different road types in terms of accessibility and mobility (AASHO, 1964)



It has been shown in southern Africa that for low volume road networks (< 1 million cumulative equivalent standard axles (MESA) over their service life), the environment (mainly climate) plays a much larger role in contributing to deterioration than the traffic does (Figure 3; SATCC, 2003). However, it should be noted that, rather than the cumulative effects of equivalent standard axles, one or two heavy, overloaded vehicles travelling on a low volume road that is flooded or has high moisture in the upper layers can cause deterioration and failure, manifested as shear failure and not the traditional subgrade rutting used frequently to describe failure.

Figure 3 Relationship between road deterioration and environment and traffic (SATCC, 2003)



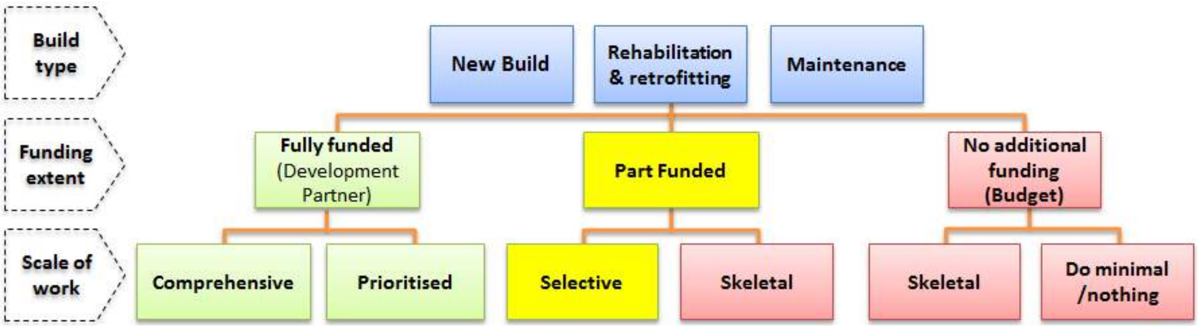
With the expected changes in climatic conditions over most of Africa (le Roux et al, 2016) resulting from global climate change (greater frequency of extreme events, together with expected changes in precipitation and temperatures), the on-going and periodic deterioration of the existing low volume rural road networks in SSA can thus be expected to continue on a more frequent and increasing scale, probably more than for conventional higher trafficked roads. Instances of impassability while roads and structures are waiting to be repaired could increase, and communities and local economies are expected to be adversely affected accordingly. A similar situation exists with respect to geotechnical structures such as cuts and fills that can result in roads becoming impassable for extended periods following large failures.

Steps to make rural roads, inclusive of drainage, bridge and geotechnical structures, more resilient to extreme weather events and to ensure all-weather passability on critical road links as far as possible are thus urgently needed. In this context, resilience is defined as the capacity to anticipate, prepare for, respond to, and recover from the impacts or consequences of significant hazard or multi-hazard threats with minimum damage to social well-being, the economy and the environment.

It is unlikely that all such occurrences can be avoided without significant cost implications. However, new road projects, inclusive of their drainage and bridge structures, as well as rehabilitation and upgrading projects, should ideally be planned and designed (within reasonable limitations) to incorporate greater climate resilience to minimise the potential for road closures and expensive damage rehabilitation.

Figure 4 shows the relationships between the different development stages of the infrastructure and the typical funding sources and allocations. Other than for newly constructed roads, funding is the biggest challenge in climate resilience adaptations. New construction should be designed to incorporate the best or combinations of best adaptation measures, which should be a part of good engineering design anyway, and are likely to result in a nominal increase in the construction costs in most cases. Those areas identified in red below typically attract insufficient funding and adaptations will need to be implanted according to the available funding on a prioritised basis, probably on a reactive basis and over some extended period.

Figure 4 Strategic approach based on type of activity and adequacy of funding available



All new road development projects currently require an environmental impact assessment (EIA) to evaluate the impact of the proposed road on the present (baseline) and expected environment. These vary from relatively rudimentary assessments to highly sophisticated, time consuming and costly exercises. However, it is becoming increasingly important that the converse, i.e., the effect of the present and expected environment on proposed (and existing) roads, is evaluated equally. Although the two processes have different aims and objectives, during stakeholder workshops on EIA, important information regarding the effects of the environment on existing roads in the area could be gleaned from stakeholders.

Several climatic impacts are exacerbated by other factors. Vehicle overloading for instance results in rapid deterioration of the pavement structure, but when combined with higher pavement moisture contents or higher asphalt temperatures, the deleterious influence can be increased exponentially.

Similarly, poor maintenance of drains affects the moisture content in the road. With possible higher future rainfall, this effect is likely to be amplified.

This **Guideline** highlights the impacts of different climatic stressors on road networks and suggests a range of engineering adaptation measures that can be implemented to overcome the problems. These can be implemented during the design phases of new roads or installed in existing infrastructure in response to potential problems arising from potential climate changes and available budgets.

"*It is also acknowledged that climate change adaptation is a difficult and complex subject and that understanding and quantifying risks and opportunities can be made difficult by the uncertainties that surround climate change"* (PIARC, 2015).

Most of the recommendations made in this Guideline are based on the adoption of sound engineering knowledge and principles advocating that 'if the problem is known, an appropriate solution will be available".

2. Climate Change Effects

2.1 General

Climate change, according to the Intergovernmental Panel on Climate Change (IPCC, 2007) and relevant to this study, refers to a change in the state of the climate. This change in the status can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or because of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods. The effects of climate change are putting large lengths of the world's road infrastructure at risk and thus need to be considered in both present road operation scenarios as well as decisions on future road infrastructure investments[4].

Several climatic changes are anticipated but these are not consistent for all countries and the degree and extent will vary from one geographic location to another. The adaptations discussed in this Guideline, however, are generic and will be applicable to countries affected by similar changes in climatic stressors.

The following primary climate changes are likely to occur to varying degrees in most parts of SSA (Le Roux et al, 2016; Dosio, 2017; Dosio et al., 2019; Weber et al., 2018):

- Increased temperatures (average, maximum and number of extremely hot days (> 35°C) per year)
- Decreased precipitation and longer drier periods
- Increases in extreme weather events – violent storms, heavy precipitation, heat waves, etc.
- Rising sea-level
- Northward migration of the tropical cyclone belt
- Increased wind speeds.

These could be accompanied by related secondary effects:

- Longer/shorter crop-growing seasons and possible changes in crop types, potentially impacting on farm-to-market traffic loading conditions
- Increase/reduction in general soil moisture
- Larger fluctuations in groundwater levels
- Changes in vegetation density and type and rate of growth, affecting sight distances around road bends and slope stability
- Flooding
- Changed frequency of extreme storm surges
- Changes in ecological equilibrium
- Changes in the optimum construction season (possibly timing and length) and conditions due to precipitation and temperature constraints, affecting availability of resources for road construction and maintenance, while also affecting the window of safe working and productivity of outdoor workforces.

Together with these climatic changes and secondary effects, the impacts of, for instance more severe flooding, increased wild-fire hazards, rising sea-levels and lowered groundwater tables on the road infrastructure need to be considered. Other associated influences such as water shortages

[4] For a review of the topic, see: Mattsson and Jenelius (2015).

under increased temperature environments because of higher evaporation could also have an indirect impact on infrastructure provision (e.g. availability of water for compaction of layer works).

It is anticipated that changes in other climatic parameters (e.g., relative humidity, barometric pressure, presence of fog, ultraviolet radiation, etc.) would have minimal impact on the engineering aspects of the low volume road infrastructure or else be incorporated into the above effects.

It has also been postulated (McGuire, 2010) that the incidence of seismic activity could be increased by global warming, with concomitant increases in destructive earthquakes and tsunamis. Although these earthquakes are likely to occur more frequently on other continents because of unloading of the landmasses due to melting ice, the effects of resulting tsunami could affect the fringes of the African continent. Actual impacts of earthquakes on the road infrastructure are not discussed in this Guideline, except to note that the instances of bridge damage and landslides are likely to increase should there be more earthquakes.

The dominant effects of each of the climate variables on rural roads are summarised below, before details of possible adaptation measures are provided in the remainder of the Guideline. The adaptation measures are not country specific as they are primarily related to the different events and not specifically to local conditions.

2.2 Temperature changes

A general increase in temperature with time is expected over most of SSA. For most pavement structures, this would have minimal influence, but secondary effects such as drying out of subgrades and surrounding soils, and increased wildfire hazards are likely. The impacts on bitumen are likely to be more significant and these will mostly be related to additional softening of bitumen during the expected increase in extremely hot days. Such temperature increases would also have significant impacts on concrete and steel structures where differential expansion and high temperature gradients within beams and members could lead to deformation and even structural failure.

It is not anticipated that temperatures will decrease to any significant degree over most of SSA. It is thus unlikely that there will be a lowering of the snow-line elevation, a significant increase in frost occurrences, or an increase in freezing of water in pavements and earthworks. Overall, the incidence of frost days would be expected to decrease.

Together with the general increases in temperature, the numbers of very hot days (> 35°C) is expected to increase significantly. The impact of this on roads will essentially be the same as the general increased temperature and this issue is not dealt with separately in this document.

2.3 Precipitation changes

It is projected that the precipitation could decrease in most areas of sub-Saharan Africa. This would have a favourable influence on most roads, where subgrade and construction materials will tend to operate under higher negative pore water pressure (high soil suction) conditions and thus have significantly higher strengths than normal. However, it is also projected that the precipitation that does occur could be in the form of less frequent but more severe storm events. Provided that the pavement drainage is such that the water is removed from the pavement structure rapidly, the temporary increased precipitation associated with these events would have little effect on the road performance. It will be essential, however, that drainage designs are improved and maintenance techniques are enhanced and implemented regularly and probably more frequently. Water will have to be removed from the road vicinity rapidly and completely.

It is well established that excessive water is one of the biggest causes of problems in road pavements and earthworks. Apart from its detrimental effect on many pavement materials (reduced shear strength), if the pavement becomes saturated with water, significant positive pore-water pressures develop under traffic loading which lead to premature failure of the pavement layers. It is anticipated that in some areas, where (i) precipitation is likely to increase and/or extreme events are more likely, and (ii) the design and surrounding drainage systems of the pavement and earthworks do not sufficiently cater for effective/ rapid removal of this water, more frequent pavement failures and earthwork instability can be expected. Better control of vehicle overloading on such roads immediately after these storm events will also be essential.

2.4 More frequent extreme events

It is projected that even though the precipitation may reduce in many areas, the precipitation that does fall is likely to be associated with fewer but more intense events. This would increase the potential for flooding, rapid stream flows, erosion and scour of stream-beds and structures, sedimentation and siltation, and could result in increased instances of slope instability. However, if these events have significant time lapses between them allowing the road environments to dry out (say 4 to 6 weeks between events), the effects on slope stability (antecedent characteristics) will probably be minimal. Road and cross-drainage will, however, need to be enhanced to cater for the individual events with larger volumes of water.

The main factor that affects the duration of flooding in an area is the topography. Longer flooding and inundation periods occur in flatter terrains than in steeper terrains. In steep terrains, shorter duration and higher water flow velocities are normally experienced (with accompanying erosion and scouring), whereas in flat terrains the water "stands" for longer periods as it slowly flows away or seeps into the substrate. The slower flow rates also allow the water derived from neighbouring higher altitudes to accumulate quicker with higher flood levels. The potential for scour and erosion is, however, significantly reduced after the initial flood episodes.

Extreme events does not only relate to prolonged and/or heavy precipitation described above but also includes heat waves, drought and cyclonic activity.

2.5 Sea-level rise

A consequence of higher global temperatures will be the reduction of land-supported ice. Melting of these glaciers and ice-sheets will increase the volume of water in the oceans and lead to a rise in sea level. In addition, increased sea-water temperatures will result in expansion of the sea water leading to the raising of the sea level. It should be noted that regional rates of sea-level rise will vary around Africa's coastline depending on local vertical land movements, sediment compaction, aquifer dewatering and static equilibrium fingerprint (cf. Kopp et al., 2014; Nicholls et al., 2014)

The impact of sea-level rise will, obviously, only be noticed at existing coastlines, but the consequences are likely to be dramatic, with significantly more damage to low lying infrastructure and extensive coastal erosion and movement of beach sands resulting mainly from increased tidal variations, wind-generated waves and storm surges. The latter are of specific interest as these could have devastating effects on transport infrastructure in coastal areas.

Sea-level rise will result in coastal flooding being more extreme due to the higher "base-levels", increased salinity of coastal river waters with the related impacts on salt-sensitive structures and increased sedimentation in tidal areas.

2.6 Migration of the tropical cyclone belt

It is anticipated that the tropical cyclone belt that is currently centred on central Mozambique, will move northwards towards the Tanzanian border (Malherbe et al., 2013). This is likely to bring increased precipitation events and winds, with associated flooding, to areas currently unaffected or affected to only minor extents, in some areas, while this will diminish in the more southern locales.

2.7 Increased wind speeds

Higher wind speeds result in quicker drying of road environments and soils (increased evaporation exacerbated by higher temperatures), a larger and quicker loss of material from unprotected sites (unpaved roads and exposed earthworks) and a greater potential for wild fires. Other less significant (but requiring increased maintenance) problems will also result from increased wind speeds such as movement of coastal and dune sands (Tsoar, 2005), damage to road furniture, road blockages due to uprooted trees, and increased wind loads on bridges.

The effects of each of these climatic variations on transportation infrastructure elements or facilities is summarised in Table 1 to Table 7 below. It should be noted that, although hazards are treated separately in Tables 1 to 7, the possibility of multi-hazards should not be overlooked (cf. Gill and Malamud, 2017).

Table 1 Hazards related to increased precipitation

Facility	Consequence - Possible Problems and Damage
Unpaved roads	▪ Flooding (excessive surface water) ▪ Softening of surfacing material ▪ More frequent impassability on poor materials ▪ Increased erosion of road surface ▪ Loss of shape of road ▪ Blockage (siltation) of drains
Paved roads	▪ Loss of strength of layer materials, especially in the upper base and subbase layers ▪ Damage to thin surfacings ▪ Damage to pavement edges ▪ Blockage of drains and culverts ▪ Erosion of unpaved shoulders
Earthworks	▪ Increased slope instability ▪ Saturation and weakening of embankment soils ▪ Erosion of soil surfaces and drains ▪ Undercutting of roads by embankment erosion ▪ Excessive (luxuriant) vegetation growth ▪ Siltation and blocking of drains
Subgrade soils	▪ Expansion and cracking of volumetrically unstable materials ▪ Collapse and settlement of collapsible soils ▪ Softening of pavement support materials ▪ More movement and deposition of saline materials ▪ Deformation of rigid structures ▪ Erosion in road reserve ▪ Increased likelihood of sinkholes in karst areas
Drainage (water from within road reserve)	▪ Accumulation of water adjacent to road ▪ Erosion of road surface, shoulders and side and mitre drains ▪ Softening of materials beneath road ▪ Weakening of unpaved shoulders ▪ More outer wheel track failures due to increased subgrade moisture contents
Drainage (water from outside road reserve)	▪ Erosion of embankments and abutments of culverts and bridges ▪ Silting/sedimentation of culverts and bridges ▪ Scour of bridge foundations ▪ Overtopping of bridges and damage or destruction ▪ Damage to bridge structures by debris in flood-waters

Facility	Consequence - Possible Problems and Damage
Construction	▪ Excessive moisture in materials – construction delays ▪ Reduced working periods and increased delays ▪ Water damage to partially completed works ▪ Need for more coffer dams or flood-control measures during drainage and bridge construction
Maintenance	▪ Additional maintenance costs incurred ▪ More frequent bush clearing ▪ Additional repairs required to drains ▪ Need to retain good shape of unpaved road surfaces – more frequent maintenance ▪ Increased and improved unpaved shoulder maintenance ▪ Increased pothole patching and crack sealing of paved roads

Decreased precipitation will generally result in improved road support conditions (drier strengths mobilising higher soil suctions) and less drainage problems. However, the reduction in precipitation is expected to be associated with less frequent but more intense storms, that could lead to stronger, more erosive runoff and stream flows with increased erosion and siltation. It is also likely that there would be more rapid damage to road structures because of water not being removed from the road surface and side-drains as quickly and efficiently as necessary. The likely consequences are summarised in Table 2.

Table 2 Hazards related to decreased precipitation (but more extreme events)

Facility	Consequence - Possible Problems and Damage
Unpaved roads	▪ Increased wear and loss of gravel from drier surface ▪ Increased dust emissions over longer periods ▪ More rapid generation of loose material and roughness (corrugations) ▪ Increased regravelling frequency due to deterioration of gravel quality caused by loss of cohesive fines
Paved roads	▪ Damage to thin surfacings and asphalt (binder ageing) ▪ More rapid binder deterioration (binder ageing) ▪ Reduced equilibrium moisture contents – stronger pavements
Earthworks	▪ Increased drying out and cracking of soils ▪ Rapid ingress of moisture into tension cracks in slopes (slope failures from shrinkage and tension cracks) ▪ Increased erosion from more intense storms ▪ Damage to vegetation by more wild-fires ▪ More difficult to establish erosion protection through bio-engineering
Subgrade soils	▪ Larger moisture fluctuations in clayey soils ▪ Increased drying out of materials ▪ Shrinkage and cracking (larger volumetric movements) ▪ More precipitation of salts in saline environments
Drainage (water from within road reserve)	▪ Drying out of drains – more susceptible to erosion when rain does come ▪ Higher risk of burning of roadside vegetation and loss of root stabilization ▪ Less vegetation to bind soil

Facility	Consequence - Possible Problems and Damage
Drainage (water from outside road reserve)	▪ More erosion ▪ More silting and sedimentation ▪ Overtopping of bridges and more frequent road closures ▪ More severe flooding ▪ Damage to bridges and culverts from debris in flood-waters
Construction	▪ Insufficient and more costly water for construction ▪ Quicker loss of compaction water due to evaporation ▪ Alternative construction methods and equipment required
Maintenance	▪ More unpaved road surface and shoulder maintenance ▪ More maintenance to drain damage ▪ Increased surface erosion repairs ▪ Better vegetation control to minimise wild-fire risks

A general increase in temperature is projected for most of SSA. The potential consequences of this are summarised in Table 3.

Table 3 Hazards related to increased temperatures

Facility	Consequence - Possible Problems and Damage
Unpaved roads	▪ More rapid drying out of road ▪ Increased cracking of clayey materials ▪ Increased development of roughness (corrugation) ▪ Quicker generation of dust and loose material
Paved roads	▪ More rapid ageing of bituminous binders ▪ Softening of bitumen in asphalt and more rapid deformation when hot ▪ Expansion and buckling of concrete roads
Earthworks	▪ More rapid drying out and cracking ▪ Loss of vegetation (or changes of species) on side slopes due to insufficient water ▪ More wildfires causing loss of root binding ▪ Increased erosion due to loss of vegetation
Subgrade soils	▪ Minimal effects ▪ Some shrinkage of clayey soils ▪ More movement of salts in saline materials caused by increased evaporation
Drainage (water from within road reserve)	▪ More rapid drying out, cracking and erosion ▪ Loss of vegetation (or change of species) on side slopes ▪ More wildfires causing loss of root binding
Drainage (water from outside road reserve)	▪ Greater expansion/contraction of bridge elements ▪ Larger temperature gradients in thick concrete members ▪ More erosion and siltation due to drier ground conditions
Construction	▪ Reduced window of safe working and productivity of outdoor workforces ▪ Quicker reactions when cement stabilising ▪ Quicker drying of concrete ▪ Greater water requirements for curing concrete and stabilised layers
Maintenance	▪ Ensuring vegetation is kept cut to minimise wild-fires ▪ Regular maintenance of bridge movement components (bearings and construction joints)

It is projected that, in general, temperatures are expected to rise but there could be localised areas where temperatures could drop slightly. It is, however, highly unlikely that these temperature decreases would result in an increase in freezing of water in the roads, which in SSA is essentially currently restricted to localised areas at extremely high altitudes. A summary of potential consequences is provided in Table 4.

Table 4 Hazards related to decreased temperatures

Facility	Consequence - Possible Problems and Damage
Unpaved roads	▪ No effects except at extreme altitudes – freezing of water in road surface leading to loss of strength (expansion and during thaw)
Paved roads	▪ Reduced windows for construction of bituminous surfacings ▪ Less rapid ageing of bituminous binders ▪ More brittle fracture of bitumen when very cold
Earthworks	▪ Possible freezing of soil surfaces at high altitudes
Subgrade soils	▪ Minimal effect
Drainage (water from within road reserve)	▪ Minimal effect
Drainage (water from outside road reserve)	▪ Minimal effect ▪ Steeper temperature gradients in large concrete members
Construction	▪ Reduced construction windows for certain operations (paving, stabilization)
Maintenance	▪ Increased maintenance of bituminous surfacings (crack sealing and pothole repair) ▪ Road closures after thawing of frozen materials

The potential for greater wind speeds appears to be relatively high. These could affect several infrastructure properties, but would mostly increase the risk for wild-fires, with specific consequences. Much of the wind problem is expected to be associated with increased numbers of tropical cyclones in coastal areas, although increased wind conditions can be expected inland as well as a result of stronger convection currents arising from higher temperatures. A summary of potential hazards is provided in Table 5.

Table 5 Hazards related to increased windiness (and consequent wild-fires)

Facility	Consequence - Possible Problems and Damage
Unpaved roads	▪ More rapid drying out ▪ Increased deterioration rates due to dust and fines loss ▪ Increased accumulation of sand on roads
Paved roads	▪ Increased accumulation of sand on pavements ▪ Possible damage to bituminous surfacings caused by wild-fires
Earthworks	▪ Loss of vegetation due to burning ▪ Higher erosion rates on side slopes
Subgrade soils	▪ No major effects ▪ Increased erosion due to loss of vegetation after fires
Drainage (water from within road reserve)	▪ Higher risk of drain blockage by windblown material, including trash ▪ Loss of vegetation due to burning ▪ More erosion of drains

Facility	Consequence - Possible Problems and Damage
Drainage (water from outside road reserve)	▪ Greater wind-loads on bridges ▪ Loss of vegetation due to burning ▪ More erosion of drains ▪ More debris in flood waters due to fire damage ▪ Fire damage to bridges (wooden mainly but also concrete) ▪ More damage to erosion protection (waves)
Construction	▪ More dust ▪ Quicker evaporation of construction water
Maintenance	▪ Increased unpaved road maintenance to minimise corrugations resulting from fines (dust) loss ▪ Regular clearing of river debris and catchment vegetation ▪ More sand removal in arid and coastal areas ▪ Improved control of vegetation to minimise fire risk ▪ Increased maintenance of road furniture and signs, particularly those with wooden supports

As well as actual damage to the road infrastructure, non-engineering issues such as poor visibility for road users resulting from smoke on the roads could lead to unsafe conditions and damage to roads and road furniture resulting from increased accidents. These are discussed in a separate section.

The effects of sea-level rise and storm surges are limited to very localised coastal areas and may only have a small impact on the road network, but should be considered in those areas of coastal roads where the population may be affected (Table 6).

Table 6 Hazards related to sea-level rise and storm-surges

Facility	Consequence - Possible Problems and Damage
Unpaved roads	▪ Flooding and storm damage ▪ Increased subgrade moisture contents ▪ Increased erosion and siltation ▪ Loss of passability
Paved roads	▪ Damage to road surfacings by salts and water hammering ▪ Deposition of debris ▪ Increased subgrade moisture contents and reduced support ▪ Loss of passability ▪ Increased salinity of soil water
Earthworks	▪ Increased soil moisture contents with sea-level rise ▪ Fluctuating moisture levels with storm surges ▪ Reduced soil strengths
Subgrade soils	▪ Increased moisture contents
Drainage (water from within road reserve)	▪ Accumulation of water adjacent to road ▪ Erosion ▪ Softening of materials ▪ Accumulation of debris in drains
Drainage (water from outside road reserve)	▪ Scour of foundations ▪ Deposition of debris ▪ Increased salt damage to concrete and steel structures
Construction	▪ Wetter conditions – reduced working windows ▪ More saline waters
Maintenance	▪ Increased maintenance in coastal and low-lying areas ▪ Increased repairs of damage caused by high storm events (waves)

Change in seasonal and rainfall totals are highly regionally dependent across Africa. Rainfall could decrease in some areas, but increase in others. This would result in changes in ground-water level, with corresponding changes in the soil properties. However, over most of SSA, existing ground water levels are deep, other than in coastal areas and near large dams and drainage structures, and fluctuations in ground water level will have minimal impact on roads. Increased ground-water levels in mountainous areas affecting slope stability will probably be minimal, due to high runoffs after prolonged dry conditions. Possible hazards related to groundwater level changes are summarised in Table 7.

Table 7 Hazards related to changes in ground-water level

Facility	Consequence - Possible Problems and Damage
Unpaved roads	▪ Wetter or drier subgrades ▪ Changes in the extent and wetness of marshlands
Paved roads	▪ Wetter or drier subgrades ▪ More saline conditions affecting pavement structures
Earthworks	▪ Slope instability (localised)
Subgrade soils	▪ Larger seasonal volumetric movements in soils possible
Drainage (water from within road reserve)	▪ Localised seepage and springs
Drainage (water from outside road reserve)	▪ Changes in run-off coefficients in catchment areas
Construction	▪ Areas with difficult (water-logged) working conditions may increase
Maintenance	▪ No marked changes ▪ Localised high moisture content areas ▪ More sub-soil drainage structures required

Many of the projected changes in climate (particularly temperature) are relatively small in terms of even day to day variations in these properties currently experienced, although they may prevail over much longer periods. Other than precipitation changes, which are likely to have a significant effect on water control, major effects of other stressors are likely to be minimal, but must certainly be considered in pavement and earthwork design. Other issues such as changes in water availability, land-use and local natural vegetation species resulting from climate change may have equal or greater impacts on some of the issues identified above. These should be viewed in the context of many road construction activities (e.g. re-gravelling, resealing, overlaying, etc.) only having expected design lives of between perhaps 5 and 10 years. Changes in land-use or demographics resulting from climate change are not considered directly in this guideline.

A simple analysis tool (spread-sheet based) has been developed and is available on CD ROM (NCHRP, 2014a). This identifies a wide range of climatic stressors, various impacts and adaptations for their minimisation using a decision based process.

It is interesting to note that maintenance activities appear in the tables above time and time again. Good maintenance is a part of good engineering and can go a long way in reducing climate change vulnerabilities. A specific section on maintenance is thus included in this Guideline (Section 5.8).

Another tool has been developed for many African countries (still incomplete in many respects) that identifies at a regional/district level, various vulnerability characteristics. The Global Facility for Disaster Reduction and Recovery (GFDRR, 2016) has created the online tool (***ThinkHazard!***), which enables non-experts to consider natural hazard information in project design. This tool should be assessed for its usefulness and applicability at country level.

Once vulnerabilities are identified and adaptations for each of these are proposed (see accompanying *Climate Change Handbook* and *Visual Assessment Manual*), adaptation plans should be developed and prepared for implementation. These should then be monitored and evaluated after implementation to ensure that they are adequate and the most appropriate and cost-effective solutions. If funding permits, it would be useful to construct adjacent "control" sections using conventional techniques for comparative purposes and to determine whether the adaptation measures are in fact cost-effective and necessary.

The importance of good design cannot be overemphasised. Although many possible adaptations are identified and described in this Guideline, conventional design criteria for rural access roads should not be forgotten. This is particularly relevant to geometric design, which is not covered in detail in this Guideline. Issues such as vertical and horizontal alignment are, except for roads being designed anew, normally controlled by the existing track or road alignments with minor adjustments for safety reasons. Horizontal geometry generally follows the existing track with perhaps some reduction in curvature at sharp bends, and where land expropriation problems are not an issue in most cases.

However, the implementation of certain adaptation measures (e.g. side drains, paved shoulders, etc.) may require changes in carriageway or road width based on engineering concerns only and not necessarily road capacity or safety concerns.

If available, it would be advantageous to obtain the projected climate changes at regional, or even better at district, level based on the most recent and representative downscaled projections from local meteorology/climatology departments/agencies[5]. In this way, the local engineering staff would be informed on potential climate changes and could direct attention to these issues that may become prevalent instead of considering the full range of possibilities, most of which might not be likely in their respective areas.

[5] Note that there is considerable uncertainty in key variables like precipitation at the local scale, and these maps are likely to change depending on the choice of climate model and downscaling method. For short-lived (5 to 10 year) road elements, a good quantification on present conditions may be sufficient. For longer-lived assets, national climate change standards and allowances may be required (e.g. ADB (2018); EA, (2016)). Also see Wilby et al. (2009) for a review of different scenario techniques matched to various adaptation options.

3 Road Elements likely to be affected by climate variability and change

The following transportation infrastructure facilities and operations can be considered vulnerable to climate change, and adaptation measures for each of these are discussed in turn in Chapter 5:

- Unpaved roads – earth, engineered earth and gravel
- Paved roads – thin bituminous, asphalt and concrete
- Earthworks – embankments and cuttings
- Subgrade soils – particularly problematic soils such as expansive, dispersive, collapsible, saline, and karst areas
- Drainage (water from within road reserve) – road and shoulder surface, side drains, mitre drains, small culverts for cross drainage of surface water, etc.
- Drainage (water from outside road reserve) – large culverts and bridges associated with water derived in adjacent catchment areas
- Construction processes and activities
- Maintenance practices and frequencies

In addition to the issues identified above, climate change will have significant impacts on the operation of the transportation infrastructure (i.e. people and freight movements). However, these are not considered in this Guideline.

It should be noted that "*Adapting to climate change is a process, which should be built into a road authority's normal planning and risk management procedures"* (PIARC, 2015). Guidance on the establishment of a practical basis for reviewing the priorities and progress on adaptation capacity building within public (and private) sector organisations is provided in (Wilby and Vaughan, 2011).

4 Overview of Adaptation Methodology

This Section presents an outline of potential adaptation strategies and methodologies that could be deployed. These would have to be customised for the particular needs and priorities of different road authorities. They are also highly dependent on available funding as described in Section 1.2.1. Most new roads should incorporate the necessary adaptation measures to ensure resilient structures. Existing roads will either incorporate those that give the best value for money in a proactive regime (retrofitting) or those that can be afforded in a reactive mode. All of these decisions must be based on the road category (Level of Serviceability), the specific vulnerabilities and the prioritisation process carried out as described in the *Change Management Guidelines*.

4.1 Adaptation strategies

Adaptation can be defined as: *Actions taken by infrastructure stakeholders to avoid, withstand or take advantage of current and projected climate changes and impacts. Adaptation decreases a system's vulnerability, and increases its resilience to impacts.*

An adaptation strategy should be put in place to enable a Roads Authority to systematically develop and implement its responses to the challenges of climate variability and change in support of the delivery of its objectives. It provides a platform for decision makers to examine their individual Departments' outputs, including standards, specifications and maintenance for the development of resilience of the road network. It provides a systematic process to identify the activities that will be affected by a varying and changing climate, determine associated risks (and opportunities), and identify preferred options to address and manage them.

Adaptation strategies are put in place to:

- Decrease the vulnerability of transport infrastructure to changing climate conditions
- Increase the resilience of infrastructure
- Support planning for placement of new infrastructure in areas which are projected to have a lower risk of potentially harmful environmental changes
- Support the identification of new and innovative construction materials and construction methods, flexible design standards, and different approaches to design to ensure infrastructure can withstand the projected changes in climate
- Prepare Roads Authorities for rapid response/reaction to climate-related events

In selecting an adaptation strategy one should take cognisance of the fact that climate change is not an exact science. Climate change modelling provide projections of possible futures, and not reliable inputs for road infrastructure engineering. Hence, decision-making frameworks should take this uncertainty into consideration, although it is highly likely that infrastructure will have to cope with a larger range of climate conditions than before. For these frameworks and adaptation strategies the following examples of approaches could be considered (Hallegatte, 2009):

- *No regret strategy* – strategies that will yield benefits even in the absence of climate change (examples of adaptation options: restrictive land-use planning; development of early warning systems, emergency response and evacuation schemes, supported by well-maintained weather monitoring networks; climate proofing of new infrastructure; storm/flood proof infrastructure)
- *Reversible strategies* – strategies that are reversible and flexible over irreversible choices with the aim so as to keep as low as possible the cost of being wrong about future climate change (examples of adaptation options: stage construction; easy-to-retrofit coastal protection; 'building back better' responsibly)

- *Safety margin strategies* – strategies that reduce vulnerability at null or low cost (example: doubling of conventional storm return periods for all new designs of drainage infrastructure or the rehabilitation/retrofitting of existing infrastructure)
- A *mix of above strategies*

Adaptation strategies aim to reduce the **impacts** of specific types of climate effects by identifying and prioritising adaptation options, which could include:

- Protecting existing assets or relocating assets away from vulnerable areas to preserve functionality
- Retrofitting vulnerable facilities
- Improving overall catchment/storm-water drainage
- Constructing new facilities
- Do little or nothing and divert funds/efforts to facilities with greater priority.

Alternatively, a strategy aims to reduce or mitigate the **consequences** of the impacts to infrastructure for impacts that have already occurred, with the purpose of, for instance:

- Preserving human life
- Reinstatement of former accessibility
- Minimising economic impact
- Replacing damaged infrastructure as quickly as possible
- Changing maintenance regimes.

As discussed in the accompanying Visual Assessment Manual and in the introduction to this Guideline, all adaptation measures implemented are dependent on the available funding and in most sub-Saharan countries with limited budgets, most adaptation measures on the existing infrastructure are likely to be reactive, using emergency funding after events occur.

4.2 Methodology

Each of the climate factors has direct implications for the condition of infrastructure as well as for its operation and maintenance. The needs of the infrastructure in this regard are determined during an assessment of the various components of the infrastructure as described in the Handbook and assessment Manual. Once the significance of the implications is assessed, road managers may select from a range of the adaptation strategies described below to respond to these impacts. It should be noted that, although this manual includes numerous adaptation options, there may be many other options that could be implemented. These need to be selected on the basis of the engineers knowledge, experience and assessment of the most "'fit-for-purpose" option as well as new technologies being developed on an ongoing basis, e.g. innovative geosynthetic products, new slope stabilisation techniques, etc.

The critical issue regarding the selection and implementation of adaptation measures is to identify and understand the current situation and future implications. This often entails a combined understanding of the geomorphological, geological, geotechnical and hydrological regimes in the area immediately surrounding the infrastructure facility as well as in the larger river catchments affecting this area.

4.2.1 Adaptation assessment

Identify all potential adaptation options

Based on an understanding of expected and current climate change impacts and vulnerabilities, a wide range of adaptation options can be identified. These must be determined after a full assessment of the existing or expected infrastructure likely to be affected, including via stakeholder consultation to capture the maximum range of options.

It is important to recognise that in some cases, the best adaptation option(s) may be beyond the scope of an existing project or beyond the remit of the road authority. For example, realigning roads away from floodplains may be the most appropriate option in some situations, but may be difficult to address at the project stage. Others may include protecting the road infrastructure at the expense of accessibility during flooding (i.e. locate infrastructure at ground level instead of on embankments; the latter standing a greater risk of getting damaged during flooding). Similarly, watershed reforestation may be the most appropriate option in some situations, although this could increase flood debris that may block or damage drainage structures after extreme events. This also is beyond the remit of the engineer and part of a wider enabling environment for adaptation that includes land use planning and integrated catchment management. It should be taken up as part of an upstream planning process and can be flagged for such higher-level discussions, usually with other affected parties or Government Departments.

It should also be noted that slope stability in mountainous terrains is a major problem that is expensive and difficult to handle. The main concern should be to ensure that the road infrastructure does not affect regional natural stability that is likely to cause large "natural" landslides or instability putting residents or water retaining infrastructure beneath high slopes at increased risk.

Conduct consultations

Identification of adaptation options will necessarily involve inputs from several stakeholders. Conducting roundtable consultations with affected parties provides useful input for the process of identifying and appraising the range of adaptation options. Local community knowledge and experience regarding historical climatic events also usually provides useful inputs into the design of adaptation measures. Information on past flood levels and intensities can be determined from such discussions with those in the area at the time.

Conduct economic analysis

The goal of the economic analysis of adaptation options is to provide decision makers with information pertaining to the expected costs and benefits of each technically feasible option and to rank these options according to the net total benefit (measured in present value terms) that each delivers. These depend critically on the assumed life-time of the project and economic discount rate (cf. Stakhiv, 2011).

The specific feature of climate change pertains to the uncertainty associated with its various impacts. Given the significant uncertainty associated with the projected impacts of climate change, conducting a cost-benefit analysis of adaptation options requires paying attention to the treatment of risk and uncertainty. Due to this uncertainty, it is often useful to carry out sensitivity analyses varying specific input parameters over the possible range that they may take.

Handling the uncertainty process is described in the ADB Guidelines, including the *methodological approach to cost-benefit analysis of adaptation options*, *Cost-benefit analysis of adaptation: Accounting for risk and uncertainty and Decision Rule* (ADB, 2011).

Prioritise and select adaptation option(s)

The adaptation assessment and need (vulnerability) study should result in a prioritised list of locations requiring adaptation measures. The adaptation options for implementation are then selected from among several possibilities identified in this guide, based on experience of the designer or after seeking specialist advice. Their prioritisation can be based on an assessment of their technical feasibility, their benefits and costs, their social acceptability, and the opportunities they may offer for synergies with national priorities. While the use and outcome of a cost-benefit analysis is often given more weight in the prioritisation process, it is important to recognise that other factors and criteria may also influence decision making.

The expertise required is multidisciplinary and as such is one of the more challenging aspects of adaptation planning. Options must be scientific, socially beneficial, and economically viable. Roundtable discussions involving different stakeholders can work well and can include, for example, the project engineers, environmental specialists, social safeguards experts, non-government organisations, implementing entities, and national climate change representatives.

4.2.2 Implementation arrangements

Establish arrangements for implementation

A lead organisation should be selected to oversee implementation of the selected adaptation measures. While this organisation may be the main executing agency responsible for the road sector project (such as a ministry of transport or department of rural roads), other ministries, organisations, and institutes may be needed for certain inputs and agreements, given the cross cutting nature of the adaptation activities. This again highlights the need for strengthening the wider enabling environment for adaptation at district to national levels.

As flooding is often a key factor affecting roads (and considering their importance in relief operations), a national disaster preparedness committee may also have a role to play.[6]

When the project partners are selected, the scope of the project is likely to be limited by each partner's lines of responsibility. For instance, while the ideal adaptation approach may include engineering and environmental measures, the latter is likely to fall outside the roles and functions of a ministry of roads/transport. This adds further reasons for addressing adaptation at the earliest stages of policy and strategy development.

Identify needs for technical support and capacity building

Capacity and awareness required to manage climate variability/change and adaptation are currently limited in most countries. Provisions for training and capacity building will be needed for executing agencies, partner institutes, local communities, project management units, engineers and contractors. An institutional assessment of existing capacity and gaps should inform this plan.

4.2.3 Monitoring and evaluation

Establishing monitoring and evaluation frameworks ensures accountability (and that lessons are learned) to inform future adaptation efforts, and is essential. This is also necessary to determine the cost-effectiveness of the adaptation measures implemented.

Design a monitoring and evaluation plan

There is currently little experience worldwide in understanding how effective the different options to reduce vulnerability to climate change are, making monitoring and evaluation all the more important to develop improved knowledge[7]. There are several challenges in doing so, including the long-term nature of actual climate change, the need to acquire appropriate baseline data and metrics for measuring vulnerability and isolating vulnerability to climate change from other sources of pressure. It is most beneficial to be able to compare an adaptation option with the conventional

[6] A variety of enabling options for flood risk management is discussed by Wilby and Keenan (2012).
[7] For a comprehensive discussion of these matters, see: Adger et al. (2005) and Moser & Boykoff (2013).

or even do-nothing option on as near as possible identical sections to obtain a valid determination of the success of the adaptation option. At the same time, the costs of construction and maintenance of the adaptation (as well as societal costs where possible) and the alternative solution must be carefully monitored to assess whether there are any long-term (life-cycle) economic benefits of installing the adaptation measures.

The development of outcome level and output level indicators to assess the impacts of adaptation investments is ongoing. ADB (2011) identifies three levels of results monitoring: impacts, outcomes, and outputs.

Table 8 provides some examples of indicators at each level. Given the challenges related to measuring impact, which may occur beyond the project life, output level indicators may be the most robust.

Table 8 Typical indicators of results monitoring (after: ADB, 2011)

Indicator Type	Indicator
Impacts (long-term effect)	▪ Increased robustness of infrastructure design and long-term investment development ▪ Increased resilience of vulnerable natural and managed systems, such as flood management
Outcomes (process indicators)	▪ Percent reduction in road closures due to structural failure, landslides or flooding ▪ Percent reduction in flooding where drainage capacity has been increased ▪ Improved decision making and sector planning based on climate change considerations ▪ Improved rural access
Outputs	▪ Transport sector planning and documents include adaptation strategies ▪ Design and specification documents have resilience measures built in ▪ Maintenance programmes routinely cover preventative measures ▪ Length of road constructed to withstand climate change impacts ▪ Area of environmental protection implemented (e.g. mangrove for coastal protection)

Feedback into policy-making and knowledge management processes

An adequate adaptation strategy is likely to consist of various activities including *engineering measures*, such as incorporating design changes, and *non-engineering measures*, such as ecosystem resilience measures and early warning systems for disasters. Lessons from adaptation measures undertaken at a project level should inform policy makers about appropriate approaches at the sector and/or national levels. Details in this regard are included in the accompanying Change Management Guidelines.

4.3 Prioritisation of adaptation needs

Whichever climate adaptation measures are implemented, they are inevitably going to increase the cost of the provision of most new roads or involve, often significant, costs for the retro-fitting of such measures to existing infrastructure. A World Bank study (World Bank, 2009) found that the cost of adapting for climate change, given the baseline level of infrastructure provision, is no more than 1 to 2 per cent of the total cost of providing the infrastructure. However, this climate resilience may decrease total life-cycle costs by preventing damage to, and interruptions of the infrastructure and improving social conditions. In general, the cost of adaptation is small in relation to other factors that could influence the future costs of the infrastructure. Because of the lack of existing knowledge related to future climatic events, it is not currently easy to carry out total life-cycle cost analyses with any accuracy. This should, however, be a part of the monitoring and evaluation analyses.

The installation of adaptation measures will initially require prioritisation of the needs. The process of prioritisation will require significant input from both road authorities and communities. Their differing needs and priorities may prevail and typically would require decisions of a strategic nature. The following will need to be considered when prioritising investment decisions[8]:

- Potential loss of life
- Availability of alternative routes
- Cost and consequences of closure
- Environmental/sustainability issues (i.e. pollution, aesthetics, etc.)
- Cost of repair
- Available funds
- Accessibility requirements.

Generally, safety (loss of life) considerations will take precedence over the others. However, other than large landslides induced by excavation for roads (and which could affect communities below the roads), the safety implications of road failures are usually minimal. It should also be borne in mind that it is still usually more important to ensure that the primary and secondary road networks are maintained in good condition before concentrating on the tertiary or low-volume access road network.

It is important that all roads are carefully and correctly classified in terms of their required or expected Levels of Serviceability (LoS) as a part of the prioritisation process. This serviceability level will be a function of numerous factors, but mostly whether the road is purely an access road or whether it is also used for mobility (Figure 2). Various levels of serviceability, for instance, based on whether the road is primarily for access or also has an important mobility function and the expected needs of the communities affected can be identified (adapted from TRH 20 (DOT, 1990)). Such a classification can be directly related to the required prioritisation as shown in Table 9 for accessibility and in Table 10 for mobility.

Table 9 Guidelines for Levels of Serviceability for accessibility

Level of Serviceability	Required standards for accessibility		
	Comfortable driving speed (km/h)	Impassability	Duration of impassability
6	N/A	> 20 days/yr	> 5 days
5	15	< 20 days/yr	Not more than 5 days
4	20	< 5 days/yr	Not more than 2 days
3	35	Never	None
2	50	Never	None
1	60	Never	None

Accessibility roads classified as LoS 1 would generally be those carrying higher traffic, leading to important services and usually not having an alternative route. Roads classified as LoS 6 on the other hand would serve very small relatively self-sufficient communities, who can handle loss of access for extended periods.

[8] Note that there can be uneven benefits from adaptation interventions depending on priorities (e.g. Clay and King, 2019).

Table 10 Guidelines for Levels of Serviceability for mobility

Level of Serviceability	Required standards for mobility		
	Max Roughness (IRI units in m/km)	Impassability	Duration of impassability
5	12	Not more than 4 days/yr	Not more than 1 day
4	9	Never	None
3	8	Never	None
2	7	Never	None
1	6	Never	None

Decisions on the classification of the level of serviceability should be based on a multi-criteria analysis and need to include issues such as social, traffic, connectivity and economic considerations. These analyses should be done at a strategic level. This will be based on the inventory of roads developed as part of the Road Asset Management System (RAMS) for any country as well as the existing condition, to identify any preliminary improvements.

Assessors carrying out conventional visual condition assessments for road management and maintenance will need to be aware of possible climate changes, which may vary from country to country and even district to district, and make specific visual assessments of potential road and structure vulnerabilities based on the specific stressors identified for their individual countries or even regions within the country. In most cases, however, specially trained assessors should be used for the vulnerability assessments, as different skills are required – typically better knowledge of geomorphology, pedology and hydrology. Detail on such assessments is described in Section 5.1. The following should, however, be considered in this assessment:

- The degree of exposure of the road infrastructure to different climatic hazards;
- The sensitivity of various infrastructure components to such changes in climate, and;
- The possible adaptations necessary to mitigate the potential for damage (inclusive of adaptive capacity).

The actions that can be taken to reduce vulnerability to changing climatic conditions include avoiding, absorbing, and/or taking advantage of climate variability and impacts. Avoiding high risk areas is probably not possible for most existing roads but could be considered for new infrastructure. In most cases, the implementation of adaptation measures to existing vulnerable assets is the only option.

It is postulated that, in many cases, older engineered roads in a country's road network would be less affected by *gradual* changes in precipitation and temperature conditions. This is because vulnerable areas of these roads would more than likely have been upgraded, rehabilitated or spot-repaired considering historical data on climate variability and as a result of previous periodic extreme events. However, the increase in extreme events (and the severity of these) that is expected to be widespread in the shorter term needs to be catered for on existing roads (and networks). The design of new roads and bridges needs to consider longer-term changes in local climatic and hydrological conditions. However, this must be done with a degree of circumspection as it is neither practical nor economical to apply blanket solutions to entire road networks. A typical example of this would be during the design of a new road with numerous cuts and fills – it would be unwise, for instance, to increase the design Factor of Safety from the traditional 1.5 to say 1.7 on all cuts and fills as a general precautionary/adaptation measure – each structure must be considered individually, preferably by a geotechnical specialist in terms of its complexity, magnitude and consequences of failure.

Table 11 below outlines typical expected useful lives for some road infrastructure assets and their components based on the assumption that the assets have been designed, constructed and regularly maintained to meet the requirements of the functional environment in which they operate (COTO, 2013). However, if climate change projections were not accounted for in design, and return periods for major storms were to change from, say, 50 years to 25 years, a reduction in the asset's useful life could be expected. Overall, the economic implications of these impacts on low-volume roads would be negligible, except for major structures such as embankments and bridges.

Table 11 Design life expectancy of several infrastructure types

Asset	Component Type	Name	Expected Useful Life
Road	Road Surfacings	Sand seal	3
Road	Road Surfacings	Slurry - Coarse	5
Road	Road Surfacings	Single Seal (All sizes)	9
Road	Road Surfacings	Single Seal (Mod. Binder)	12
Road	Road Surfacings	Double seal (All sizes)	10
Road	Road Surfacings	Double seal (Mod. Binder)	12
Road	Road Surfacings	Asphalt	14
Road	Road Surfacings	Asphalt Modified	16
Road	Road Pavements	Granular	20
Road	Road Pavements	Cemented	20
Road	Road Pavements	Bituminous	20
Road	Road Pavements	Block Pavements	20
Road	Road Pavements	Concrete	30
Road	Formations including Drainage	Low Standard	30
Road	Formations including Drainage	Medium Standard	40
Road	Formations including Drainage	High Standard	50
Bridge	Bridge – General		80
Bridge	Bridge – Arch		80
Bridge	Bridge – Cable-stayed		80
Tunnel	Civil	Cut and Cover / Lined Rock	100
Drainage	Kerbs and Inlets		30
Drainage	Lined Drains	Concrete	30
Drainage	Bridge – Cellular		80
Ancillary	Retaining Wall		30
Ancillary	Retaining Structures	Gabions	20
Ancillary	Retaining Structures	Ground Anchors	40
Ancillary	Retaining Structures	Soil Nails	40
Ancillary	Retaining Structures	Soil Reinforcement	40
Ancillary	Walkway - Paved	Walkways - Bituminous	20
Ancillary	Walkway - Paved	Walkways - Blocks	25
Ancillary	Walkway - Paved	Walkways - Concrete	30

(Source: COTO, 2013)

Several sub-Saharan countries with coastlines administer small islands off their coasts. In addition, much of the economic activity and habitation of the countries is centred along the coastal areas, which are highly vulnerable to sea-level change. Particular attention will need to be paid to these areas.

No indication of costs is included in this Guideline as these will be very project and country specific. Each proposed project will need to be assessed in terms of the costs of adaptation versus the cost of doing nothing, considering all of the engineering, social and environmental costs and the discounted overall life-cycle costs to allow for fair comparisons. For example, certain sandy areas of Mozambique have no available aggregate, whilst other areas have ample material suitable for crushing. The adaptation measures for a similar problem in these two areas would need to be different in order to account for this situation and would have significantly different cost implications.

The overall economic impacts of making the infrastructure climate resilient are, however, expected to be massive. As an example, the World Bank (2010) has estimated that climate change has the potential to result in a $ 3.1 billion impact to roads in Ethiopia (through to 2100) when the effects of temperature, precipitation and flooding increases are taken into consideration. They also indicate that these costs could be reduced by 54 per cent if adaptation policies are adopted through policy changes by the government. However, even with these adaptations, the potential cost to Ethiopian roads from climate change could be as high as $ 1.4 billion (World Bank, 2010).

Numerous adaptation options are available and can respond to various degrees of risk. These include:

- Avoid the risk (often impracticable);
- Remove or reduce the risk to a level that minimises the consequences and that can be handled using existing resources – this would make use of appropriate technological solutions;
- Implementation of appropriate adaptation measures.

It is imperative that consultations are held with communities and other stakeholders to ensure that any adaptation measures implemented and the road affected are acceptable to the stakeholders.

4.4 Adaptation options in the roads sector

The types of actions that can be taken to reduce vulnerability include avoiding, withstanding, and/or taking advantage of climate variability and impacts as discussed above. Avoiding areas projected to have a higher risk of potentially significant climate impacts is an important factor in planning decisions. If such locations cannot be avoided, steps need to be taken to ensure that the road infrastructure can withstand the projected changes. For example, the potential for increased flooding might be a reason to increase bridge elevations beyond what historic data might suggest. It should, however, be noted that most of the problems experienced are related to existing infrastructure that cannot be as easily relocated.

Secondly, the result of adaptive action either decreases a system's vulnerability to changed conditions or increases its resilience to negative impacts. For example, increasing temperatures could cause pavements on the highway system to fail sooner than anticipated. Using different materials or different approaches that recognise this vulnerability can lead to pavements that will survive expected higher temperatures better.

With respect to resilience, operational improvements could be made to enhance detour routes around flood-prone areas. Another example of resiliency is well-designed emergency response plans, which can increase resilience by quickly providing information and travel alternatives when roads are closed and by facilitating rapid restoration of damaged structures. By increasing system resilience, even though a facility might be disrupted, the entire road network still functions.

Adaptation options can generally be divided into engineering and non-engineering[9] with this Guideline only discussing the engineering adaptations, as follows:

- ***Subsurface conditions*** - the stability of any type of infrastructure depends on the materials on which it is built (subgrade). An important factor pertains to the degree of soil saturation, fluctuations in moisture content and the expected behaviour of the soil under saturated conditions. The type, strength, or protection of subsurface conditions and materials may have to be modified to control and prevent soil saturation or dehydration from damaging the overlying infrastructure. Once a road is constructed over unsuitable materials, it is extremely costly and time-consuming to "repair" the subgrade. It is, however, possible (but costly) to improve drainage around the road and control water movement within the pavement support structure.
- ***Material specifications*** - materials of appropriate quality must be used in both unpaved and paved roads and unsuitable materials may have to be replaced or enhanced to preserve the expected lifetime of the road or structure. This would be typical of un-engineered or engineered earth roads.
- ***Cross section and standard dimensions*** - Standards may need to be revised, for example, to increase the cross-fall of pavements in areas where one can expect a need to remove more water from the road or to accommodate improved side and mitre drains. Similarly, standards (or guidelines) pertaining to road elevations or the vertical clearance of bridges may have to be revised upward where increased precipitation or extreme events are likely.
- ***Drainage and erosion*** - improved standard designs pertaining to drainage systems, open channels, pipes, culverts and surfacing options (e.g. for steep hill road sections) are needed to reflect changes in future expected runoff or water flow and consequential potential for damage caused by erosion.
- ***Protective engineering structures*** - can be used to address rivers in spate, rising sea levels and storm surges. These may include drifts, dykes, seawalls, rocky aprons and breakwater systems.
- ***Construction and maintenance*** – It is essential that all aspects of construction and maintenance related to roads, drains, structures, protection works and vegetation control are diligently and timeously addressed. Most problems will be precluded by good maintenance. Adaptations to protect workforce well-being and productivity should also be addressed.

4.5 Do nothing or do minimal options

In many cases, there is just not enough budget to deal with all affected areas, roads and structures, or the consequences of climate change are too severe to justify comprehensive physical adaptation. In these circumstances, no adaptations are implemented but a planned programme of dialogue with affected communities, well disseminated information and contingency programmes are necessary to minimise the adverse effects of this decision. The 'do nothing' scenario must be programmed in line with the prioritisation of the road and should be limited to category 5 and 6 roads in Table 9, and even then should only be considered if there is no or limited funding available.

Although this may be termed the 'do nothing' scenario, the fact that a programme of dialogue with stakeholders must be planned indicates that at least something is done. Moreover 'doing nothing' is a conscious decision in which the consequences are understood, accepted and subject to review.

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[9] See also Biagini et al. (2014). Adaptation was typified into the following ten engineering and non-engineering categories: (i) Capacity Building; (ii) Management and Planning; (iii) Practice or Behaviour; (iv) Policy; (v) Information; (vi) Physical Infrastructure; (vii) Warning or Observing Systems; (viii) Green Infrastructure; (ix) Financing; (x) Technology.

5 Adaptation Options

5.1 Hazards, exposure and vulnerability

During the design of new infrastructure, climatic impacts should be determined as part of the Environmental Impact Assessment or Strategic Environmental Assessment and can thus be considered in the design, which can incorporate the necessary adaptation measures at minimal cost.

For existing roads, however, during the routine visual assessment of roads for input into Pavement Management Systems (PMS), it will be essential to include a separate (or parallel) assessment of the vulnerability of the road and associated structures (bridges, culverts, embankments, materials, slopes, etc.) to variability and changes in the climate. Potential vulnerabilities and their mitigation will need to be identified, typically on a once-off basis. Guidelines for this will need to be included with the visual assessment manuals for the Asset Management System to assist assessors with these decisions, although in many cases assessors with different backgrounds or training may be required. These should be developed in conjunction and to be compatible with the regional Asset Management Project currently being carried out under the AfCAP umbrella. Duplication of work must be avoided. However, the vulnerability assessment requires integration of the expected climate changes and the current condition and design of the infrastructure network. Routine visual assessment should characterise the selected conditions of the road and structures seen at the time, whereas for vulnerability assessments different issues are assessed and projections as to possible future effects must be made.

Unlike the prioritisation process, the vulnerability assessment would be a more tactical operation. The climate sensitivity of all components of the road infrastructure needs to be identified in terms of two primary parameters during routine road condition assessments. These are the potential for:

- *Damage (i.e. physical harm that impairs the value, usefulness or normal function of an asset)* – this can normally be repaired rapidly by local works teams and would usually be classified as a degree 3 defect (See *Visual Assessment Manual* and Annex A)
- *Collapse (i.e. structural failure initiated when the material is stressed beyond its strength limit)* – this is usually costly to repair and involves significant construction and repair works, often by specialised teams requiring a tendering process and can lead to road closures for extended periods. During assessment, such conditions would be classified as a degree 4 or 5 defect

To minimise the cost of acquiring data on the climate vulnerability of assets, vulnerability assessments should be carried out simultaneously with routine road condition assessments where possible and all necessary data elements should be captured. However, the lack of effective asset management in many SSA countries will impact on the availability of historical asset condition data that would inform and support climate vulnerability studies and the identification and prioritisation of adaptation options. To achieve the latter, data will need to be collected directly for each road in the network.

In the Climate Threats Report (le Roux et al, 2016), risk is defined as a function of hazards, rural access road exposure and vulnerability in terms of rural community access. In particular, the following definitions apply:

- **Hazards**: The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. Within the scope of this study, hazards are climate-related events that have the potential to cause damage to and/or interruption of service of rural low volume access road infrastructure as well as potential loss of life (e.g. floods);

- **Exposure**: The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected by hazards. Within the scope of this study 'exposure' is the location of low volume road facilities, the associated structures and road environment as well as rural communities in places that could be adversely affected (within the hazard footprint);
- **Vulnerability**: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. Within the scope of this study it is the propensity to be adversely affected, considering the dependence of rural communities on these low volume access roads.

Adaptive capacity is the ability of the infrastructure to accommodate changes in climate with minimum disruption or minimum additional cost. This could be gauged by assessing the response to the following questions:

- What is the ability of the infrastructure, as it currently stands, to withstand the anticipated climate impacts?
- What are the regulatory, physical, managerial or competing-use barriers that could impede the ability of the infrastructure to accommodate climate impacts?
- To what extent does the current state of repair of the infrastructure (under-designed, old or poorly maintained) limit its ability to accommodate climate impacts?
- To what extent are the changes in climate likely to exceed the infrastructure's capacity for adaptation faster than the infrastructure can be adapted?
- What steps currently underway are necessary to address climate variability that may impact the infrastructure?

The assessment of vulnerability of infrastructure to even current climate variability is challenging because of the range of factors, in addition to climate, which contribute to vulnerability. The assessment of road network vulnerability to changing climate is even more challenging because of the dynamic nature of the climatic effects and the resulting vulnerability.

Thus, the need for specialist training of assessors to identify potential vulnerabilities in the road infrastructure – it is probably not cost-effective to include special assessors specifically to identify and record potential vulnerabilities, although this may be beneficial for the initial assessments. The routine assessment will thus need to include the field identification of potential vulnerabilities as well as an estimate of the associated risk, both requiring special training and skills to ensure useful results. Most pavement condition assessors typically have a civil engineering background, whereas for vulnerability assessments a background in materials, geomorphology, hydrology or geotechnics is preferable.

Using a structured programme, the identification of vulnerabilities can be relatively easily learned and can be based on an assessment form, identifying specific areas to be assessed and including an attribute and a potential severity in terms of consequences. An example of such a form is included in Annex A. Both current and future vulnerabilities should be identified, if there are any suspected differences.

This assessment form should be used in conjunction with the *Visual Assessment Manual* (Paige-Green et al., 2019), which describes each of the factors to be assessed with illustrations of the different degrees and severities. In this way, uniform assessments should be able to be obtained from different assessors. This is essential if the assessments are to be used to prioritise the adaptations requirements.

For prioritisation purposes, the hazard and the consequences need to be converted to some form of risk. The most promising and convenient means of doing this successfully in SSA is probably using a likelihood/consequence estimate of the risk (FHWA, 2012) or an impact/criticality assessment (WSDOT, 2011).

In general, the vulnerabilities can be classified as those that are "ground-related" and those that are "topography related". The ground-related vulnerabilities are related to parameters that describe landforms, hydrology and material properties and can be quantified, while the topographic vulnerabilities are more related to the concentration and surface flow of water as related to slope lengths, angles, surface characteristics, etc. It is important to note that with respect to slope instability, it is not a one-off storm that usually creates instability, but more the antecedent conditions and recent past precipitation events as discussed in Section 5.3.3.

Life-cycle cost analyses should include a factor for climate resilience of the facility, although assumptions will mostly have to be made regarding the benefits – little precedent is available to assist with estimating these benefits. Any climate resilient road or structure is likely to cost more than conventional structures to construct. However, the total life-cycle cost is generally expected to be less for such structures, unless no extreme events occur and the additional resilience was not called upon and becomes redundant (effectively becoming an insurance policy). This is, however, probably an unlikely scenario during the life cycle of most infrastructure facilities.

5.2 Consequences and adaptation

Road infrastructure should always be designed taking local environmental conditions into account (climate, topography, traffic, etc.). Historical records of climate are generally used to determine temperatures and precipitation trends. This existing data is probably inadequate in the short to medium term with the accelerating climate change trends being observed, although some preliminary trends may be usefully based on the weather records over the past 5 or 10 years. However, for general design purposes, it is probably better to make use of the high-resolution climate change projection maps that are becoming increasingly and more readily available[10].

Modern, high volume roads are designed to last from 30 years (pavement structures, excluding the surfacing) to 100 years (major structures) or longer (i.e. long-life pavements). Similarly, low volume engineered earth roads are expected to last between 5 and 6 years with the wearing course of gravel roads between 6 and 10 years, whilst their drainage structures and bridges are expected to last between 50 and 100 years (cf. Table 11). Low volume paved roads are normally designed for 10 to 20 years. Hence, changes in climate would have to be factored in and considered in the design of all new roads and major rehabilitation projects to equal or improve on the typical life expectancies referred to above.

The consequences of climate change are wide and varied and need to be assessed case by case. Adaptation, however, should preferably be done pro-actively, but there will always be instances of extreme conditions that were not planned for. In general, pro-active adaptation is essentially related to identifying the potential problems and then applying good engineering practice, including design, construction and maintenance. Normal engineering principles applied properly, for example would provide for correct pipe diameters for culverts based on the current expected water flows, as well as specific return periods. Adjustments to the return periods (factored for expected changes in water flow rates) based on climate projections, however, will generally need to be made, or where these are not available, longer return periods can be used. It is suggested that in the interim, the conventional return periods in current design guides be at least doubled (i.e. a recommended return

[10] These should be used with caution and their limitations should be understood. There is considerable uncertainty in key variables like precipitation at the local scale, and these maps are likely to change depending on the choice of climate model and downscaling method.

period of 25 years in current manuals should be replaced with a current one of 50 years for large culverts and small bridges and 100 years for large bridges).[11]

Various climate change parameters or "stressors" such as average temperature, temperature ranges, number of hot days per year, average and seasonal precipitation, lower humidities, higher wind speeds and extreme weather events, etc. could all contribute to the need for more resilient engineering solutions. Changes in precipitation intensities and duration are probably more likely to have major influences on the road infrastructure than the actual changes in precipitation.

Climatic effects on roads are mostly considered using some form of moisture mapping, such as the Weinert N-value or Thornthwaite's Moisture Index, the latter becoming more popular recently. Both indices are based mainly on historic temperature, rainfall and evaporation (or evapotranspiration) data and updated maps or data specific to individual sites, indicating the change of these with time will need to be developed for the SSA region. The input parameters to calculate these indices are normally monitored routinely by local meteorological stations and/or agricultural communities. The potential hazards related to the different expected climatic stressors for the various low volume road facilities and associated structures and their likely consequences are discussed in detail below and further summarised in Table 16 to Table 22.

5.3 Roads

This section deals with adaptations required for roads in terms of the different road attributes.

It is interesting to note that in Ghana, it has been concluded that the engineering solutions needed to make a climate-resilient road can to a very large extent be found in the existing design manuals, "from solutions to hydraulic-related problems, such as scour and sedimentation, to problem soils and sub-grade problems as well as slope stability and surface drainage solutions" (COWI, 2010). The problem identified is a *lack of appropriate and timely maintenance*. While it is agreed that current designs are probably sufficient if implemented properly and with *adequate drainage* facilities for extreme events for critical infrastructure, there are several adaptations or specific design decisions that can increase the resilience of roads to climate change. These are detailed in the remainder of this section.

5.3.1 Unpaved roads

Unpaved roads consist of earth roads or gravel roads. Earth roads may be either constructed using the in situ material that has been moved and shaped (engineered earth roads) or the in situ material that has "evolved" into a "road" by vehicles moving along it (un-engineered earth roads – typically constructed at natural ground level). Good gravel roads, on the other hand, are constructed of well-compacted, selected gravel, resilient to erosion and weakening by water and are, by their nature, generally classified as all-weather roads. It should be noted that all unpaved roads, including gravel roads, can be impacted by erosion on steep gradients in mountainous or hilly terrain or by extended periods of submergence under water.

The main climate impacts on unpaved roads are related to the presence of excessive water on the road surface and within the pavement structure, which is one of the scenarios projected for many parts of SSA (***increased precipitation or extreme events***). The impact is also strongly related to the duration and intensity of the precipitation. ***Increased temperatures*** will result in more rapid and prolonged drying out and shrinkage (and cracking) of the road structures where excessively plastic materials are used.

[11] In Denmark, concerns about increased precipitation levels leading to flooding, and concerns that existing drainage systems will no longer be able to cope, let to a policy decision to construct all new drainage systems 30 per cent larger than was the norm to ensure that enough capacity will be available to handle future rain intensities (PIARC, 2012)

To ensure adequate climate resilience, however, the unpaved roads must not only be designed and constructed adequately with a good shape, but must be regularly maintained to ensure that the shape is retained and the road surface sheds water rapidly and effectively, without excessive erosion.

The resilience to extreme weather events of the different types of unpaved roads is very different and each of these is dealt with separately below.

5.3.1.1. Un-engineered earth roads

Description

In the case of un-engineered earth roads, the quality of the material on which the vehicles move (driving surface or wearing course) is purely a function of the in situ material, which seldom complies with the specifications for good wearing course gravel. This material has normally only been subjected to traffic compaction (usually minimal) and has no constructed shape or drainage (Figure 5). Un-engineered earth roads are thus highly susceptible to a range of problems:

- They have little mechanical strength because of their minimal compaction - densities are low, making them more permeable, weaker and more prone to deformation (shearing and rutting) under traffic when wet
- They are usually at or below natural ground level and precipitation will not be removed from the road surface or surrounding environment unless they are on a grade
- Traffic initially wears away the organic binders (roots and grass) and then starts developing a track below natural ground level that becomes a flow path for precipitation
- The low strengths and densities increase the potential for material being lost by water and wind erosion.

Figure 5 Typical un-engineered earth road showing damage caused by water retention

Design considerations

There is nothing that can be done to un-engineered earth roads in terms of adaptation designs for ***changes in precipitation, temperature or extreme events***. Even increased grader maintenance will only lower the road surface further below the natural ground level exacerbating any problems.

For a more resilient road, un-engineered earth roads must thus be improved by shaping and raising to at least engineered earth road standard, but preferably to a properly designed gravel road standard, inclusive of the provision of adequate side and cross drainage as well as river crossings. Only if the natural in situ material satisfies the specification requirements for a wearing course gravel should it be upgraded to an engineered earth road, in which case shaping and good compaction are required.

The main influence of climate change on un-engineered earth roads will be through ***increased precipitation and groundwater level fluctuation with temperature changes and increased windiness*** having minimal impact, unless impacted by local flooding.

5.3.1.2. Engineered earth roads

Description

Engineered earth roads are still constructed from the in situ materials but these materials are typically moved during the forming of side drains on to the road surface to raise the road above the natural ground level and provide better cross-sectional shape. This results in better drainage of the road surface and enhanced performance (Figure 6). However, the degree of compaction applied to engineered road surfaces is normally minimal, if any, and there is usually no quality control testing carried out. In addition, the materials comprising the wearing course seldom comply with the necessary specifications for good wearing course gravels. Their performance is thus only marginally better than un-engineered earth roads when subjected to either high traffic counts or inclement weather conditions.

Figure 6 Typical engineered earth road showing shaped structure and side drains

Design considerations

As is the case for un-engineered earth roads, unless the in situ material actually complies with the prescribed gravel wearing course specifications, there is little that can be done to engineered earth roads in terms of adaptation designs for ***changes in precipitation, temperature or extreme events.*** The road surface must be raised well above the natural ground level, and adequate side and cross drainage as well as river crossings must be provided. If the material complies with the necessary specification, then properly controlled construction must be carried out, carefully ensuring that excessive oversize material is removed and that the specified degree of compaction is achieved. In addition, the shape of the road (i.e. cross-fall and crown) must be carefully controlled. Overall, if the in-situ material properties do not comply with the specification for wearing course gravels, the road must be upgraded to an imported gravel road standard to ensure climate resilience.

The main influence of climate change on engineered earth roads will be through ***increased precipitation,*** with ***temperature changes, increased windiness and groundwater level fluctuation*** having minimal impact, unless impacted by localised flooding.

5.3.1.3. Gravel roads

Description

Gravel roads are properly engineered roads without any bituminous, concrete, block or other protective surfacing (Figure 7). The engineering component of gravel roads, however, differs significantly from one road authority to another. A gravel road should consist of a properly shaped structure, raised above the natural ground level to an extent that allows suitable cross-drainage structures. In addition to this, appropriate side and mitre drains (turn-outs) should be constructed and a wearing course gravel complying with certain criteria should be placed on top of the pavement structure, with or without an underlying "subbase" depending on the quality of the supporting layers. The wearing course must be placed, compacted to an appropriate density to optimise the benefits of the good quality gravel and shaped with a 4 to 5% cross-fall to ensure good drainage from its surface. Without any of these inputs, the selected material, no matter how good it is, will be rapidly lost under traffic and climatic effects, as seen in many SSA countries.

Shoulders are considered as part of the gravel pavement and these too should be designed and constructed to ensure that the road sheds all rain-water rapidly and effectively, without significant softening, erosion or scouring.

Depending on the traffic and climate, and if appropriate and timely periodic maintenance is carried out, the wearing course would normally be expected to last for between 6 and about 10 years, by which time it will have worn away (traffic and weather wear) and would need to be replaced. Poor construction (mostly insufficient compaction and poor material selection) will result in the material not lasting even the minimum 6 years expected. If the road is not timeously regravelled with a good material, it effectively becomes an engineered earth road and will not be climate resilient.

Apart from the obvious problems related to ***extreme precipitation*** events and erosion of unpaved roads, the impact of ***less rainfall*** on unpaved roads will be notable. Unpaved roads deteriorate quicker in the dry season, when the moisture in the wearing course dries out and the effective cohesion due to soil suction is lost. This results in greater dust emissions, the loss of the cohesiveness (in the dust), the greater propensity to form loose material and corrugations and a more rapid material loss.

Figure 7 Typical gravel road showing shaped structure and gravel wearing course

Design considerations

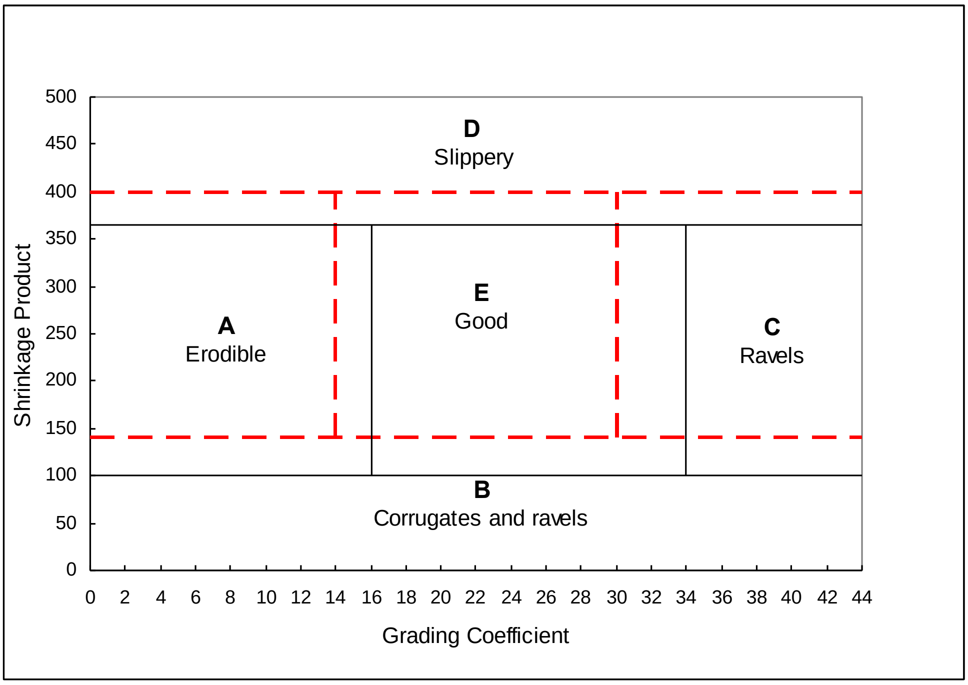
A properly designed and constructed gravel road with appropriate wearing course materials should be able to withstand even the most severe climatic effects, except for those on steep gradients where they could be impacted by erosion (discussed in section 5.3.3.3).

Excessive water (***increased precipitation or extreme events***) is really the only climatic attribute likely to have a significant effect on the performance of gravel roads. This water could arise from local precipitation or rainfall somewhere distant that flows down nearby rivers causing flooding, as occurs in the Limpopo and Zambezi valleys in Mozambique. The optimum solution in these areas is to place the road outside the normal flood limits, but this is usually impracticable. The alternative is to raise the road above the expected flood levels, preferably incorporating a rock fill or capillary cut-off layer beneath the wearing course and upper selected layers.

To obtain the best durability and performance (and hence the best climate resilience), the material should comply with performance-related specifications as far as possible. Material deficient in plasticity, grading or strength will not perform satisfactorily, without increased maintenance, and will not be climate resilient.

Typical specifications for good gravel wearing course materials are summarised in Figure 8 for material test results using ASTM/AASHTO based test methods (black lines) and for results based on BS test methods (broken red lines).

Figure 8 Specification for wearing course gravels using ASTM/AASHTO based test methods (black lines) and BS test methods (broken red lines)



In areas that are expected to have ***higher precipitation*** or those where more ***frequent extreme events*** are to be expected, it will be important to ensure that the minimum Shrinkage Products in Figure 8 are maintained and that the Grading Coefficients remain between the respective lower and upper limits shown, i.e. 16 and 34 for ASTM testing and 14 and 30 for the BS test methods. Materials with properties outside these limits will be particularly prone to erosion and damage under heavy precipitation.

It will be equally important that the roads are constructed properly. Construction requirements are primarily that excessive oversize material is removed (this interferes with compaction and results in roads more prone to erosion) and that the wearing course material (and shoulders) is compacted to a minimum of 98% heavy compaction effort, or preferably to refusal density. A good road cross-sectional shape (cross-falls of 3-4%) to allow efficient shedding of water is also essential and must be achieved during construction.

Regular and high quality grader maintenance must be applied to the road. This must ensure that depressions (ruts or potholes) are not permitted to form in the wearing course, the shoulders are properly shaped to ensure that water runs off the wearing course into the side drains and that no windrows are left parallel to the edge of the road after blading that will impede removal of water from the wearing course surface.

Periodic maintenance should also be adapted to improve the resilience of the road network. During regravelling or ripping and reshaping, the material properties should be modified where necessary (typically by stone removal and/or blending of additional materials) and the construction quality can be improved where it is found to be deficient.

The generation of dust from unpaved roads is almost inevitable from most materials that have a significant silt (fraction between about 5 and 75 μm) content. In areas where the ***dry/drought season*** becomes longer, it may be necessary to apply dust palliatives to selected sections of the road, such as those passing schools or clinics or where geometrics and sight distance are poor to minimise the additional dust from the dry roads. Chemicals such as lignosulphonates and magnesium/calcium chlorides are usually cost-effective in these cases. The loss of dust also reduces the plasticity of the materials resulting in quicker formation of corrugations, which need to be maintained more regularly. Generally, corrugations form quicker than other defects and regular dragging with tyre drags is a cost-effective means of maintaining these roads.

There will be areas where even properly engineered and constructed gravel roads are subject to on-going damage due to flooding, which may require costly and frequent maintenance. In these areas, consideration should be given to localised lengths of paved or even concrete roads. Where water flows over the road, measures to minimise turbulent flow should be installed, as described for embankments (section 5.3.3.2).

5.3.2. Paved roads

Low volume paved roads usually consist of a series of layers of material with properties that improve towards the top of the pavement. On top of the base course is a wearing course that can consist of various materials, typically a thin bituminous surfacing (surface treatments). However, thin asphalt, concrete, interlocking bocks, cobble-stones or various other weather-resistant surfacings could be used.

Paved roads may be sub-divided into those surfaced with a bituminous surfacing (asphalt or surface treatments) and those with non-bituminous surfacings (concrete, block paving, cobble stones, paving slabs, etc.). Their respective performances under wet and hot conditions can differ and they will thus be dealt with separately in terms of their adaptation measures.

As in the case of unpaved roads, there may be areas where conventional paved roads with thin bituminous surfacings are not effective and, again, consideration should be given to retaining them in an unpaved condition (the environmentally-optimised design concept) with the planned capacity to apply more frequent maintenance when necessary, e.g. after severe flooding.

5.3.2.1. Roads with thin bituminous surfacings

Description

The bitumen is the most important part of thin flexible bituminous pavement surfacings (surface treatments) in terms of waterproofing the pavement structure, and deterioration of this will result in degradation and eventual failure of the surfacing. Bituminous binders deteriorate through the loss of volatiles and oxidation, which are enhanced by ***high temperatures and increased ultra-violet radiation***. This deterioration of the bitumen results in hardening and drying of the bitumen and ultimately cracking of the seal and the ingress of water into the pavement if the cracks are not timeously maintained. Reseals and rejuvenation of the binder can assist with prolonging the binder life.

Conversely, one of the problems with high water pressures beneath an intact or uncracked road surface is that under the imposed hydraulic pressure, the impermeable surfacing can lead to high uplift pressures beneath it resulting in lifting and disintegration of the surfacing (Figure 9).

Figure 9 Loss of surfacing caused by high uplift pressures during flooding[12]

Extreme water conditions and prolonged saturation will inundate the structural layers beneath the surfacing leading to weakening of these materials and structural failure of the road.

Typical thin bituminous surfacings on roads generally need to be rejuvenated or resealed every 7 to 10 or 12 years, depending on the nature of the bituminous surfacing. The necessary adaptations to the bitumen type and seal design for climate change can thus be incrementally introduced over time during such periodic maintenance interventions.

Design considerations

The main design adaptations in terms of bituminous surfacings will be to make use of bitumens that are being continually modified over time by the producers to provide better resistance to climatic deterioration. The use of multiple seals also provides better protection of the bitumen deeper in the seal and will thus be slightly more resistant to cracking and deterioration over time.

Increases in moisture content in the subgrade caused by ***increased precipitation or extreme events*** will result in higher pavement deflections under heavy loading, which in turn will cause more rapid fatigue cracking of aged binders that have stiffened up. The periodic and managed application of binder rejuvenators or dilute emulsion fog spays can maintain the bitumen in a more ductile condition and avoid such cracking to a major extent. On the other hand, reductions in moisture content in the subgrade due to ***lower precipitation, higher temperatures or general groundwater lowering*** will lead to lower deflections and less potential for fatigue cracking. However, if the subgrade dries out with significant shrinkage, cracking of the overlying pavement structure could occur. Good drainage of the road environment is essential to minimise such moisture fluctuations (see Section 5.5).

In areas with the potential for ***increased rainfall***, it will be important to avoid pavement designs that produce a “bath-tub” effect, i.e. where the pavement structure is more permeable than the surrounding layers resulting in accumulation of water in the structural layers of the pavement and the development of high pore-water pressures under traffic loading. This is best done by ensuring that layerworks (particularly base and subbase) continue to the edge of the structure and are not terminated under the edge of the paved area.

It is well-known that the materials within and beneath the pavement structure reach an equilibrium moisture content in the central areas of the pavement, outside the “zone of seasonal moisture

12 Photograph: Department of Transport and Main Roads, Queensland, Australia

movement". The actual moisture contents at equilibrium are generally between about 55 and 85% of Optimum Moisture Content (OMC) in the structural layers and at about OMC in the subgrade. Prediction models for these values make use of the subgrade material properties and the climate, in terms of Thornthwaite's moisture index (I_m). Should climate change result in significantly ***less precipitation and higher evapo-transpiration,*** these figures may change slightly, but it is highly unlikely that the materials in the equilibrium moisture zone will dry out to the extent that shrinkage that will lead to cracking will occur.

However, in the zone of seasonal moisture movement (between 1 and 1.5 m from the edge of the surfacing), the variation may be significantly higher leading to shrinkage and cracking. One way of avoiding this is to move the zone of seasonal moisture variation away from the pavement carriageway, by sealing the shoulders with an impermeable surfacing and minimising trafficking of these shoulders. The sealing of shoulders with a different type of seal (e.g. double seal on the carriageway and single seal on the shoulder) is often used for delineation of the carriageway and safety reasons. Poor sealing operations of the shoulders could, however, lead to cracking and ravelling of the shoulder seal (Figure 10), which in turn could cause greater seasonal moisture variation within the pavement carriageway, potentially resulting in shrinkage and cracking. Flattening of embankment slopes (to 1:4 V:H preferably with clayey materials) can also assist in reducing moisture movements.

Figure 10 Deterioration of single chip seal shoulder compared with double chip seal on carriage way

In areas where drainage of the pavement environment is difficult and the formation has inadequate height, periodic flooding is likely to result in the moisture contents within the structural layers increasing to more than OMC (up to about 125% in the saturated condition) and the structural properties of these layers decreasing significantly. It may be necessary in some instances to close the road or impose load restriction measures after periods of intense/extreme rain or flood events. Such restrictions are, however, usually difficult to control and enforce and should be avoided as far as possible.

As pavement technologies develop and are implemented, some of the more innovative developments such as "Water Retentive Pavements" which have a sub-layer consisting of water retentive materials that absorb moisture and then evaporate it through capillary action when the pavement heats up or "Heat-shield Pavements" which reflect near-infrared radiation by the application of special coating materials on their surfaces may actually benefit from changes in climate.

In summary, apart from normal good engineering, adaptation measures for bituminous surfacings are probably most likely to take care of themselves as binders evolve over time to cater for changing conditions.

Regular maintenance of surfacing will, however, still be essential.

5.3.2.2. Asphalt surfacings

Description

Although it is not very common, some low volume roads may be paved using thin hot-or cold-mix asphalts. Asphalt is a thermally dependent visco-elastoplastic material and as such is affected strongly by high and low temperatures. It is also usually more costly than traditional spray seals. Significant reductions in temperature will make asphalt stiffer and more prone to cracking under heavy loads while significant increases in temperature will result in softer asphalt that is more prone to rutting and deformation under traffic (Figure 11). Bearing in mind that asphalt is not used frequently on low-volume roads and the number of heavy vehicles is usually small, this is unlikely to be a major problem in most rural areas.

In addition, as the life of a new asphalt surfacing layer is typically 10 to 15 years, after which they are overlaid or covered with some other seal type, adjustments in their design can be made at regular intervals during their service lives. Designing for different temperature conditions in the future is unlikely to influence the cost of resurfacing as there are only small difference in the costs of different bitumen types, necessary to adapt the design for differing temperatures.

It should be noted that there are currently wide seasonal and daily variations in temperature within roads, and the expected long-term changes are probably going to be minimal with respect to these variations. Temperatures at depths of 20 and 200 mm in the road as well as the ambient air temperature have been monitored by the CSIR in a variety of road types across South Africa over a period of nearly two years. Figure 12 shows the daily and seasonal fluctuation of air and in-situ road temperatures of Road N14-5 near Upington. Typically, the range of air temperatures was between -6 and about 50°C while the upper road temperature varied between 4 and 60°C and at a depth of 200mm between 9 and 48°C. The question of whether a 3 or 5°C temperature change over time would have a notable impact on such a road then arises.

Figure 11 Rutting and deformation of asphalt resulting from high temperatures and traffic loading

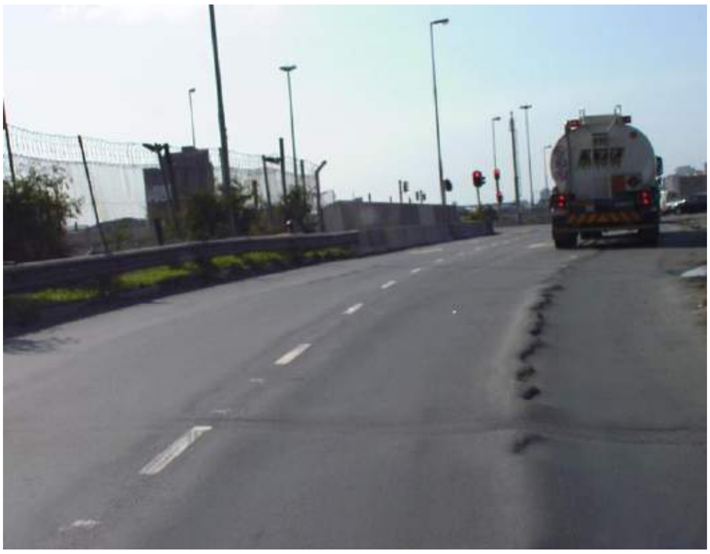
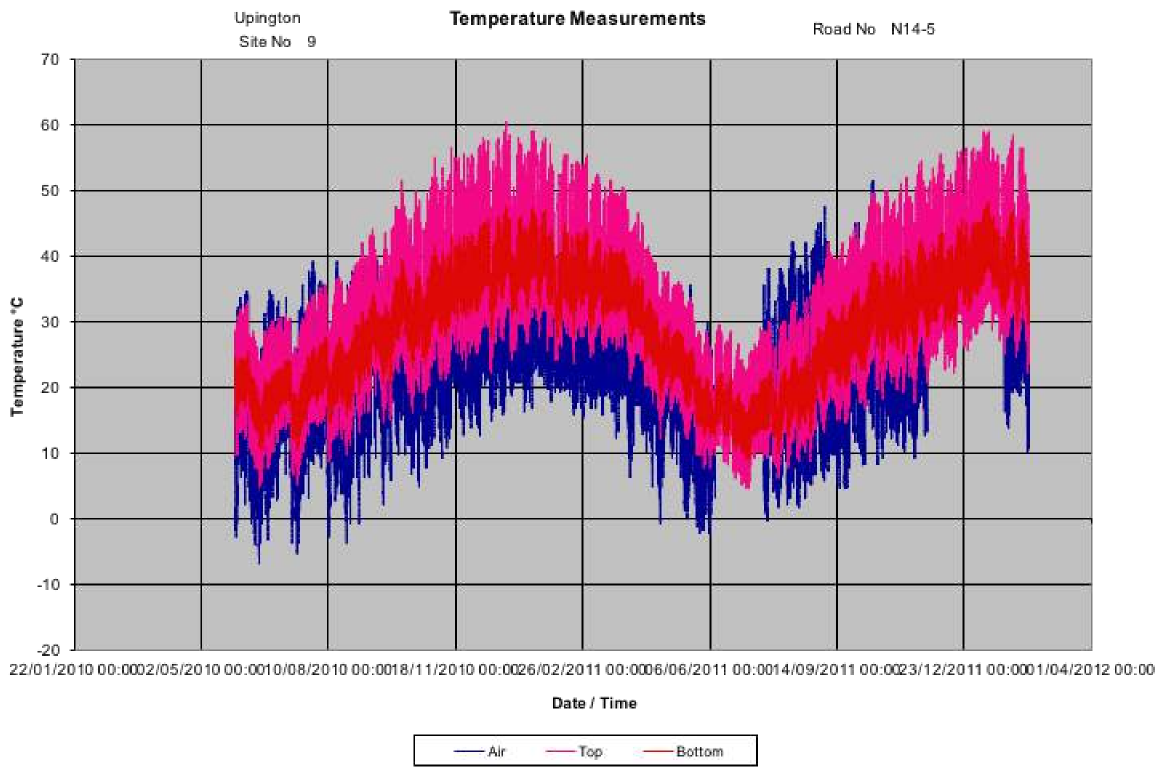


Figure 12 Daily and seasonal fluctuation of air and road temperatures (blue = air, pink = 20 mm below road surface and red = 200 mm below road surface)



Typically for asphalt designs, the design criteria include the average and standard deviation of the yearly 7-day average maximum air temperature and the yearly 1-day minimum air temperature. These are converted to the yearly 7-day average maximum and the yearly 1-day minimum pavement road temperatures using standard data. What is most likely to change in future is the number of extremely hot days per year (taken as those days hotter than 35°C) which are likely to double in many areas of SSA over the next 50 to 80 years (le Roux, 2016).

As there is an international move towards classifying bitumen binders according to the performance-grading (PG) specification, which is essentially temperature based, problems regarding temperature variations will be reduced. The PG classification uses a minimum and maximum temperature range for each binder, e.g., a PG 76-28 bitumen would perform in the range between minus 28°C and plus 76°C. The low temperatures will seldom be encountered in SSA (i.e. with the lowest minimum being about -10°C and the upper temperatures being about 80°C specified: these are generally higher than those normally encountered on most low volume roads in SSA.

Design considerations

Asphalt is normally designed to perform best within a specified temperature range – this includes the expected minima and maxima.

In areas where ***higher temperatures or longer periods of extreme temperatures*** (> 35°C) are expected, bitumen binders with slightly higher softening points or modified binders should be used. This can be ongoing and it is likely that the properties of binders will evolve with their modification by suppliers as ***temperatures increase*** over time. As each road is resealed or overlaid during planned periodic maintenance or structural enhancement interventions, this modification can be included and there is no real need for proactive intervention. Where ***temperatures are expected to decrease***, bitumens with slightly lower softening points may be more desirable to promote their durability and minimise excessive cracking due to higher stiffnesses.

Increased rainfall will require that damage to asphalt surfacings is timeously repaired to ensure that water does not enter the pavement. It may also lead to higher pavement deflections requiring slightly less stiff asphalt layers to minimise possible fatigue cracking.

Some design principles for asphalt, e.g. 7-day average maximum air temperature, will need to be adjusted over time.

5.3.2.3. Concrete surfacings

Description

Roads with a concrete upper layer are probably the most resilient of all "paved" roads towards weather effects (traditional concrete pavements are usually designed to last 30 years), but their use is rather limited in the provision of low volume roads to restricted problem areas, such as very steep gradients, climbing curved areas and in built-up areas without proper (waste) water removal. Concrete is a high strength engineered material that is designed specifically for the situation it will be used in and is resistant to erosion and deformation. Various types of concrete roads can be implemented, including jointed and continuously reinforced concrete and roller-compacted concrete. However, problems related to excessive thermal expansion when movements at both ends of the block are constrained can result in buckling and uplift, especially in the case of thin-layer continuously reinforced concrete (Figure 13). This could be exacerbated if the number of ***consecutive very hot days*** increases.

Figure 13 Lifting of thin continuously reinforced concrete road resulting from thermal expansion

Although concrete pavements are generally more resilient to any climatic effects than bituminous pavements, the potential for underlying layers and edge supports to be eroded remains high under ***extreme events*** and thus could lead to "undermining" and collapse of the concrete pavement. Water is usually only likely to enter and affect concrete roads from the shoulders, unsealed expansion cracks and unrepaired potholes and cracking. Good maintenance at the edges of concrete roads is thus essential.

Design considerations

To avoid buckling of concrete roads under prolonged ***high temperature*** conditions[13] it will be necessary to ensure that appropriate expansion joints are included in the concrete, even in

[13] Albedo can be increased by using white aggregates to reduce solar heat gain. High Albedo Pavement Materials are materials that are light in colour and reflect sunlight away from the surface. With less sunlight absorbed by the pavement, less heat is radiated by the pavement.

continuously reinforced layers. These joints will need to be sufficiently wide to accommodate any potential increased expansion and will have to be fully sealed with a rubberised joint sealing compound to exclude the entry of water. The joint sealing compounds will need to be regularly checked and replaced should they indicate signs of detachment or drying out.

It is of utmost importance that the shoulders alongside concrete roads are kept well shaped by regular maintenance, at or slightly below the concrete surfacing height and are able to efficiently move water away from the concrete slab into the side drains. Any accumulation of water on the shoulder adjacent to the slab will seep into the underlying layers potentially leading to weakening and edge-break of the slab.

5.3.2.4 Other non-bituminous surfacings

Description

Many different types of surfacings consisting of discrete elements (e.g. interlocking blocks, cobble-stones, hand-packed stone, etc.) may be used for low volume roads, especially when labour-based construction techniques are expedient. Nearly all of these include openings between the individual blocks that will allow water to penetrate through the "surfacing" into the underlying support layers. Trafficking of the roads in this condition will inevitably result in deformation of the blocks and failure of the road (Figure 14). The main benefit of this type of construction, however, is that the blocks can be manually removed, the support layers can be strengthened (e.g. with the addition of stronger material or aggregate or even localised chemical stabilisation where appropriate) and the blocks can be replaced.

Figure 14 Damage to hand-packed stone road after flooding

Design considerations

It is recommended that surfacings consisting of discrete elements are not used in areas that are likely to be subjected to flooding or overtopping by rivers resulting from ***increased rainfall or more frequent extreme events***. They can be used in the approach areas but concrete pavements are typically the best alternative in the actual areas likely to be flooded. Rollcrete is a useful form of concrete for such areas. Where discrete element surfacings are used for specific reasons, it is better that they are laid on a strong, well compacted subgrade (CBR > 30%) and a climate-resilient (probably chemically stabilised) subbase. Grouting between the individual elements can be done by using a cement paste for the full depth of the element, but this practice could reduce the load bearing flexibility of the pavement system (i.e. the layer could behave as a weak rigid pavement if not provided with a strong support).

5.3.3. Earthworks

The main earthwork types considered in this Guideline are cuttings and embankments (fills) – conventional formations necessary to raise the road above natural ground level are covered in Sections 5.3.1, 5.3.2 and 5.5. Cuttings are considered as any excavation through in situ soil or rock such that an unsupported slope remains after completion of the excavation. This may occur on one side of the road only (side cutting) or on both sides (box cutting). Landslides are considered as natural events affecting large slopes, but these may be triggered by construction excavations if care is not taken in their design (e.g. undercutting higher slopes, over-steepening of slopes, etc.).

Embankments are designed and constructed from imported material placed to raise the level of the road above the natural ground and expected water levels. They may be constructed on the side of a hill, through a valley, on flat ground to raise the level of the road for drainage purposes or as approaches or abutments to bridges. They can also be associated with inland riverine or coastal estuarine or marine environments. It is important that embankments constructed on sloping ground be carefully designed to ensure that water does not enter the embankment structure. Appropriate cut-off and internal drains must be incorporated into the design.

Other than closures of rural roads because of flood damage, the most common cause of rural road closures is probably slope failures/landslides, either including part of the road or placing material on the road from above (Figure 15), blocking and damaging the road. Closures due to slope instability can be costly and time-consuming to repair.

Figure 15 Road closure due to slope failure. Note deviation on the left created to by-pass the failure

Recent investigations in Nepal[14] have shown that poor road construction, together with high rainfall has led to a marked increase in the number of landslides in various areas. Residents (Himalaya Times, 2016) have indicated that the "haphazard use of heavy equipment for road construction has brought problems; elsewhere; national and community forests are being destroyed for road construction projects". It should be borne in mind that uncontrolled excavation at the toes of high natural slopes and the lack of appropriate surface and sub-surface drainage will inevitably lead to slope instability as discussed in the following sections (Section 5.3.3.1 and Sections 5.7 and 5.8).

It is not the intention of this Guideline to describe in depth the requirements of stability investigations and analyses, but to provide some indicators that will assist the assessors and new

[14] http://blogs.agu.org/landslideblog/2016/07/29/2016-monsoon-1/

designers in determining when specialist geotechnical input is necessary for any slopes. There are also many comprehensive texts available that discuss potential slope instability investigation techniques and countermeasures (Turner and Schuster, 1996; PIARC, 1997).

It is advisable to include, as part of the Asset Management System of all road authorities, at least a basic Slope Management System (SMS) allied with instability susceptibility mapping that identifies the potential for failure and consequences of failure of all slopes within their jurisdiction. High risk slopes on the rural road network can then be prioritised for attention, or at least regular surveillance. This is normally carried out at strategic level for the road network, while actual surveillance activities would be carried out at a tactical or operational level.

It is important to recognise that no economic design is a guarantee against failure and that the likelihood of failure is seldom zero – the risk is only reduced to acceptable engineering standards. It is thus important to estimate the likelihood of failure and the potential consequences in terms of loss of life, accessibility interruptions and overall economic costs.

5.3.3.1. Cuttings

Description

One of the main causes of failures of cuttings (instability) is an ***increase in water level*** within the cut slopes, leading to a decrease in material strength due to excess pore water pressures. Most natural slopes are in a state of equilibrium with the prevailing environment/climate (i.e. they have a factor of safety of close to unity under the existing (and recent historical) worst moisture (and seismic, where appropriate) condition and any disturbance, particularly at the toe of the slope, during road construction will lead to a reduction in this safety factor and a potential for failure when the moisture condition in the slope worsens.

Experience has shown that the antecedent rainfall is probably equally important as new precipitation in initiating slope instability. ***High rainfall after dry periods*** seldom leads to large-scale instability, whereas moderate rainfall after extended wet periods is far more likely to cause major instability (Fourie, 1996).

Different techniques are required for the stability assessment of new road developments and for existing ones and these are discussed separately.

New roads

During the investigation and design of new roads, an assessment of potential slope instability problems is (or should be) made. This involves a review of the topography, geology, soil and rock properties and weathering, surface and groundwater drainage and inspection of existing slopes and past instability history in the area and is best carried out by a geotechnical or engineering geological specialist. Cuttings that are likely to have any significant consequence should they fail need to be designed by geotechnical experts incorporating the necessary stabilisation measures. This would involve an assessment of the potential for failure (either limit equilibrium or probabilistic) requiring inputs such as the likely mode of failure, shear strength and density properties of the soils and rocks involved and likely groundwater and seepage conditions. Carefully designed and conducted site investigations are necessary to obtain the required design information.

For low volume rural roads, cuttings should be limited in depth as far as possible in order to minimise excavation costs, even often at the expense of reduced geometric standards. It is, however, often more cost-effective to handle instability during construction rather than to spend large sums of money on the preliminary investigation and prevention of instability. This, of course, does have implications in terms of contractual arrangements and potential delays and claims.

Particular care must be taken where important structures (e.g. dams, railways or pipelines) or habitations are situated beneath a cutting and any resulting failure could cause large masses of earth or rock to move towards these developments.

To assist in identifying when a geotechnical or slope specialist should be consulted, the decision chart shown in Figure 16 can be used. The effect of the cut being at the foot of a higher slope (Step 2 in Figure 16 and the impact on the adjacent hillside (dipping rock strata) is illustrated in Figure 17.b compared with the smaller volume of material likely to be affected in shallower cuts as shown in Figure 17.a.

Figure 16 Decision chart for design of road cuttings

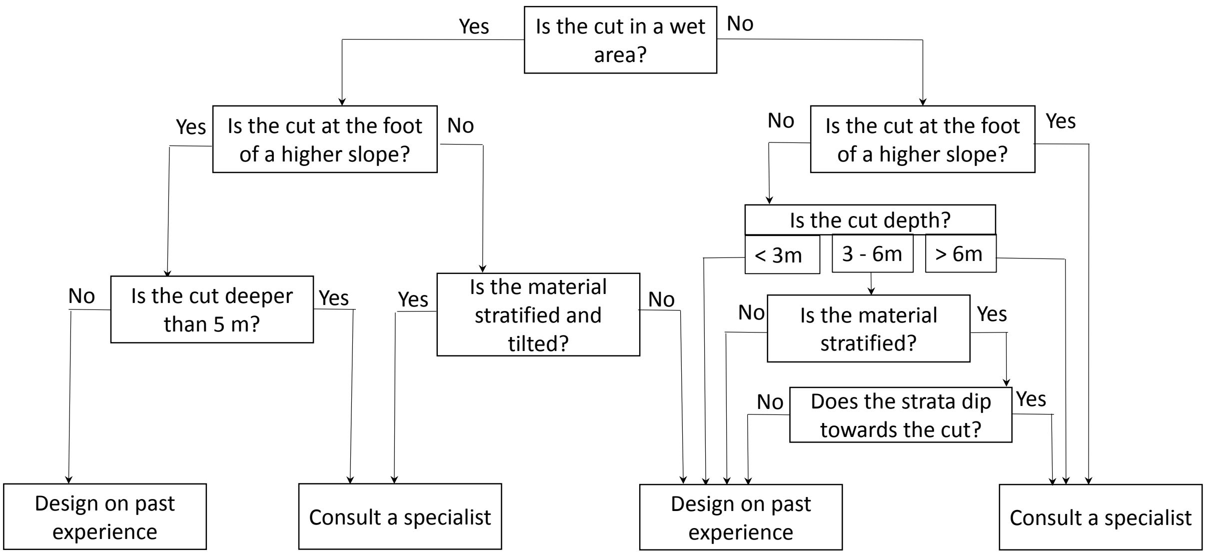
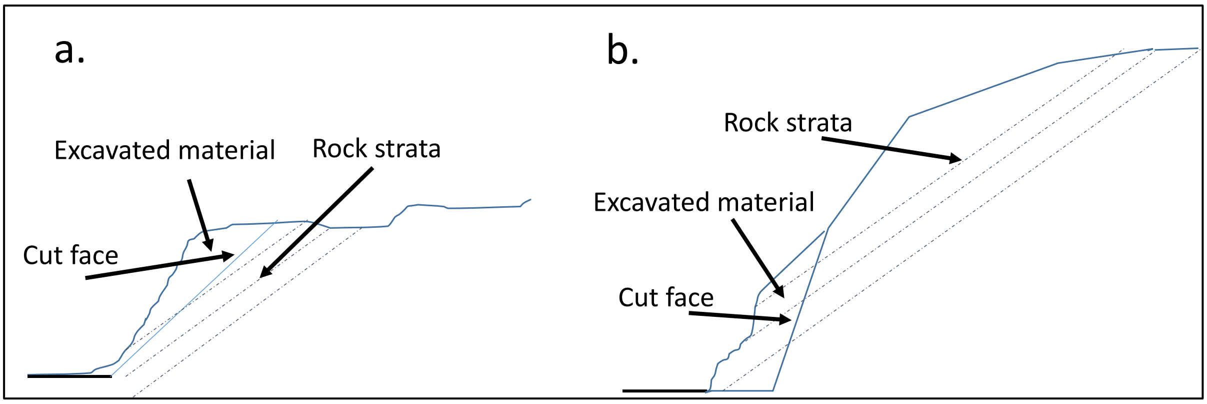


Figure 17 Effect of topography on volume of failed material



Existing roads

An assessment of the stability of existing slopes is necessary to identify those with any significant potential to fail. Standard evaluation procedures such as misshapen trees, deformation of fences, bulging of toes of slopes, seepage of water, the presence of tension cracks, etc. should provide an early indication of potential problems that need further assessment.

One major issue with slopes is the sudden removal of dense vegetation, including trees, from above and behind the slope. Many instances of slope failure have resulted from increased ground-water levels in the slope after the removal of trees, which have literally been able to “evaporate” large volumes of water from the ground prior to their removal. In addition, as the roots of the vegetation die off and decompose, their binding/reinforcement effect on the soil will be lost, effectively reducing the shear strength of the soil.

Increases in the potential for wildfires will also affect the slopes. Apart from the effect of the increased impact of raindrops on the exposed soil after burning, which will lead to easier loosening and removal of soil (erosion) by water, the binding effect on the soil of roots of plants that are destroyed by the fire will be lost, adding to an increased erosion potential.

Design considerations

The adaptation measures for cuts and embankments are very similar. The major differences are that embankments are constructed in a controlled manner from materials with known/controlled properties and drainage, while cuttings retain the nature of the existing geology/soil with variable properties, geological structures and water regimes.

The main influence on the stability of cuts and fills is the effect of water. In areas where ***precipitation is expected*** to increase, instability can also be expected to increase. However, in many areas, precipitation is projected to decrease but the incidence of ***extreme events*** is likely to increase. If the general drying out of slopes occurs, extreme events will have a lesser impact on stability due to the concept of antecedent rainfall. However, if two or more extreme events occur in quick succession, failure of marginally stable slopes is highly probable, but it is not practicable to design all slopes for this eventuality.

There are generally local and international best practices that need to be applied during the design, construction and remediation of cuts and fills that can help to minimise the occurrence of slope instability (e.g. Keller and Sherar, 2003). These cuts and fills are best investigated and designed by geotechnical specialists experienced in the area with its unique micro-climatic and material conditions.

Many slope stabilization techniques are available for increasing the stability of slopes but these are mostly expensive and require sophisticated designs by experienced geotechnical specialists, certainly for higher slopes. For low volume roads, it is more typical to minimise excavations, and use lower cost slope protection techniques, such as carefully-located cut-off drains and small retaining structures (gabion baskets, retaining structures, etc.) to improve stability. On the rare occasion where larger excavations or excavations that remove the toe of high slopes are required for low volume roads, a full geotechnical investigation should be carried out by a geotechnical specialist to ensure the most cost-effective and stable design. Detailed methods for this are discussed in such manuals as Turner and Schuster (1996).

Typically, cuts are designed using a factor of safety (FoS), which indicates that the slopes will be stable under most conditions but could possibly fail during extreme events. A FoS of 1.5 is generally used for most cuts and fills, which usually go through many decades without failing. It would not be viable to apply a blanket increase of the FoS to say 1.7 to account for climate change. The cost of this would be exorbitant and ultimately only a small percentage of the total slopes would benefit from the increased costs.

Areas likely to be prone to instability would normally have a lower class of road in terms of their geometric standards, which would be both cheaper to build and less costly to repair and maintain when slope failures do occur – this should go together with the priority of the road but preferably have less strict horizontal and vertical standards to minimise earthworks and lower design speeds. However, new alignments in mountainous areas are likely to prove particularly troublesome and will usually require geotechnical specialist inputs.

It is possible to install relatively simple early warning systems for potential instability of slopes and embankments – piezometers, extensometers, inclinometers, etc., are all relatively simple, but may be prone to vandalism and theft unless adequate community involvement is included in their installation, monitoring and upkeep. However, if a Slope Management System (SMS) is implemented, usually as part of the overall Asset Management System, potentially unstable slopes can be prioritised for remedial action and stabilization as part of the climate resilience plan. Either integrated in or developed independent of an SMS, the implementation of slope failure incident maps should be considered. By implication, an SMS will include regular inspections of the slopes and thus a reduced probability of catastrophic failures.

In terms of direct climate change effects, under scenarios of ***higher rainfall***, properly designed and graded surface interceptor and cut-off drains behind the crest of slopes are essential to control excessive water. Control of water seeping out of the slopes at their "toes" is also essential and sub-surface drains between the toe of the slope and the road structure will help in controlling seepage beneath the slope into the pavement structures. ***Temperature changes*** may affect the integrity of rock slopes – bigger volumetric changes may occur under higher and more variable temperatures and thus fractures/discontinuities could open more quickly and wider. In most cases, increased aridity will result in improved stability conditions.

The uncontrolled flow of water down slopes can result in significant erosion and it is important to collect as much of the water at the top of the slope and divert it away from the actual exposed slope. This is best done with a "catch-water drain" just behind (within one metre) of the break-point of the slope. It is important that this drain is well graded and removes the water efficiently around the sides of the slope to drains at the toe. Depending on the material type (absorbent and high permeability particularly), it may be necessary to line the catch-water drains with concrete. These linings should, however, be regularly checked for any cracking or deterioration. It must be noted that these "catch-water" drains differ from the interceptor or cut-off drain some distance behind the slope provided to avoid water seeping into the slope material. All drainage measures should be implemented in conjunction with appropriate bio-engineering techniques to both stabilise the slopes and decrease the susceptibility to erosion. Some bio-engineering techniques are summarised in Table 12 (Shrestha et al, 2012).

The role of water in slope stability has recently been clearly shown in areas of California, which experienced one of the worst droughts in living memory in 2016. Significant decreases in landslides and slope instability were reported during this past drought period, even after the occurrence of storms (Bennett et al., 2016).

Table 12 Bio-engineering uses and options (Shresta et al, 2012)

Phenomenon	Erosion problem and condition	Suitable bioengineering techniques
Landslide	Deep-rooted landslide (>3 m depth)	Smoothing to a suitable slope gradient Diversion canals, channel lining, catch drains, waterways Stone pitching and planting of trees, shrubs, and grass slip Bamboo fencing with live poles, planting and seeding grass Terracing and planting with bamboo, trees, shrubs, grass Live peg fence, wild shrubs, live check dams Contour strips planted with grass, shrubs, and pegs Fascines, brush layering, and palisades Planting bamboo with or without a structure Check dams planted with deep-rooted species (e.g., bamboo, trees)
	Slumping	
	Planar sliding	
	Shear failure	
	Cut and fill area at deep and shallow-rooted landslide (<3 m depth)	
	Bare and steep slope or newly exposed surface	
	Cracking zone	Bamboo fencing above zone; zone covered with polythene sheet Catch drain with vegetation Fascines, brush layering, and palisades
	Head scarp of landslide or slope failure	Slope excavated to an appropriate gradient and rounded (when high and steep) and planted with deep-rooted plants (e.g., bamboo, trees) Bamboo fencing, planting grass, seeding, and mulching Fascines, brush layering, and palisades Jute netting or straw mat covering soil, seeds, and compost mixture; turfing Stone pitching; planting of trees, shrubs, and grass slip Planting grass slip and seeding grass
Debris flow	Sediment production zone	As for landslides
	Sediment transportation zone	Series of gabion check dams, retaining wall, and side wall planted with deep-rooted species (e.g., bamboo, trees) Bamboo fencing; grass planting, seeding, and mulching
	Sediment deposition zone	Diversion canal, channel lining, retaining wall, and side wall planted with trees, shrubs, and grasses Plantation of deep-rooted species (e.g., bamboo, trees)
Soil Erosion	Sheet and rill erosion	Planting of bamboo, trees, shrubs, and grass with or without terracing Live peg fence, wild shrubs, and live check dams Contour strips planted with grass, shrubs, trees, and pegs Fascines, brush layering, and palisades with wild and thorny shrub species.
	Gully erosion	Diversion canals, channel lining, catch drains, waterways, cascade retaining wall, and side wall, planted with trees, shrubs, and grasses Bamboo fencing with live pegs Planting of bamboo, trees, with or without check dams Series of retaining walls and plantation Vegetated stone pitching in small gullies and rill beds
	Erosion on bare land, degraded steep sloped land, dry and burnt area	Planting of deep-rooted species (e.g., bamboo, trees) Bamboo and live peg fencing and live check dams Vegetated stone pitching in small sheets and rill beds Stone pitching and planting of trees, shrubs, and grass slip
	Degraded shifting cultivation areas, newly excavated or exposed areas on terrace bund, degraded forest, and grazing land	Bamboo fencing with live poles, planting and seeding grass Planting of bamboo, trees, shrubs, and grass with or without terracing and structure Live peg fencing and live check dams Vegetated stone pitching in small gullies and rill beds Contour strips planted with grass, shrubs, trees, and pegs Planting fascines, brush layering, and palisades
	Water induced degraded land (spring, water source damaged area, canal command area)	Planting of bamboo, trees, shrubs, and grass with or without terracing and structure Stone pitching and planting of trees, shrubs, and grass slip Planting of deep-rooted species (e.g., bamboo, trees) Live peg fences and live check dams Vegetated stone pitching and loose stone masonry walls or check dams
	Cut and filled area or newly exposed area on slope*	Jute netting and straw mats covering soil, seeds, and compost Live peg fences and stone masonry walls Plantation, seeding, and planting grass Live wattling with terracing and seeding

*Exposed slope surfaces must be carefully maintained. A cut and newly exposed slope surface should usually be covered, depending on the type of soil material and other factors.

5.3.3.2. Embankments

Description

The primary types of embankment related to rural access roads are those constructed to raise the road above normal formation level, particularly in flood-prone areas and at approaches to bridges or stream crossing structures.

Embankments deteriorate or fail in one or more of three ways. They can either deform due to differential settlement (consolidation) of the underlying (in situ) materials; they can fail in shear (within the embankment or through weak subgrades) leading to collapse of part of the embankment; or, and perhaps more commonly in the context of rural access roads, by erosion and undercutting of the embankment and road structure during flooding or by uncontrolled runoff water.

Settlement of the embankment under rural roads (usually the result of consolidation of soft, wet subgrade materials beneath the embankment induced by the mass of the embankment materials) is seldom a significant problem, only leading to deformation of the road surface, which can be relatively easily and cheaply repaired. Like cuttings, stability failures usually result from a decrease in strength due to excessive pore water pressures, and normal design precautions should be followed on these cases.

Embankments placed on colluvial (hillwash) materials, even on relatively gentle hillslopes, need particular care in their design. Water often flows through the colluvial materials lying on bedrock beneath the embankment structure due to permeability gradients. To compound matters, colluvium is often poorly consolidated and has high void ratios and low shear strengths. An embankment on colluvial material thus has a strong potential to slide down the hillslope. The control of surface and-near-surface water in these instances is essential.

Major problems have been seen to occur, however, when embankments are overtopped during flooding. Localised turbulent flow on the downslope side can result in severe erosion and eventually collapse of the embankment and road (Figure 18 and Figure 19).

Figure 18 Undercutting and collapse of pavement due to erosion of embankment

Figure 19 Complete loss of embankment and road due to turbulent flow conditions during overtopping and weak subbase

Complete loss of embankments, as in the example shown in Figure 19, will have significant implications from a financial perspective (reinstatement costs) and an economic perspective (impairment of mobility and access), whilst potentially also affecting road user safety if early warning systems are not implemented timeously.

Design considerations

When assessing embankments for adaptation measures, it is important to identify the potential water paths and approach angles (water approaching perpendicularly is easier to control than water approaching at a more acute angle), whether the water will flow over the embankment and the impact of the water on the embankment materials. In areas where erosion of the embankment is likely, the installation of rip-rap protection is necessary or flatter vegetated side-slopes can in many cases prevent damage. However, if the local materials are liable to be easily eroded, the rip rap should be grouted and measures (Figure 120) taken to ensure that the water cannot enter the embankment from above and (especially) behind the erosion protection. It is also necessary to include “weep-holes” that allow water that does inadvertently get behind erosion protection measures to escape without permitting water to enter these holes.

Figure 20 Grouted stone embankment protection of erodible material

Damage of the pavement on embankments is best avoided by constructing a “capillary cut-off” or free-draining layer beneath the structural layers in the pavement above the expected maximum flood level such that water flows through this layer and does not affect the overlying layers – it also avoids the capillary suction of water into the structural layers. This should consist of a permeable layer (100 to 150 mm thick) of coarse sand, gravel or rock at least 150 mm above the expected highest water level and not less than 600 mm below the pavement structural layers.

It has been highlighted that a protection technique that was successful at one site may not necessarily be the optimum solution at other sites (NCHRP 496, 2016). The following technical issues need to be addressed for each situation: hydrologic, hydraulic, geological and geotechnical factors. Issues such as legal and funding aspects and acceptable risk often, however, play a major role in the design decisions.

As embankments associated with drainage structures are subjected to the same conditions as the actual drainage structures, the same hydrologic data must be used to give an estimate of the expected maximum water height, any potential overtopping height if overtopping is likely and the water flow velocities. This will involve the careful selection of return periods considering future extreme events.

The associated geological considerations include the subsurface conditions, topography, water flow paths and channel dimensions, the susceptibility to erosion and deposition of the river surroundings and the basin characteristics. Key geotechnical characteristics include the erodibility and scour potential of the embankment materials, their properties (strength and permeability) and structure (culverts and bridges) and pavement-related considerations.

To avoid damage to embankments the best choice among numerous design options must be made. These include:

- Identifying and quantifying the expected design flood
- Designing for overtopping, particularly in terms of erosion on the down-stream side of the embankment
- Counteracting seepage through the embankment
- Counteracting seepage under the embankment
- Avoiding the erosion effects of wave action where this is likely (e.g. placing rip-rap)
- Considering the effects of softening of the soils by saturation
- Countering lateral sliding of the embankment
- The provision of adequate and well-spaced culverts (cf. Section 5.5)
- Design of moisture resilient pavements on the embankment
- Ensuring embankment stability during rapid drawdown conditions
- Flattening side slopes to reduce flow velocities
- The elimination of low points in the pavement such that turbulent conditions do not occur
- The elimination of trees and termite mounds from embankment slopes that will cause localised turbulence
- High degrees of compaction in embankments and the elimination of cavities caused by termites
- Application of more cohesive materials on and bio-engineering of embankment slopes.

It is clear from the list of options above that the input of an experienced hydrologist to determine the hydrologic inputs is essential. Hydrologists usually make use of return periods and modifications to these for future climatic scenarios will need to be made. Detail in this regard is provided in the Change Management Guidelines. Of particular importance in the hydrological analyses of catchment and potential flooding areas is the estimation of the areas that will be impacted by flooding from regional catchment basins. In many areas, catchment areas of large rivers extend into neighbouring countries, where water-retaining structures (dams and lakes) may be present. These affect the flows of rivers during flooding periods, particularly when the outflow from dams can be controlled by water authorities. As dams fill up, increased outflows are often generated in order to minimise overtopping and relieve stresses on the dam structures. The volumes of such released water and their potential flooding impacts are difficult to model in the catchment analysis but consideration of their impacts is essential.

Materials used for embankment construction must be selected to minimise potential problems. Erodible and dispersive soils must be avoided or encapsulated within the embankment by better quality materials. Expansive clays should also be avoided where possible or should only be used if they can be isolated from large moisture changes by encapsulation. Unfortunately, many expansive soils are usually associated with the underlying rock types (e.g. basic igneous rocks) and often cover large areas making the importation of alternative materials costly. Compaction of such materials to high densities is also difficult giving more reason to avoid them as far as possible.

The stability of embankment structures is generally a function of the side-slope angles, although low shear strengths in the underlying material will lead to failure. Flattening of side-slopes will usually improve stability but requires significantly greater quantities of material and results in a larger footprint of the embankment, which must also include the side drains. This is thus often not possible in steep terrain or in agricultural areas where land-rights may be compromised.

New embankments:

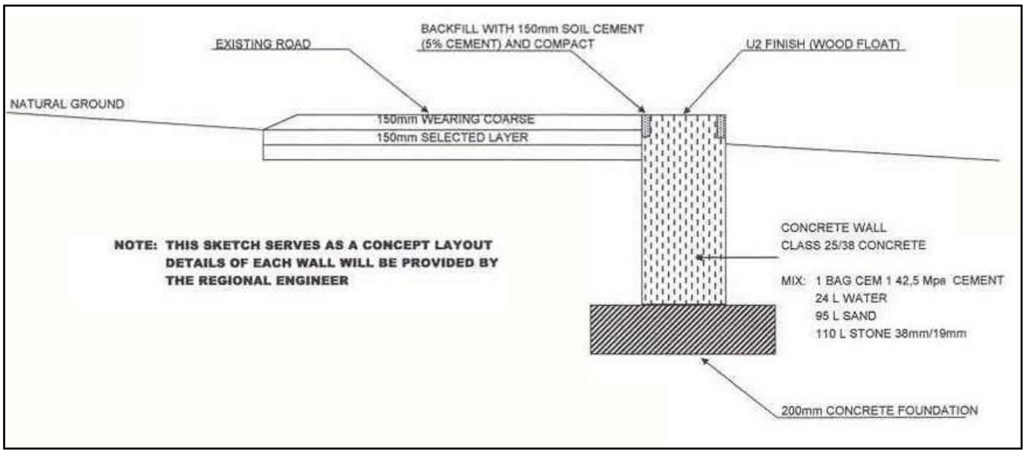
For the construction of a new embankment in a potentially problematic area, the selection of the optimum road location is essential. A comprehensive understanding of site characteristics and constraints, such as geology and soils, geotechnical characteristics, stream hydraulic characteristics, upstream and downstream conditions, construction activities, and storm-water management facilities is needed. This should include the assessment of vulnerability factors for fill slope failure, such as distance from the edge of the slope for a range of failure volumes, to estimating the influence zone for fill slope failure. By identifying and quantifying these issues, an appropriate design can be adopted. Such designs could include relocating the embankment, stabilizing the stream or designing for the possible failure modes.

Existing embankments:

In case of an old problematic site, it is essential to understand the key issues leading to recurring damage. Possible issues include an increase in the ***severity of flooding events*** and the effects of stream instability caused by changes in upstream or downstream conditions (including man-made activities).

In many cases, the use of embankments for lightly trafficked rural access roads should be avoided. It is better to allow the water to run over the road at natural ground water level than to interfere with the flow of the water. This should be associated with as flat and level a vertical profile as possible to minimise areas of concentrated flow of water. The potential for erosion of sandy materials may be increased, but this can be overcome using mass concrete walls on the downstream side of the road and retaining the road as an unpaved one (Figure 21). This will usually eliminate the erosive effects of flood waters and unpaved wearing courses can be easily maintained after the waters subside to restore the riding quality should the need arise.

Figure 21 Mass concrete wall to minimise flood damage in valleys in erodible materials



An alternative to this is to use concrete drifts. These can be complex structures to minimise erosion (Figure 22) or simple structures, possibly combined with the mass concrete walls as shown in Figure 21. It is, however, preferential that they are at the natural ground level to minimise sedimentation on the structure and erosion downstream of the structure due to turbulent flow conditions.

Figure 22 Complex concrete ford with water velocity controllers and stilling pond

5.3.3.3 Erosion

Description

Additional information on erosion to that discussed earlier is included here under earthworks as it is mostly related to impacts on the surface of cuts, embankments and drainage structures, more than actually undercutting embankments due to turbulent water conditions discussed previously. Sloping soil surfaces over which water flows will erode as a function of the velocity of the water flowing on the surface and the erosion resistance (cohesion) of the soil surface.

Some form of vegetation should be used on all roadway slopes that will accept plant growth. Such vegetation should ideally be resilient to anticipated changes in temperature and rainfall. Slopes should also be designed as far as possible to encourage vegetation, usually at batters less than

1V:1.5H. The vegetation helps to reinforce the soil, prevents excess erosion and reduces water impacts, runoff velocities and friction. Local deep-rooted grasses should be used as far as possible but certain vegetation types (e.g. vetiver grass (*chrysopogon zizanioides*), a native to India), is particularly useful and is used internationally. It is a non-invasive, bunchgrass whose roots can penetrate between 2 and 4 m deep and is thus able to bind soil and resist erosion.

Eroded material mostly gets deposited as soon as the runoff velocity reduces and is usually deposited on the road or in the side or cross drains. These all require more frequent cleaning (maintenance) as erosion increases.

Foot and vehicle tracks leading off the road and down slopes result in a loss of grass growth, which soon causes erosion and material loss when rain falls on such areas (Figure 23). Care should be taken in such areas and properly designed accesses should be constructed to minimise erosion problems.

Figure 23 Erosion caused by access of vehicles, pedestrians and animals off the road

A major factor affecting soil erodibility, after the material properties, is the effect of fire. Fire damage causes rain to fall directly onto the soil (loss of vegetation protection on burnt land), leading to loosening of the unprotected soil particles by the impact of raindrops. These loose particles are then more easily washed away (eroded) in water/runoff flowing over the soil (Figure 24). The steeper the grade, the faster the water will flow down the surface and the more serious the loss of material will be. The potential for wild-fires leading to these problems will be significantly increased by ***stronger winds, higher temperatures and drier conditions***.

To protect soil slopes against loss of vegetation by wild-fires, the use of deep-rooted, drought-resistant vegetation should be considered. Also, maintenance teams should ensure that vegetation is kept cut to minimise wildfires adjacent to road pavements.

Figure 24 Loss of unprotected soil in centre of photograph. Burnt area on left is exposed to rain impact and erosion compared with vegetated area on right

In summary, the following protection techniques are commonly used to minimise surface erosion:

- Bioengineering
- Riprap and geosynthetics
- Gabions
- Articulated concrete blocks
- Concrete lining or grouted stone-pitching
- Paving
- Geocells

The location and extent of the protection must be designed dependent on the anticipated flow mechanisms, the types of soil/materials involved, anticipated water quantities, etc. A unique design solution is usually required for each individual case.

It is becoming increasingly popular to combine road embankments with water ponding or harvesting features (road-ponds), where the water can be retained by the road embankment for agricultural purposes or other human needs (AfCAP, 2013). This requires a careful embankment design where the standing water (usually against the embankment slope) does not detrimentally affect the stability or operation of the embankment structure. This can be achieved by incorporating clays (usually bentonite) into the soils on the embankment slopes as a "waterproofing agent". Similarly, there should be no unplanned permeable layers in the embankment that allow the ponded water to pass through the embankment. Other water-harvesting facilities include using the embankment to contain run-off water which can then be led from side, and mitre drains through culverts into small reservoirs or sumps for use by farmers operating adjacent to the roads. Borrow pits used as sources of fill materials can also be shaped to become water reservoirs.

5.4 Subgrade soils

The impact of poor or problem subgrades on roads can be equally or even more important than climate in many cases. However, the combined impact of climate and the subgrade is critical to the performance of road pavements.

It is easier, cheaper, and more feasible to deal with future subgrade problems during the initial construction of a road than as a re-construction option later. There is no possibility of routine subgrade maintenance or repair after construction as it is covered by the upper layers of road material and once constructed cannot be easily accessed for repair or modification without removal of the entire overlying pavement structure.

Raising the road on an embankment helps to promote positive drainage away from the road surface and avoids moisture build-up in the pavement materials. The danger is that a dam effect for water that would otherwise move downstream is created and increased flooding in other areas can result. If the roadway is raised, then the design needs to incorporate more culverts or free draining rockfills underneath the road section that gives the water free movement. The use of embankments for harvesting water in small dams adjacent to the road has been implemented in some areas (discussed in the previous section), but this needs careful design to ensure that the water collected does not have a deleterious effect on the embankment or pavement structure.

The use of capillary cut-offs as discussed under embankments should not be underestimated to assist in overall drainage and drying of embankments, but could interfere with water harvesting operations, if installed.

Various problem subgrade materials are likely to occur and these need to be addressed individually. Problematic subgrade soils, if not timeously identified and appropriate countermeasures taken, can have a significant effect on both pavements and embankments and potentially can be severely affected by climatic changes. These potential problems are all ***moisture related*** and mostly lead to cracking of bituminous seals, increasing the likelihood of water entering the pavement structure and deterioration of the road (with concomitant increased maintenance requirements and costs).

It is important to delineate the subgrade conditions as these will dictate the pavement structure required to carry the design traffic over its design life. Different procedures are required for new roads and roads that are being upgraded from gravel to paved standard. The objective, however, is to understand the underlying materials and to identify any possible problem soils timeously. The mechanisms of problem soils and their identification are summarised in Annex B. Only some of the possible design considerations to make them climate resilient and minimise future problems are included in this section. These should be considered together with methods for their alleviation provided in local design guides.

5.4.1 Expansive Clays

Although the estimation of potential heave is imperative for structures on expansive clay, it is not as critical for subgrades under roads, particularly rural access roads where road roughness requirements are not as stringent as primary mobility roads carrying higher traffic. It is more important to identify the possible existence of the problem and the potential for differential heave along the road and take the necessary precautions. These will generally be based on the expected degree of swell determined from laboratory testing (see Annex B).

If the calculated potential heave exceeds 25 to 50 mm (product of potential heave and thickness of expansive layer) countermeasures should be installed. If there is likely to be significant differential movement because of variable material properties or thicknesses, changing loading conditions or localised drainage differences, the countermeasures will need to take this into account to avoid localised sections of road with poor riding quality. However, reductions in riding quality can be considered acceptable on lightly trafficked roads (< 100 000 ESAs) where expensive countermeasures are probably not justified.

Where culverts or small bridge structures are involved, it is usually necessary to quantify the potential movement more accurately as movements here can lead to cracking of the concrete components. This is best done using oedometer testing of specimens cut from block samples.

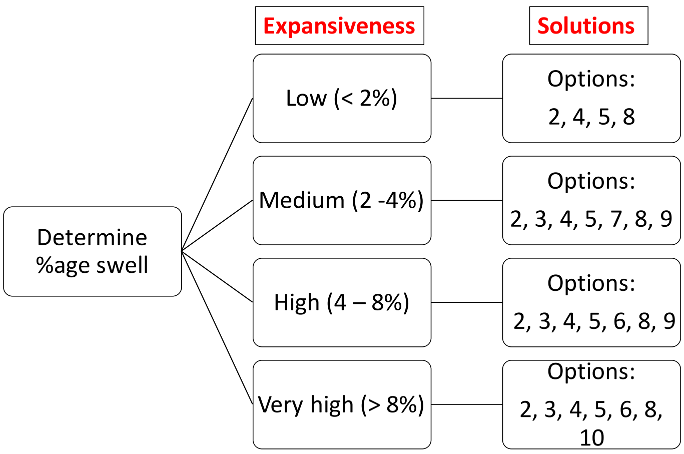
Correct orientation of the block samples is imperative as expansive clays tend to be highly anisotropic with significantly lower swells in the horizontal direction. This testing needs to be carried out in conjunction with good estimates of the potential changes in in situ moisture content from season to season.

Solutions that can be considered for low volume roads over expansive clays include:

- Retain the road over the clay as an unpaved section and keep maintained,
- Flattening of side slopes between 1V:4H and 1V:6H depending on depth of clay)
- Remove expansive soil and replace with inert material,
- Pre-wetting prior to construction of the fill or formation (to OMC),
- Placing of un-compacted pioneer layers of sand, gravel or rockfill over the clay and wetting up, either naturally by precipitation or by irrigation (100 to 500 mm thick depending on thickness of clay and swell potential),
- Lime stabilization of the clay to change its properties (expensive – up to 6% lime may be required),
- The blending of fine sand with the clay to change its activity (optimum blend ratio to be determined by laboratory experimentation,
- Sealing of shoulders (not less than 1m wide).
- The compaction of thin layers of lower plasticity clay over the expansive clay to isolate the underlying active clays from significant moisture changes, and
- Limited success has been achieved using waterproofing membranes and/or vertical moisture barriers, which are generally geosynthetics.

Figure 25 provides a preliminary indication of possible counter-measure options (numbered as above) as a function of potential expansiveness determined as indicated in Annex B. It should be noted that usually a combination of these is most effective and all should go together with careful design and construction of side-drains, which should preferably be sealed.

Figure 25 Possible solutions for roads on active clays related to potential expansiveness



The optimum solution will depend on local conditions and in many cases more than one solution can be used in combination. In many cases, for low volume roads, it may be better to retain the road as a gravel road over the expansive clay sections and apply the necessary maintenance.

One of the most important considerations is to try and minimise the zone of seasonal moisture movement beneath the road (Figure 24) and increase the zone of moisture equilibrium. A combination of slope flattening, material replacement, sealed shoulders and lined side drains as shown in Figure 25 is usually the most cost-effective means of achieving this, but the design of counter-measures needs to be specific to any situation. By minimising the zone of seasonal moisture movement, the effects of ***increased or decreased precipitation, higher temperatures, drying out***, etc. can be almost nullified.

Figure 26 Typical moisture movement regime under roads on expansive clays

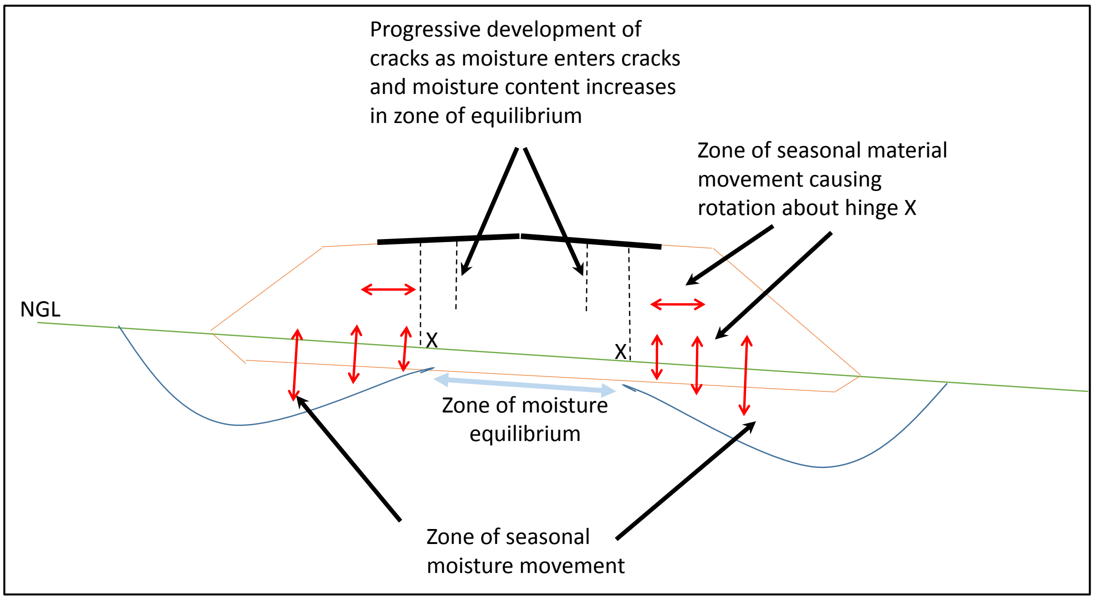
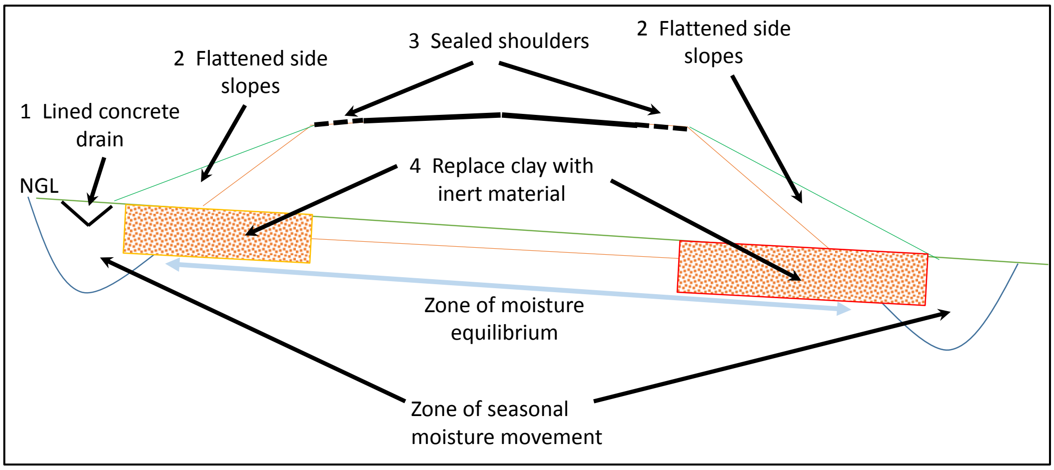


Figure 27 Some countermeasures used to increase zone of moisture equilibrium



Expansive clays are often thick and laterally widespread and this makes the implementation of countermeasures costly. The most successful technique for counteracting subgrades susceptible to high movement is to remove the expansive clay beneath the road structure and replace it with a raft of inert material. This would typically involve the excavation and removal of between 600 and 1 500 mm (or even deeper in some cases) of material over the entire footprint of the road prism (or at least beneath shoulders and side slopes) combined with drainage structures that remove all water from adjacent to the fill slopes and culverts. Removal of material results in the reduction of the swell potential as well as increasing the load on the expansive subgrade with a usually denser, better compacted material. Unfortunately, the large volumes of material required often make this impracticable or uneconomic for low volume roads, unless the problem is localised. Commonly, expansive materials cover a wide area and the importation of substitute material involves the haulage of large quantities of inert material over long distances.

The recommended and probably most economical solution specifically for low volume roads showing high to very high potential swell is to partially remove the clay from the subgrade (300 to 400 mm) and replace it with a less active material, increase the fill height using inactive material to provide a greater load on the clay, seal the shoulders of the road and flatten the fill slopes using the material removed from the subgrade and side drains. This has the effect of moving the zone of seasonal moisture fluctuation away from the pavement structure and inducing movements and cracking in the more flexible fill slopes rather than in the stiffer pavement structure.

Particular attention should be paid to culverts. The clay beneath them must be replaced with an inert material, all joints must be carefully sealed to avoid leakage and inlets and outlets well graded to avoid ponding of water. It is essential, however, that a proper understanding of the potential moisture movements in and around the road is obtained and this is then related to the swell potentials of the various pavement materials (fill, shoulders, subgrade, etc.).

It is also good practice to remove and control the re-establishment of "water loving" trees. The roots of such trees seek water beneath the pavement and remove it from the clay, causing significant settlement of the road during the dry season, which may or may not recover in the wet season. This is usually associated with arcuate and/or longitudinal cracking (Figure 26).

Figure 28 Example of cracking due to dehydration caused by trees next to road leading to subsidence in excess of 150 mm in patched area

Changes in subgrade moisture due to climate change effects (***increased or decreased precipitation, higher temperatures, increased windiness and wild-fires***) will have a significant impact on ground surface movements and associated structures. Increased cracking of pavement structures is likely and the necessary countermeasures against such changes will need to be implemented.

5.4.2 Dispersive soils

The countermeasures for avoiding dispersive soil damage in the road environment are relatively simple:

- Avoid its use in fills as far as possible
- Remove and replace it in the subgrade
- Manage water flows and drainage in the area well

As the presence of sodium as an exchange cation in the clays is the major problem, treatment with lime or gypsum will allow the calcium ions to replace the sodium ions and reduce the problem. The use of gypsum is recommended over lime as lime may lead to soil stabilization with its associated shrinkage and cracking, allowing water to move through the cracks.

It is also important that the material is compacted at 2 to 3 per cent above optimum moisture content to as high a density as possible.

To avoid problems with slaking and erodible soils, the drainage must be well controlled. Covering of the soils with non-erodible materials and careful bio-engineering, assisted by geosynthetics where necessary, is usually effective. Once erosion has occurred, the channels and gullies should be back-filled with less erodible material and the water flows redirected. It is important to note that bio-engineering is not just dealing with re-vegetation but is an engineered combination of biological, mechanical, and ecological concepts, such as anchoring, staking, stone packing and geosynthetics all combined with appropriate vegetation.

Figure 27 shows a section of road more than 50 years old with localised areas requiring regular reconstruction. Highly dispersive soils were used for the embankment in these areas.

Figure 29 Example of recurring distress in embankment due to highly dispersive soil used as the fill material

5.4.3 Saline soils

The following measures should be considered:

- As soluble salt problems arise from the accumulation and crystallization of the salts under the road surfacing and in the upper base layer, minimisation of salts in the pavement layers and subgrade should be attempted.
- If the surfacing is sufficiently impermeable (coefficient of permeability, k in nanometre/ second)/ surfacing thickness, T in mm or $k/T < 30$ $(\mu sec)^{-1}$) to avoid water vapour passing through it, crystallisation will not occur beneath the surfacing.
- Construction should proceed as fast as possible to minimise the migration of salts through the layers. Only impermeable primes should be used, e.g. bitumen emulsions.

- The addition of lime to increase the pH to more than 10 will also suppress the solubility of the more soluble salts.

Even for the lowest classes of road, the effects of excessively saline materials can lead to a rapid and total loss of the bituminous seal and precautions should thus be taken for all road classes. The use of non-bituminous surfacings should be considered over saline materials. Because of the general relationship between aridity and saline material problems, ***decreased precipitation and higher temperatures*** are expected to make soluble salt problems more widespread.

5.4.4 Soft clays

Road embankments built on soft clays need careful control during their construction to avoid stability failures as pore water pressures increase under the applied loads. It is recommended that embankments in these areas are constructed slowly, layer by layer, while monitoring pore water pressures and additional layers are only added once the pore water pressures have dissipated adequately. Despite even these measures, long-term settlement continues and problems are often encountered with large differential settlements between the approach fills founded on the clays and bridges founded on piles. These long-term differential settlements require ongoing maintenance to provide an adequate performance of the road.

The use of the wide range of geosynthetic products as separation layers and to facilitate and accelerate drainage has contributed to improved construction over such areas in the past decade or two, and specialist advice in this respect should be obtained.

Rising sea-levels will cause more deposition of fine alluvial materials in coastal areas and the presence of these soft clays can be expected to increase in thickness in current coastal areas as well as further upstream as the waters rise. **Higher temperatures and drier conditions** could result in significant volume changes in such materials.

5.4.5 Wet areas/high water tables

The treatment of wet areas for roads can be costly if the aim is to reduce the water tables using sub-surface drainage systems. These would seldom be warranted for low volume roads.

The best and most cost-effective measures for low volume roads are to raise the level of the road to at least 750 mm above the natural ground level, with a permeable gravel or rock fill layer (at least 100 to 150 mm thick) on the natural formation (after removal of the topsoil and vegetation). Properly designed and graded side drains should also be constructed to avoid the presence of standing water adjacent to the road.

The installation of sub-soil drainage systems is seldom warranted for low volume roads because of the high cost and the ongoing need to maintain them diligently. However, in cases where they are essential, they should be designed by a drainage/ground-water specialist based on the local water regime and flow-paths.

Changes in precipitation will either improve the situation if precipitation decreases and the areas dry out or the situation will remain similar and the countermeasures described above will still be relevant. Although ***increases in temperature and wind speed*** may reduce the impact of the problem, the fundamental cause of the water problem will not be affected under these scenarios.

5.4.6. Collapsible soils

If potentially collapsible soils are identified, specialist assistance should be used for their treatment underneath paved roads to avoid excessive rutting. In general, a high degree of wet vibratory compaction is required to remove collapse potential. However, as most of these materials are in relatively arid areas, the use of high energy impact compaction (without the addition of scarce water in these areas) has proved to be most effective. Deformation that is likely to affect unpaved roads will be removed during conventional routine grader blading and no significant precautions are necessary.

5.5. Drainage (water from within road reserve)

5.5.1 Description

Water falling directly onto the road carriageway, shoulders and embankment slopes and which ultimately flows into the side drains requires particularly good control. The primary objective is to make sure that this water does not get into the pavement structure, whether it is an unpaved or a paved road. Other requirements are that the water does not accumulate on the surface of unpaved roads (leading to softening and deformation), that the water flows off paved roads so as to minimise the risk of skidding/aquaplaning, movement of the water off the surface does not lead to erosion of the road surface (paved or unpaved) or the shoulders and that the water actually gets into the side drains where it can be effectively removed from the road environment.

Most of these problems are solved by ensuring that the road surface is even with a uniform crossfall towards the shoulders and a slightly larger crossfall on the shoulders towards the shoulder breakpoint if unpaved. Rutting and potholing will interfere with the water flow and increase any potential problems. Similarly, the common practice in SSA of building up the shoulders, usually with either grass or soil, but often both (Figure 28), results in accumulation of water at the edge of the surfacing, which then flows into the shoulder and edges of the pavement structure, often leading to extensive outer wheel-path failures.

Figure 30 Grassed and built-up shoulders negating effectiveness of drainage from road surface

5.5.2 Design considerations

Unpaved roads

To avoid the access of water into the wearing course and underlying layers, the road surface needs a good shape and a pronounced camber, not less than 4-5%. Any depressions (potholes) or unevenness in the surface (both carriageway and shoulders, usually consisting of the same materials) will accumulate water, which will soften the layer and result in enlargement of the depression, at the same time allowing the water to seep into and weaken the underlying layers. Retention of good road shape can only be ensured by regular maintenance, using a motor grader operated by an experienced and competent operator.

On grades steeper than 5 or 6% and cambers or super-elevations steeper than 5%, runoff water causes erosion of most material types, other than good well-compacted granular gravels complying with the specifications outlined in the Section on "Side Drains" below. On grades up to 6%, the camber should be steeper than the grade as far as possible to ensure that precipitation runs off the road laterally into the side drains and not down the grade, where it can gather enough speed to cause significant erosion. Several techniques are available for capturing this water and moving it off the road at the necessary spacings. These include humps, rubber strips or wooden boxes and each needs to be assessed in terms of its suitability.

It is essential that there are well-graded side drains that collect the water and move it alongside the road and into mitre drains or culverts as discussed in the Section on "Side Drains" below. A typical cross section of an unpaved road with adjacent drains is shown in Figure 29. The requirements for h_{min} (height between road crown and invert of side drain) are shown in Table 13 and d_{min} (minimum depth between bottom of wearing course and natural ground level) should not be less than 150 mm. The width of the drains must be such that the water is removed effectively and will depend on the prevailing slopes.

Figure 31 Drainage requirements for unpaved roads

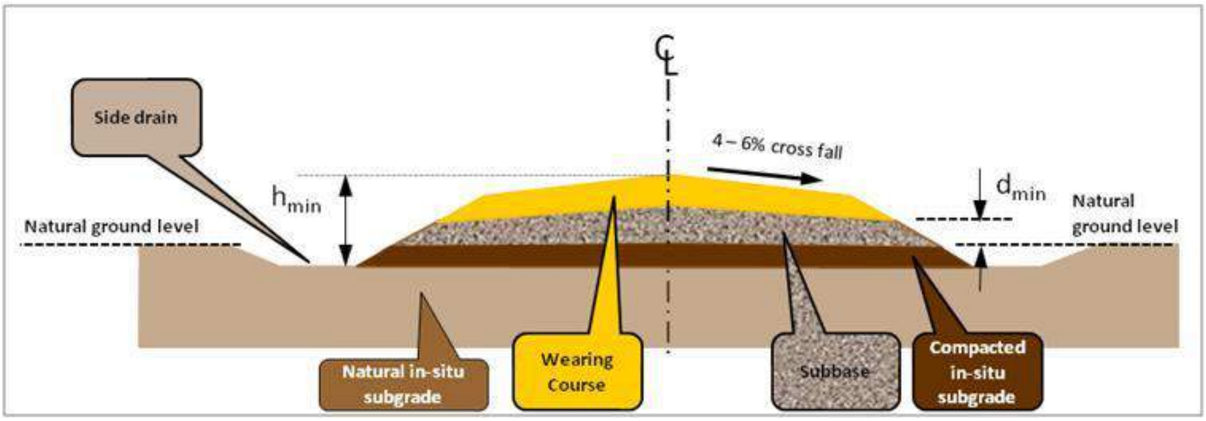


Table 13 Values for h_{min} for unpaved roads

Traffic (mesa)	h_{min} (mm)		
	Rainfall < 600 mm	Rainfall 600 – 850 mm	Rainfall > 850 mm
< 30 000	250	300	350
30 000 – 100 000	350	400	450
> 100 000	450	500	550

Increased precipitation and extreme events are the only significant climate stressors that will affect unpaved road drainage. However, provided that the issues discussed in this section are addressed, climate resilient roads should be possible.

Bituminous paved roads

The access of water into sub-layers in bituminous paved roads usually occurs through unsealed cracks, unpatched potholes and poorly maintained shoulders. Again, only the correct application and management of routine and periodic maintenance, assuming that the original surfacing design was appropriate and the seal was well constructed, will ensure an impermeable surfacing.

Unpaved shoulders on paved roads should be handled in the same manner as a gravel wearing course. As described above, it is essential that road shoulders are slightly lower than the paved surfacing and that they slope away from the road at a suitable camber to remove water without suffering from excessive erosion and are well compacted. Good and frequent maintenance of the shoulders is essential to ensure that they retain their draining capacity.

As for unpaved roads above, ***increased precipitation and extreme events*** are the most significant climate stressors that will affect paved road drainage. However, a lack of routine maintenance of the paved surface under projected ***increased temperatures*** could result in additional cracking that may allow access of water into the pavement.

For paved roads, the drainage design is shown in Figure 30 with a minimum d_{min} of 150 mm and h_{min} depending on the type of drain and the slope as shown in Table 14 with a capacity to satisfy the requirements for the design storm return period.

Figure 32 Drainage requirements for paved roads

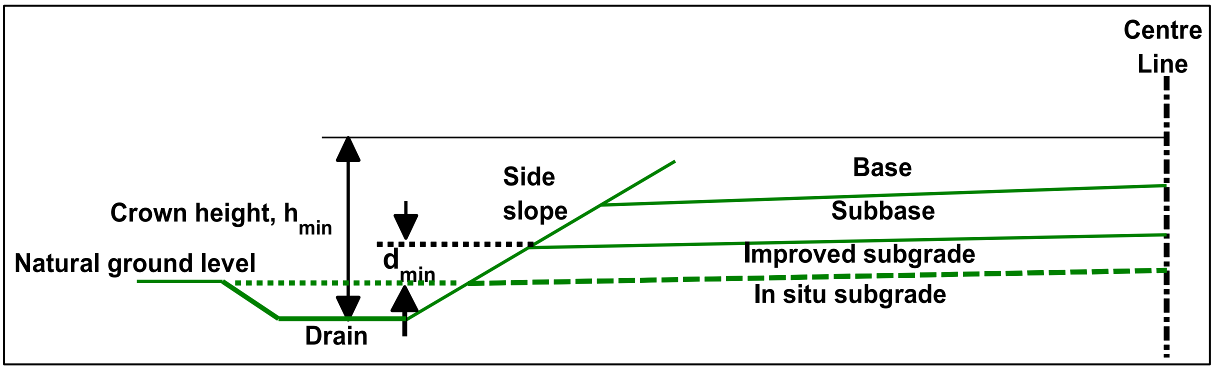


Table 14 Values for h_{min} for paved roads

h_{min} (mm)			
Unlined drains		Lined drains	
Gradient < 1%	Gradient > 1%	Gradient < 1%	Gradient > 1%
750	650	650	500

Side drains

The water from both unpaved and paved road and shoulder surfaces must move into properly shaped and graded side drains along the road as soon as possible. These should allow the water to flow, without any ponding, and be conducted into mitre drains at suitable intervals from where the water can be moved away from the vicinity of the road into adjacent fields and natural water courses. The side drains should be at the base of the formation or embankments, preferably at least 2 m from the breakpoint of the shoulder.

Three main shapes of side drains are used: V-shaped, rectangular or trapezoidal. Those with trapezoidal cross-sections are normally the easiest to maintain and are best constructed and maintained using manual labour. They should be at least 500 mm wide with a minimum longitudinal gradient of 1%. If motor graders are to be used for maintenance, V-shaped drains should be constructed.

The drains should be designed using conventional techniques to limit flow velocities such that erosion/scour does not occur. With the projected ***increases in extreme events*** the capacity of side drains will need to be re-evaluated. Without detailed local knowledge of changes in ***precipitation*** and return periods, it is suggested that existing calculated capacities be increased by 100% to cater for likely increases.

Should scour be unavoidable due to material and topographic constrains, the installation of scour checks or even concrete or mortared stone linings in the drain should be considered. Scour checks should be spaced such that the water in the drains does not build up a high velocity, with typical spacings of about 5 m on steeper gradients (>10%) and about 15 m on gradients less than about 5%.

These can be very simple installations consisting of, for example, a pegged down log (Figure 31) to sophisticated gabion baskets, palisades, grassed water ways, brush layering, bamboo fencing, wattle fencing, and similar measures depending on the situation.

Figure 33 Log scour check

Additionally, by removing the water from the side drains into the mitre drains at regular intervals the water flow volumes and velocities and the potential erosion in the side drains will be reduced. Water should be moved into the mitre drains on the same side of the road as the side drain to reduce the number of culverts along the road. However, in cut areas, it is usually necessary to move the water across to the open side of the cutting periodically for dissipation. Typical spacings of mitre drains depend on the gradient of the side drain and the natural materials in the drain. Suggested intervals based on the main author's experience are provided in Table 15.

Table 15 Suggested intervals of mitre drains as a function of gradient and material cohesion

Side drain gradient (%)	Maximum mitre drain interval in material type (m)	
	Non-cohesive materials	Cohesive materials
12	10	50
10	10	60
8	20	75
6	30	100
4	40	150
2	50	300

Note: At a gradient of less than about 2%, water velocities are low and siltation and grass growth may become a problem. This requires regular maintenance.

Mitre drains should lead off from the side drains at an angle of between 30 and 45° and the side drains should be blocked off to "force" the water to move into the mitre drain. Mitre drains should have a gradient of 2 to 3% and should lead gradually away from the side drains getting progressively shallower and wider. Figure 32 shows a poorly constructed mitre drain that is too short and blocked at the end.

Figure 34 Short mitre drain that is unable to dissipate collected water effectively

In flat terrain, dissipation of the water is often difficult and arrangements should possibly be made with adjacent land-owners to create shallow sumps where the water can accumulate and penetrate the ground slowly or be conserved as temporary sources for irrigation or stock (water harvesting). Mitre drains that stop within 7 or 8 m of the road should be avoided and the end should be below road level, able to dissipate the water collected fast and effectively and preferably discharge water outside the road reserve.

5.6 Drainage (water from outside road reserve)

5.6.1 Description

The water from outside the road reserve is characterised by the precipitation that is collected in catchment areas and moves downslope towards the sea or large dams or can be the result of local flooding of large rivers. This water crosses the roads at strategic points, typically the lowest part of the valley, and usually requires a bridge, large culvert or some other (major) structure to permit the water to flow underneath (or sometimes over) the road. It should be borne in mind that the major catchment areas of large rivers (e.g. Limpopo, Zambezi, Nile, Volta, etc.) may be located outside the country's boundaries – this, together with the presence of large dams that allow river flow to be controlled, could make quantification of river flows very difficult in-country.

The ***expected higher temperatures, higher rainfall, more intense storms and more frequent and larger storms*** could have a devastating effect on the inland bridge and culvert infrastructure. Bridges in coastal areas will also be affected by changes in water salinity resulting from sea-level rise as well as more intense storm surges. These climate change factors will lead to the need to cope with generally more water, more frequent floods, and faster and more destructive water velocities, probably more than the current structures were designed for. Much of the historic data on which hydrological design is based will no longer be valid. Consideration in this regard is discussed later in this section. However, it will be important to:

- identify the most vulnerable structures and increase the 'safety factor' inherent in their designs;
- ensure that the drainage systems are well maintained and functioning correctly; and

- identify critical areas or high priority roads where the consequences of failure and closure are severe. Local realignment, if appropriate, may be required, but this will usually only be considered as part of a repair and rehabilitation project after storm damage has occurred.

Increasing the safety factor includes:

- using drifts and vented drifts that can be safely overtopped instead of culverts or small bridges that can become blocked by debris
- providing additional protection to culverts that might be blocked by debris
- better surface drainage so that water is dispersed off the road more frequently
- reducing water concentration by means of additional cross drains and mitre drains to reduce the volume of water that each one needs to deal with.

Bridges are generally the costliest component of the road infrastructure and require additional protection. Increased intensity of storms will produce more water with higher flow velocities, which the bridge may need to cope with, leading to erosion of abutments (Figure 33) and increasing the potential for damage to the bridge structures through debris in the water. Figure 34 shows an example of the total loss of an embankment and culvert during a severe storm with the final location of the 2 m diameter metal pipe 100 m downstream.

Figure 35 Flood damage to bridge abutment after overtopping of embankment

Figure 36 Damage to steel culvert after storm with total loss of embankment. Photograph on right shows final location of metal pipe

Debris carried by the river during flooding (e.g. large trees) often cause direct damage to bridges or else block the bridge inlets leading to changes in hydraulic capacity and overtopping of the structure.

In 1919, Lewis published a paper in which he stated that "Too much importance must not be attached to the formula (for calculating maximum floods). No formula is likely to be discovered, which will apply to all drainage areas. The maximum flood depends on too many uncertain circumstances, such as intensity of rainfall, size and shape of catchment and channel and permeability of the ground surface". This is still true today, nearly 100 years later, particularly in terms of the changing intensity of the rainfall and changing permeability of the ground surface.

In the design of major structures, the expected maximum flow related to the catchment area of the river/stream is usually used to determine the bridge flow capacity and required openings. The rain falling in the catchment area is determined based on the expected return period of specific storm events usually based on past measurements. It is this return period that is likely to change (i.e. under more severe storm event scenarios the amount of rain falling during a future storm with a return period of 100 years will be more than that currently experienced during a 100-year return period storm) and needs to be modified for future designs. Extreme events after extended dry periods will result in more of the precipitation being "absorbed" by the ground, but high intensity precipitation will also result in rapid flows before the water can soak into the ground, depending on the hydrologic properties of the ground surface.

Research carried out in Ghana (COWI, 2010), as an example, indicated that the present 100-year storm in Ghana, can be expected to occur once every 18 years in the future (2050) based on existing projections for Ghana – more than five times more frequently than a 100-year storm would be expected today.

Water crossings need to be designed with a capacity to handle the expected change in **rainfall intensity** and runoff such as to balance construction costs with the economic and societal costs of not having sufficient drainage capacity and consequently suffering excessive erosion damage or even collapse of larger structures. The high costs of structures relative to overall low volume rural roads costs should certainly dictate the increased use of appropriate fords and drifts that are designed to be "overtopped" for limited periods, without damage to the structures or unnecessarily extended durations of flooding.

Existing bridge structures near the coast will also need to be carefully re-assessed. Sea-level rise will result in new water levels for the rivers/estuaries, reducing the bridge opening and potentially leading to overtopping and damage to bridges during flooding. A marked increase in sedimentation in these areas can be expected, which will, however, reduce the potential for scour of foundations of existing bridges due to the deeper water and sediment.

One of the main potential problems with actual bridge structures is the effect of changes in temperatures on the volumetric characteristics (expansion and contraction) of the bridge components. Differential expansion at different parts of the bridge structure and those parts constantly in shadow will result in increased stresses developing within the bridge components.

The type of bridge has a major impact on the thermal effects. Steel, concrete or wooden structures all have different coefficients of thermal expansion and thus behave differently. Wooden structures are probably the least affected by thermal gradients and seldom require specific thermal design considerations. Thermal effects on steel structures on the other hand can be modelled relatively simply as the coefficients of expansion of the steel are generally known and fairly uniform throughout the structure. Reinforced concrete is a composite material including aggregate, cement paste, sand and steel, all with potentially different thermal characteristics.

The major factors influencing thermal movements in concrete are:

- The nature of the aggregate;
- The moisture content of the hardened concrete;
- The percentage of aggregate in the concrete mix by volume; and
- The amount and distribution of reinforcement in the concrete.

The effects of other factors such as cement type, design strength and age of concrete and curing techniques are less significant. The coefficient of expansion of partially moist concrete is higher than that of completely dry or saturated concrete resulting from the thermal behaviour of cement paste, which has a maximum coefficient at intermediate moisture contents and lower coefficients in the saturated and the completely dry condition. Values for the coefficients of thermal expansion of aggregates range between 3.5 and 12.5 microstrain/°C for temperatures up to 65°C with non-quartzitic materials being the lowest and quartz-rich materials having the highest values (Owens, 2009).

The coefficient of thermal expansion of hardened cement is between 11 and 16 microstrain/°C for “normal air temperatures”, which may not prevail in future. Rocks having an arithmetical average coefficient of expansion in all crystallographic directions greatly differing from this value may be deleterious in concrete (Owens, 2009) due to differential expansion, particularly if the coefficients of thermal expansion are low in relation to those of the concrete. Thus, more care may need to be taken with the aggregate type used for concrete bridge components. Complicating matters, the inclusion of reinforcing steel results in different volumetric movements within the actual concrete members.

The effect of higher temperatures certainly needs to be considered by structural engineers in the design of concrete bridge structures and it may be prudent in fact to increase the use of wooden structures in certain low volume road situations to minimise potential problems. However, they are more susceptible to damage by wild-fires. Additionally, higher temperatures (and stronger ultra-violet radiation) will have a significant impact on the durability of rubber-based expansion joints in concrete bridges, which will deteriorate more rapidly and require more frequent maintenance and replacement.

It should be emphasised that roadway embankments are not normally designed as flood control structures, although in certain areas they could well be. There are also significant differences between riverine and coastal flood and erosion mechanisms, which impact on the most effective way of minimising road embankment damage due to flooding. Common failure mechanisms of road embankments are overtopping, seepage, piping, wave erosion, lowering of material strength by soaking and lateral sliding over the foundation soil. There is a wide variety of adaptation techniques and countermeasures that cannot be comprehensively covered in a Guideline of this nature and reference to, for instance, NCHRP Synthesis 496 (2016) should be made for such measures.

Bridges are usually designed by specialist structural engineers, most of whom should be aware of impending climate changes that are likely to affect bridges during their design life, and should take such considerations into account. The design of future bridges will require that the structural/bridge engineer is fully aware of the projected change in climate in the catchment area of the river/stream that the bridge will span, as well as the impact of changes in precipitation in regional catchment areas. Expected temperature and windiness changes as well as the number of hot days will all need to be considered in the design.

An important issue affecting bridge structures is undermining or loss of support of piers due to water scour (Figure 35). All rivers undergo natural scour, but the construction of piers and abutments of bridges changes the flow characteristics of the river flow (direction, velocity ad increased turbulence) leading to additional scour adjacent to the new structures. This effect depends on the characteristics of the river channel configuration as well as the volume and velocity of the water. With the expected increases in storm intensities, such damage is likely to increase and the designs will need to incorporate additional scour and erosion protection measures. Numerous techniques for predicting and handling scour are available (TRL, 2000) but will need to be modified to take into account future climate changes. In general, the shape of piers should be designed to reduce turbulence up- and down-stream from them.

Figure 37 Subsidence of bridge deck due to scour damage of support pier

Scour around footing foundations is generally limited (Figure 36) but the footings should be designed or protected to avoid such problems.

Figure 38 Localised scour around bridge pier footing

The need for protection of the soil surrounding culverts from erosion must also not be underestimated. It is essential that adequate head and wing-walls are provided. Examples are frequently seen where the wing walls “separate” from the head wall allowing water behind the wing-wall and eventually leading to erosion and collapse (Figure 37).

Figure 39 Separation of wing-walls from headwall on relatively new culvert

Ensuring that the drainage system is working correctly is essentially a maintenance issue although there will be examples of poorly designed culverts with improper alignment or grade relative to the channels and ditch lines that will need to be repaired or replaced, usually after failures have occurred.

It is important that the road does not reduce floodable areas significantly, or else the potential larger volumes of water would be constricted to narrower flow-paths resulting in higher peak flow velocities and more potential for erosion.

5.6.2 Design considerations

There are many guidelines and codes available for the design and construction of larger structures using concrete and steel, such as Overseas Road Note 9 (TRL, 2000). However, little guidance is generally available concerning small structures. In this respect, the guideline document *Small Structures for Rural Roads: A Practical Planning, Design, Construction & Maintenance Guide* (Larcher et al, 2010) provides comprehensive information to assist engineers and technicians in the planning and provision of small road structures.

Bridges

Various issues regarding bridge design need to be considered as bridges will normally be designed to last between 50 and 100 years (or more for bigger structures). Apart from the loadings that bridges are designed to carry, they need to be designed to handle the expected volume of water that will flow through them during peak flooding as well as other potential issues described below:

Maximum water flows

Maximum water flows can be calculated using various standard techniques which are not described in detail here. However, these make use of return periods, which are probabilistic determinations of the frequency of the calculated peak flows for different storm intensities. The predominant changes to conventional design methods for bridges will be in terms of the return periods. These will need to be updated on a regular basis using the latest projections of expected ***rainfall***, determined from local climate modelling[15]. In the absence of such revised return periods it is also possible to use actual worst case scenarios based on specific rainstorm intensities, but these will normally result in more conservative and costly designs.

The water flow quantities and velocities are also based on various surface characteristics (e.g. soil type and exposure, vegetation cover, etc.). With climate change, these too are likely to change with time and issues such as this will also need to be considered in the calculation of river flows. Changes in vegetation because of ***temperature or precipitation changes*** are also likely to affect the type of debris transported by the rivers (increased or decreased trees, bigger or smaller trees, larger boulders, etc.) and this should also be considered in the design.

To cater for the potential increased water flows, bridge decks will need to be higher, spans may be longer and earthwork volumes in approach fills will be significantly increased (possibly with better quality materials), with inevitable large increases in the costs of the structures.

Abutments

The materials behind bridge abutments must be as resistant to erosion as possible and compacted to as high a density as possible to avoid damage during flooding. They should also be protected from water flows by raising wing-walls, applying mortared rip-rap or other erosion protection methods (gabion baskets or Reno mattresses) and minimising turbulent flow around them. Numerous techniques for protecting abutments from erosion and scour are included in NCHRP Report 587 (Barkdoll et al, 2007) and the optimum choice will depend on the local situation and materials available.

Piers

Piers are primarily damaged by scouring of their foundations. Scouring is a function of turbulent flow upstream, downstream and surrounding the foundations. This is best reduced by ensuring the optimum shape of the piers and founding the supports on material unlikely to be scoured. The depth and extent of scouring can be estimated from various models (e.g. TRL, 2000) and this, together with the type of foundation and substrate material should be used to optimise the design. The stream-bed characteristics will usually have the most influence on the type of foundation, which will have an effect on the scour potential as well as being affected by the induced scour. If the stream-bed has only thin alluvial material deposits, footings directly on the bedrock or other competent layers can be used. If the stream-bed has thick deposits of fine material, piles are normally used. These can be either end-bearing piles if the bedrock or other hard layers are not too deep, or friction piles where excessive deposits of fine materials occur. Friction piles should be designed to ensure that should

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[15] Intensity, duration and frequency (IDF) tables with climate change allowances, with some regional variations in allowances to expected climate change, should ideally be centrally developed by national agencies and kept under review (e.g. EA, 2016 and ADB, 2018).

scouring occur, the length of the unexposed pile is still adequate to provide the necessary frictional support.

Structures

The effects of increased temperatures and larger seasonal and diurnal changes on bridge structures and their components will need to be considered during their structural design. These are normal design considerations but should be given a little more thought to handle expected conditions in 50 or 100 years' time. Increased expansion of the materials will require larger expansion joints, which in turn will require better waterproofing and sealing materials, as well as increased maintenance to ensure their continued serviceability. The wider use of monolithic structures that avoid or minimise bearings and expansion joints could also be considered.

A challenge with bridge expansion joints is that they are a flexible component and require a high amount of maintenance. Some types of joints are themselves an entrance point for water which can leak onto substructure elements and accelerate deterioration. The amount of expansion in the bridge depends on the actual structure type, temperature changes, the length of bridge, and the type of material used (reinforced concrete, steel girder, etc.).

Most countries have "bridge design codes" and these will need to be continually updated incorporating features that will make bridges more climate resilient.

Culverts[16]

It is essential that culverts are aligned carefully along the road, preferably perpendicular to steams and drainage paths crossing the road. Where moving water must change direction suddenly, the potential for severe erosion is rapidly increased. Similarly, the protective measures around the culvert should be such that erosion of the adjacent formation or embankment is minimised during normal water flow events. It is not usually economically possible to protect long distances of embankment from erosion, other than to ensure that the embankment is covered with a good deep-rooted local grass, which is kept well maintained.

The capacity of the culverts, like bridges, should be designed to move the expected water through them without causing any damming upstream. Examples have been observed, for instance, where a railway line running parallel to and slightly uphill of a road had several culverts each consisting of 3 one-metre square boxes. The parallel road had culverts in the same locations downhill of the railway culverts but these consisted of only one 600 mm pipe – the capacity was thus obviously inadequate and damage would be expected to occur to the road embankment during heavy rainstorms.

Where overtopping of the culvert is likely, low points should be eliminated and the road should be as flat as possible to avoid localised turbulent flow over the embankment. The downstream slope of the embankment over the length of potential overtopping should also be flattened to reduce water velocities and minimise erosion and undercutting.

In large catchment areas, the use of upstream flood-control dams and structures (usually in cooperation with other national agencies) should be considered to try and minimise the effects of storms where doubt exists in the calculation of the flow volumes. This could be considered as part of water harvesting operations.

5.7 Construction

Several climatic change factors could impact on the construction of future road and bridge infrastructure, some negatively and others positively.

During the projected extended ***dry periods*** in some areas (also being ***hotter***), the availability of construction water may be limited for longer periods and longer haulage distances may be

[16] See also ADB, 2018.

necessary. The cost of the water is also expected to rise as construction competes with other uses for its limited availability. Simultaneously, the water applied to the layers during these periods for compaction will evaporate much quicker and greater quantities of water will be required for construction.

Where stabilization of materials is used on a wide scale (e.g. the sands of central Mozambique), the working time of the stabilization (i.e. from the addition of water until the time of final compaction and trimming) will be significantly reduced under higher working temperatures.

The rates of other chemical reactions affecting stabilisation and mineral degradation may also be increased under high temperatures. A possible benefit, however, of higher temperatures may be longer windows for bituminous paving through the year, i.e. shorter cold periods).

Adaptation

In terms of construction, differentiation should be made between existing infrastructure, which cannot be changed overnight, and infrastructure that needs to be constructed anew. In the case of the latter, ample opportunity would be available to introduce more climate resilient road infrastructure solutions.

In the case of existing infrastructure, the outcomes of a risk analysis would dictate which actions would require immediate attention (e.g. retrofitting of drainage systems). Adaptation actions could be phased in over time (e.g. during scheduled maintenance or rehabilitation/upgrading) depending on the priorities.

Climate change could require some adjustments in construction processes. ***Drought conditions***, for instance, are likely to lead to greater shortages of water, which will drive up the cost of water and simultaneously the cost of construction projects, unless surfactants (compaction aids) are added to the construction water and/or compaction methods are adapted to cater for this water scarcity (e.g. high-energy impact compaction).

As well as affecting availability of resources for road construction (and also maintenance), climate change could also affect the window of safe working and productivity of outdoor workforces, requiring adjustments in operations. In the case of extreme heat, for instance, construction operations could be moved to night time to reduce the risk for heat stress.[17]

In future, construction seasons may shorten or lengthen, and could shift earlier or later within the year. These changes are unknowns at this stage, and will differ from country to country, but relevant ministries or road departments should be made aware of this possibility, record changes to the status quo and plan accordingly.

To minimise problems with climatic changes on roads it is essential that construction at least complies with the minimum requirements in the recommended standard specifications, if not exceeds them. In some cases, it may be necessary to modify or adapt local specifications to take the various potential climate changes into account, and these may be country or even district specific as appropriate. For example, compaction (of subgrades, formations, embankments, abutments and pavement layers) to higher densities than those currently specified immediately increases the stiffness, reduces permeability and erosion potential and reduces voids and rutting potential. Compaction is one of the cheapest construction activities and should not be skimped on. The incorporation of improved durability requirements for base materials may be necessary where groundwater or local sea-level rises are expected.

The loss of water during construction on hot and dry days can be minimised by constructing at night as well as by using recycling equipment for the addition of water. If these options are not feasible, quicker delivery of greater quantities of water (more water bowsers on site) and decreased

[17] See also: Kjellstrom, et a. (2009); Dunne et al. (2013) and Vivid Economics Ltd (2017).

construction processing time (construction of shorter lengths, additional rollers and graders, etc.) will be necessary. Investigations into methods for making use of poorer quality waters (e.g. sea-water, brackish borehole water, recycled effluent, etc.) should be initiated to alleviate these problems.

Various other construction practices will need to be modified to cater for climate change. With cement stabilisation for instance, it may be necessary to construct shorter sections at a time, to use alternative slower reacting cements for stabilization (CEM IV and CEM V) or even blends of lime and fly ash. The choice of stabiliser type (e.g. cement grade) will become important to allow maximum working time. The use of in situ recyclers to mix the stabiliser and decrease the construction time should also be considered. Their high cost may be justified by the potential reduction in construction problems, often encountered with modern cements. The breaking times of bitumen emulsions will be much quicker on hot days, which would also require modification of standard construction techniques.

There is nothing that can be done about more rapid deterioration of non-durable materials in the road structures under higher temperatures (e.g. use of low-viscosity binders in asphalt) – it will be necessary to make sure that all materials used are acceptably durable, although few examples of failures due to material deterioration or pure durability have been observed in low volume roads. On the contrary, durability is seldom a specification requirement for low volume road materials.

When large concrete members are being constructed during hot weather, precautions should be taken to limit any significant heat build-up in the concrete. If final set occurs when the concrete is in an expanded condition due to high temperatures, additional "thermal" shrinkage may result in a large potential overall shrinkage of the member. Similarly, the risk of early age plastic shrinkage cracks or thermal cracking due to temperature gradients may define the requirements for curing and protection of the concrete. Furthermore, increase temperatures mean increased evapotranspiration, therefore the concrete skin should be protected properly against evaporation until a certain maturity or strength is obtained to ensure sufficient strength and durability. Methods and tools to help the concrete producer plan and predict the hardening process of a concrete structure under various and changing ambient conditions will need to be improved. As a minimum, the concrete producer should consult local weather forecasts to obtain temperature data. Increased temperatures may also require the placement of mass concrete for structures and pavements at night. Note that *improved local weather forecasts* is an example of a low regret adaptation tool.

5.8 Maintenance

5.8.1 Description

Maintenance is a fundamental area that will certainly need to be addressed. Road maintenance should not be seen or evaluated as an adaptation measure - maintenance is not related to climate change but has always been necessary irrespective of the climatic conditions. The techniques are unlikely to change significantly: however, the frequency and types of maintenance will need to be adapted to changes in climate, especially extreme weather events and higher temperatures.

Particular attention will need to be paid to mowing of any more luxuriant grass growth, more frequent trimming of shrubs and bushes in the road reserve and drains (to minimise fire risks and obscuring sign boards), cleaning of roads, (particularly of flood debris and wind-blown sand), **cleaning and maintenance of drainage systems**, removal of storm damage, etc. Recently, damage to guardrails and bituminous surfacings caused by wild-fires has been observed, for the first time ever in some areas (Figure 38).

Figure 40 Damage to guardrail posts and bitumen surfacing caused by wildfire

Based on interviews held with road authorities across Africa, it has been identified that about one-third of road expenditure in many African countries is on maintenance. Based on international best-practice, about half of road expenditure should be on maintenance and the other half on new road investment. It is thus clear **that current maintenance expenditure is inadequate** and the need for additional maintenance expenditure to cope with possible climate changes is going to be inevitable in most areas.

5.8.2 Adaptation

It has been suggested that the optimal measure to adapt to climate change will be to maintain the roads so that they are always in as near to perfect condition as possible in which case their resilience to climate impact is at all times at a maximum (COWI, 2010). This is, however, usually easier said than done, mostly because of funding, skills and resource challenges. However, good and regular maintenance is a fundamental requirement for climate resilience.

The establishment of a comprehensive road database with regular visual condition assessments of all of the conventional attributes (e.g. surfacing condition, pavement condition including cracking, rutting, potholes, patching, deformation, etc. and riding quality) will be crucial to effective maintenance strategies[18]. This will allow the monitoring of changing road condition and consequent maintenance requirements over time, which can be continuously related to changing climatic conditions and can be used to identify changing trends and budget needs. However, this is based on the assumption that information on evolving road and climate conditions will be kept up to date. Issues such as cracking of paved roads, edge-break and potholes will be identified during visual condition surveys and such distress needs to be rectified before rainfall is experienced to avoid large-scale damage to paved roads.

Drainage maintenance in particular will be critical. There is a strong possibility that, due to extended periods of drought that are projected, drainage maintenance may be reduced or neglected. However, within these drought periods, the potential for more intense and severe storms will be

[18] AfCAP is currently funding a research and capacity building project on asset management for rural roads

much higher and the consequent damage to the infrastructure could be devastating if the drainage maintenance has been neglected and is poor. It will be important to ensure that all side, mitre and cross-drains are clean, well graded and effective at all times.

In areas where drier (and windier) conditions are expected, the approach to vegetation control on formation, embankment and cut slopes will need to be such that it is regularly cleared by cutting to minimise the potential for uncontrolled burning during wild-fires. In specific areas, the actual grasses planted will need to be selected to provide a mix of deeper rooted grasses as well as surface (or rhizomous) grasses to both protect the surface from erosion, the roots from severe fire damage and to provide some soil stabilization effects. The grasses will need to be appropriate for the area (local and drought resistant where necessary) and planted on flattened slopes where appropriate to assist their growth, bearing in mind that it is usually difficult to establish vegetation on slopes steeper than about 1:1. It may also be necessary to change the species in areas as climatic changes occur in order to encourage more drought resistant plants, for instance.

The maintenance personnel will need to be more carefully trained in the actual maintenance techniques and operations so as to ensure that they are carried out competently and effectively, ensuring a full understanding of the reasons for doing various activities and the implications of these not being done properly.

It is also important that the correct balance between equipment and labour-based maintenance is achieved. Certain operations cannot be effectively done using manual maintenance techniques and it is essential, for instance, that a motor grader is used periodically to restore shape to an unpaved road – the removal of ruts and depressions on unpaved roads cannot be done effectively using labour, for instance.

Where labour-based maintenance is likely to be efficient and effective, community-based maintenance systems should be instituted. This usually results in increased ownership of the facilities as well as the motivation, experience and resources to carry out quick and effective repairs as required, but particularly following immediately after an extreme (shock) event.

Optimising maintenance for climate resilience is similar to normal maintenance programmes in requiring a number of inputs and phases as follows:

- Develop a database for road maintenance, alongside an up to date database of relevant (changing) climate variables
- Prioritise maintenance and drainage upgrades in areas that are most at risk of flooding
- Increase the frequency of drainage maintenance that is discussed in the manuals in relationship to the increased frequency of large storms
- Repair and clean channel and drainage structures in high-risk areas before the rainy season, although the timing of this is likely to become less predictable in future
- Allocate more funds for maintenance of the current roads.

Climate resilient maintenance procedures and day-to-day actions should be developed in manuals specific to the environment and the expected changes in environmental conditions within a district or region.

One aspect of maintenance that must not be underestimated is that of **emergency repairs** following intense storms or flooding. It is inevitable that damage to roads and bridges will occur periodically, and systems and procedures should be in place to facilitate rapid deployment of resources to restore mobility and access following such events. Normal procurement processes are inappropriate in such cases and appropriate resources must be available at short notice. Innovative techniques for the temporary restoration of structural damage should be developed and supplies of the appropriate resources kept on standby. Contingency funds are needed to support these rapid reaction measures.

In line with the above, operational response to climate extremes will have to be actioned by relevant road authorities, where warranted and feasible. This will include emergency teams being on standby and informed by high-quality local weather forecasts to impose access restrictions on certain roads, clear debris on roads, divert traffic to alternative roads (if feasible), and implement actions to restore accessibility. In addition to the above, communication should be in place to inform communities on impaired road links and associated actions to restore accessibility.

5.9 Other issues

Other issues should not be underestimated in the effects of climate change. These are mostly related to increased temperatures.

An example has been noted where the expansion of metal guard-rails has affected the rails. Where the anchorages were loosely tightened to allow movement, such movement occurred with no deformation of the rails or supports (Figure 39.a). Where the rails were tightly bolted to the support (wooden in this case), they had been disrupted and some deformation of the guard rails and anchor points was noted (Figure 39.b).

Figure 41 Effect of expansion of metal guard rails: a) loosely tightened and b) tightened so as to avoid thermal movements and cause deformation (daily movement visible in left photograph)

A similar issue related to sustained higher temperature conditions is the impact of road markings. Most rural low volume access roads do not have markings (centre-lines, etc.), but where they are found, particularly on asphalt, they are often associated with significant cracking around them. This is an effect of the differential temperatures between the heat absorbing dark asphalt and the heat reflecting white road paint and the consequent differential expansion. Such cracking would require regular maintenance (crack sealing).

5.10 Summary

The potential *adaptation* measures for each climate variable and *engineering* issue are summarised in the following tables (Table 16 to Table 22). It should be noted that many of these are generic solutions and innovations and particular solutions based on local knowledge, recent experience and proprietary products available in the area should be considered where cost-effective. As the main objective is to make the facility as climate resilient as possible for the minimum cost, it is essential that simple, cheap measures are assessed initially for their suitability and practicality. If these are eliminated on the basis of being unsuitable, more costly measures must be considered. However, experience has shown that simple techniques can be highly cost-effective.

Table 16 Hazards and adaptations related to increased precipitation

Facility	Consequence - Possible Problems and Damage	Proposed Preventive Measures Suggested Remedies
Un-engineered earth roads	Flooding (excessive surface water) Softening of material More frequent impassability on poor materials Erosion of surface Loss of shape of road Blockage (siltation) of drains	Upgrade to engineered earth road standard Raise level
Engineered earth roads	Flooding (excessive surface water) Softening of material Impassability Erosion of surface Loss of shape Blockage of drains	Improve construction processes Improve drainage Upgrade to gravel road (raise riding surface and improve drainage).
Gravel roads	Softening of material Erosion of surface Loss of shape Blockage of drains	Improved material selection Improved construction Improved maintenance
Paved roads	Loss of strength of layer materials Damage to thin surfacings Damage to pavement edges Blockage of drains and culverts Erosion of unpaved shoulders	Raise road level Use appropriate structural designs and surfacings Ensure high quality construction Use appropriate surfacings Increase culvert numbers and cross-drains and invert grades Good maintenance (especially of surface cracking and potholes)
Earthworks	Increased slope instability Saturation and weakening of soils Erosion of surface and drains Undercutting Excessive vegetation growth Siltation and blocking of drains	Higher compaction efforts Good drainage (surface and sub-surface) Good design (higher factors of safety) More slope stabilization measures Increased maintenance Bio-engineering techniques to stabilize slopes. Good maintenance
Subgrade soils	Expansion and cracking Collapse and settlement Softening of support More movement of saltine materials Deformation of rigid structures Erosion in road reserve Increased likelihood of sinkholes	Correct identification of problem subgrades Correct remedial actions for problems Avoidance or appropriate treatment of problem subgrades Good design Good drainage
Drainage (water from within road reserve)	Accumulation of water adjacent to road Erosion of road surface and drains Softening of materials beneath road Weakening of unpaved shoulders More outer wheel track failures	Good drainage design and construction Use of better quality materials Regular, high quality maintenance

Facility	Consequence - Possible Problems and Damage	Proposed Preventive Measures Suggested Remedies
Drainage (water from outside road reserve)	Erosion of embankments and abutments of culverts and bridges Silting/sedimentation of culverts and bridges Scour of bridge foundations Overtopping of bridges Damage to bridges by debris	Modify return periods in design or use expected extreme rainfall Increase culvert and bridge openings Good design including potential for overtopping (embankments and drifts at natural ground level Good maintenance Design to minimise effects of debris (removal or upstream barriers/traps) Use of flood-control dams
Construction	Excessive moisture in materials – construction delays Reduced working periods and increased delays Water damage to partially completed works More coffer dams during construction	Difficult to mitigate against Construct in dry season Greater use of unslaked lime Improved construction programming informed by weather forecasts
Maintenance	Additional maintenance necessary More bush clearing Additional damage to drains Need to retain good shape of unpaved road surfaces Improved unpaved shoulder maintenance Pothole patching and crack sealing of paved roads	Adequate resources and systems in place, aligned with weather forecasts Local community maintenance programmes Good training of maintenance inspectors and teams More regular maintenance Good quality maintenance

Table 17 Hazards and adaptations related to decreased precipitation (but more extreme events)

Facility	Consequence - Possible Problems and Damage	Proposed Preventive Measures Suggested Remedies
Un-engineered earth roads	Increased wear and loss of gravel from drier surface Increased dust emissions over longer periods Increased development of loose material and roughness (corrugations) More rapid deterioration of gravel due to loss of cohesive fines	Compact material better Upgrade to engineered standard
Engineered earth roads	Increased wear and loss of gravel from drier surface Increased dust emissions over longer periods Increased development of loose material and roughness (corrugations) More rapid deterioration of gravel due to loss of cohesive fines	Improve construction processes Increase compaction Increase maintenance Upgrade to gravel or paved standard
Gravel roads	Increased development of roughness (corrugation) Increased material losses Longer dust period	Improved material selection Improved construction Improved maintenance Upgrade to paved standard

Facility	Consequence - Possible Problems and Damage	Proposed Preventive Measures Suggested Remedies
Paved roads	Damage to thin surfacings and asphalt More rapid binder deterioration Reduced equilibrium moisture contents – stronger pavements	Use appropriate structural designs Ensure high quality construction Use appropriate surfacings and binders Good maintenance
Earthworks	Drying out and cracking Rapid ingress of moisture into tension cracks in slopes (slope failures from shrinkage and tension cracks) Increased erosion from more intense storms Damage to vegetation and road furniture by more wild-fires More difficult to establish erosion protection through bio-engineering	Good drainage to dissipate periodic intense rain quickly Good design Bio-engineering techniques to stabilise slopes Keep vegetation cut to avoid wild-fires Use drought resistant plants and grasses Avoid wooden roadside furniture (guardrails, signposts etc.) Reduce slope angles to slow run-off
Subgrade soils	Larger moisture fluctuations in clayey soils Increased drying out of materials Shrinkage and cracking More precipitation of salts	Correct identification of problem subgrades Correct remedial actions for problems Good design Construct at estimated in-service moisture condition
Drainage (water from within road reserve)	More erosion (drier soils) More silting and sedimentation Higher risk of burning if un-maintained Less vegetation to bind soils	Good drainage design Vegetate drains Keep vegetation cut
Drainage (water from outside road reserve)	More erosion More silting and sedimentation Overtopping of bridges More severe flooding Damage to bridges and culverts from debris	Modify return periods in design Design to avoid scouring and erosion after drought periods Good structural design Good maintenance
Construction	Insufficient water for construction Quicker loss of compaction water due to evaporation	Use of innovative compaction techniques and water reducing agents Larger or different rollers Use of poorer quality water for construction Modified construction techniques
Maintenance	More unpaved surface maintenance More maintenance to drain damage Increased surface erosion repairs	Maintenance management system Keep grass and bush short to avoid fires Keep drains and culverts well-maintained

Table 18 Hazards and adaptations related to increased temperatures

Facility	Consequence - Possible Problems and Damage	Proposed Preventive Measures Suggested Remedies
Un-engineered earth roads	More rapid drying out of road Increased cracking Increased development of roughness (corrugation) Quicker generation of dust and loose material	No mitigation Improve to gravel road standard

Facility	Consequence - Possible Problems and Damage	Proposed Preventive Measures Suggested Remedies
Engineered earth roads	More rapid drying out of road Increased cracking Increased development of roughness (corrugation) Quicker generation of dust and loose material	No mitigation Improve to gravel road standard
Gravel roads	More rapid drying out of road Increased cracking Increased development of roughness (corrugation) Quicker generation of dust and loose material	Improved material selection Improved construction Improved maintenance Application of dust palliatives
Paved roads	More rapid ageing of bituminous binders Softening of bitumen in asphalt and more rapid deformation when hot Expansion and buckling of concrete roads and structures	Use more appropriate surfacings Use different (harder) binders in asphalt Changes to concrete mixes and reinforcing Use of concrete additives More frequent maintenance
Earthworks	More rapid drying out and cracking Loss of vegetation (or change of species) on side slopes (insufficient water) More wildfires causing loss of root binding Increased erosion due to loss of vegetation	Better compaction and slope protection to minimise drying out Improved soil surface material selection Use of deep-rooted, drought resistant vegetation on soil slopes Bio-engineering techniques to stabilize slopes. Keep grass and bush cut low to reduce fires
Subgrade soils	Minimal effects Some shrinkage of soils More movement of salts in saline materials	Isolation of susceptible soils to minimise drying out. Use of deep-rooted, drought resistant vegetation on soil slopes Avoid saline materials in pavements
Drainage (water from within road reserve)	More rapid drying out, cracking and erosion Loss of vegetation (or change of species) on side slopes More wildfires causing loss of root binding	Increased maintenance Better surfacing material or type selection Keep vegetation cut low
Drainage (water from outside road reserve)	Greater expansion/contraction of bridge elements Larger temperature gradients in concrete members More erosion and siltation	Good design – concrete and reinforcement Innovative bridge structures (integral, etc.) Good maintenance
Construction	Quicker reactions when cement stabilising Quicker drying of concrete Greater water requirements for construction Risk for heat stress (work force)	More rapid construction processes (recycling machines) Larger or different rollers Better concrete curing required Use of water reducing products Align construction programming with weather forecasts
Maintenance	Ensuring vegetation is kept cut to minimise wild-fires Regular maintenance of bridge movement components Risk for heat stress (work force)	More frequent maintenance Maintain vegetation at low heights Align maintenance programming with weather forecasts

Table 19 Hazards and adaptations related to decreased temperatures

Facility	Consequence - Possible Problems and Damage	Proposed Preventive Measures Suggested Remedies
Un-engineered earth roads	No effects except at extreme altitudes – freezing of water in road surface	
Engineered earth roads	No effects except at extreme altitudes – freezing of water in road surface	
Gravel roads	No effects except at extreme altitudes – freezing of water in road surface	
Paved roads	Reduced windows for construction of bituminous surfacings Less rapid ageing of bituminous binders More brittle fracture of bitumen when cold	Use appropriate surfacings and binders More frequent maintenance
Earthworks	Minimal effect	
Subgrade soils	Minimal effect	
Drainage (water from within road reserve)	Minimal effect Steeper temperature gradients in concrete members	
Drainage (water from outside road reserve)	Minimal effect	
Construction	Reduced working periods for certain operations (paving, stabilization)	Use of innovative designs
Maintenance	Increased maintenance of bituminous surfacings (crack sealing and pothole repair Road closures after thawing of frozen materials	

Table 20 Hazards and adaptations related to increased windiness (and consequent wild-fires)

Facility	Consequence - Possible Problems and Damage	Proposed Preventive Measures Suggested Remedies
Un-engineered earth roads	More rapid drying out Increased deterioration rates due to fines loss Increased accumulation of sand	Improve to gravel road standard Precautions against sand accumulation (increased maintenance, sand traps, etc.)
Engineered earth roads	More rapid drying out Increased deterioration rates due to fines loss Increased accumulation of sand	Improve to gravel road standard Precautions against sand accumulation (increased maintenance, sand traps, etc.)
Gravel roads	Increased deterioration rates due to fines loss Increased accumulation of sand	Improved material selection Improved construction Improved maintenance Precautions against sand accumulation (increased maintenance, sand traps, etc.)
Paved roads	Increased accumulation of sand Possible damage to bituminous surfacings caused by fire	Precautions against sand accumulation (increased maintenance, sand traps, etc.)
Earthworks	Loss of vegetation due to burning Higher erosion of side slopes Damage to road furniture by fires	Bio-engineering techniques to stabilize slopes. Keep vegetation low Avoid wooden road furniture
Subgrade soils	No effect Increased erosion due to loss of vegetation (fires)	Improved maintenance
Drainage (water from within road reserve)	Loss of vegetation due to burning More erosion of drains	Good drainage design Regular, high quality maintenance (short vegetation to minimise fire risk)
Drainage (water from outside road reserve)	Greater wind-load on bridges Loss of vegetation due to burning More erosion of drains More debris in flood waters due to fire damage Fire damage to bridges (wooden mainly but also concrete) More damage to erosion protection (waves)	Design stronger bridges Maintenance of vegetation and bush to avoid fires Avoid wooden structures Improved erosion protection measures
Construction	More dust Quicker evaporation of construction water	Dust palliation Modified construction techniques
Maintenance	Increased unpaved road maintenance to minimise corrugations resulting from dust loss Regular clearing of river debris and catchment vegetation	Dragging of roads for corrugation removal Clearing of drainage facilities More sand removal in coastal and arid areas Improved vegetation control to minimise fires

Table 21 Hazards and adaptations related to sea-level rise and storm-surges

Facility	Consequence - Possible Problems and Damage	Proposed Preventive Measures Suggested Remedies
Un-engineered earth roads	Flooding and storm damage Increased subgrade moisture contents Increased erosion and siltation Loss of passability	No mitigation possible Improve to higher standard
Engineered earth roads	Flooding and storm damage Increased subgrade moisture contents Increased erosion and siltation Loss of passability	No mitigation possible Improve to higher standard
Gravel roads	Flooding and storm damage Increased subgrade moisture contents Erosion and siltation	Improved material selection Improved construction Improved maintenance Place on raised embankment
Paved roads	Damage to road surfacings by salts and water impact Deposition of debris Increased subgrade moisture contents and reduced support Increased salinity of soil water	Use appropriate surfacings Use soaked subgrade designs More frequent maintenance Protection against salt damage
Earthworks	Increased moisture contents with sea-level rise Fluctuating moisture levels with surges Reduced soil strengths	Protection by barriers Reconstruction to increase road level above natural ground level Concrete drifts and pavements
Subgrade soils	Increased moisture contents	Thicker pavements to protect weak subgrades
Drainage (water from within road reserve)	Accumulation of water adjacent to road Erosion Softening of materials	Good drainage design Regular, high quality maintenance
Drainage (water from outside road reserve)	Scour of foundations Deposition of debris Increased salt damage to concrete and steel	Increase protection (barriers) Use chloride resistant coatings on concrete Avoid iron and steel components More use of embankments/levy's Good design Good maintenance
Construction	Wetter conditions Saline waters New roads (planning and design)	Innovative construction procedures Take soluble salt precautions Seek avoidance of high risk coastal zones
Maintenance	Increased maintenance in coastal and low-lying areas Increased damage caused by storm events	Ensure adequate drainage Use vegetation for moisture control (bio-engineering) Develop rapid response systems informed by high-quality weather forecasts

Table 22 Hazards and adaptations related to changes in ground-water level

Facility	Consequence - Possible Problems and Damage	Proposed Preventive Measures Suggested Remedies
Un-engineered earth roads	Wetter or drier subgrades	No mitigation Improve to gravel road standard
Engineered earth roads	Wetter or drier subgrades	No mitigation Improve to gravel road standard
Gravel roads	Wetter or drier subgrades	Thicker or thinner pavement structures as necessary Sub-soil drains where necessary
Paved roads	Wetter or drier subgrades More saline conditions affecting pavement structures	Thicker or thinner pavement structures as necessary Precautions against soluble salt damage Sub-soil drains where necessary
Earthworks	Slope instability (localised)	Incorporation of slope stabilization measures
Subgrade soils	Volumetric movements possible	Design for problem soils
Drainage (water from within road reserve)	Localised seepage and springs	Incorporate sub-surface drains
Drainage (water from outside road reserve)	Changes to surface type for assessment of run-off Otherwise as for any other structure	No special requirements Changes in run-off quantities
Construction	Difficult working conditions	Use of innovative construction techniques and water reducing agents
Maintenance	No marked changes	Possible sub-surface drain maintenance to be added to normal maintenance

6 Summary and Conclusions

Africa is one of the most vulnerable regions in the world with respect to impacts of climate change. In the past four decades, African countries have experienced more than 1,400 recorded weather related disasters resulting in the death of more than 600,000 people, left 7.8 million people homeless (99 per cent due to flooding and storms) and affected an estimated 460 million people.

Limited funding for adaptation of the road infrastructure and mitigation of climatic impacts is challenging AfCAP partner countries to acknowledge the threats that are posed by climate change, develop adaptation approaches, incorporate changes into immediate, mid-range and long-term development plans, and secure funding for the proposed and necessary adaptations.

Most low-volume rural roads in Africa are used for accessibility, as opposed to mobility. With the expected changes in climatic conditions (le Roux et al, 2016) resulting from climate change, the on-going and periodic deterioration of the existing low-volume rural road networks in SSA can thus be expected to continue on a more frequent and increasing scale.

This Guideline addresses the issues of appropriate and economic methodologies for vulnerability and risk assessments; prioritisation of adaptation interventions; and identifies a range of design considerations to improve the resilience of rural access roads. The availability of funding is crucial to the implementation of any adaptation measures and a delicate balance between the appropriate measures and available funding will need to be found. The wide range of measures identified in the Guideline cover most eventualities and the most appropriate ones or combinations of measures will need to be identified and designed by the engineers involved, following normal high quality design principles. Many of the counter-measures require specialist design, and this should not be omitted.

The critical importance of adequate drainage, with timely and good maintenance practices, is also highlighted and guidance given. Frequency and types of maintenance will need to be adapted to changes in climate, especially extreme weather events and higher temperatures.

This Guideline should be used in conjunction with the accompanying *Climate Adaptation Handbook,* the *Change Management Guidelines* and the *Visual Assessment Manual*.

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ANNEX A: Data assessment collection form

Road Number:		Date:		Assessors:		Weather:	S. PC. C. R. H. Cold	Topography	F. R. H. M.	Landcover and use	A. F. N. PU. D. O.

Chainage	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9		0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	
Grade																				
Access to facilities																				
No. of alternative roads																				
Common vehicle types																				
GPS and photo No																				
Erodibility																				
Sugbrade																				
Road surface - unpaved																				
Side drains - unlined																				
Embankment slopes																				
Cut slopes																				
Subgrade problems																				
Material type																				
Moisture																				
Drainage (in reserve)																				
Road shape																				
Shoulders																				
Side slopes																				
Side drains																				
Mitre drains																				
Drainage (streams)																				
Structure																				
Approach fills																				
Erosion of approach fills																				
Protection works																				
Flood plain																				
Slope stability																				
Cut stability																				
Fill stability																				
Construction																				
Overall finish																				
Erosion protection works																				
Maintenance																				
Quantity																				
Quality																				
COMMENTS:																				

Example of completed field data collection sheet for climate resilience assessments with supporting photos

Road Number:	B - G	**Date:**	2018/08/01	**Assessors:** PPG	**Weather:**	S. **PC.** C. R. **H.** Cold	**Terrain**	F. **R.** H. M.	**Landuse**	**A.** F. N. **PU.** O.

Chainage	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1	1,1	1,2	1,3	1,4	1,5	1,6	1,7	1,8	1,9	2
Grade	F	F	F-U	U	U	U	U	U	U - F	F - D	D	D	D	D	D - F	F	F	F	F	F
GPS and photo No	08.1123 38.3535						65													
Erodibility																				
Subgrade	0	0	0	4/4	0	0	0	3/3	0	0	0	0	0	0	0	0	0	0	0	0
Road surface - unpaved	Paved																			
Side drains - unlined	2/4	5/1	0	4/5	0	0	4/5	4/3	0	0	0	0	0	0	0	0	0	0	0	0
Embankment slopes	0	0	0	5/4	5/1	0	3/3	3/3	0	2/1	2/1	2/1	3/2	3/5	3/5	0	0	0	0	0
Cut slopes																				
Subgrade problems																				
Material type	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Moisture														Possible	Possible					
Drainage (in reserve)																				
Road shape	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Shoulders	0	0	3/3	4/3	4/5	4/5	3/3	2/3	0	0	2/3	2/2	2/2	0	0	1/2	0	0	0	0
Side slopes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Side drains	0	0	5/5	0	0	0	0	5/3	5/3	0	0	0	0	0	0	0	2/1	0	0	0
Mitre drains																				
Drainage (streams)																				
Structure	3/1 - 1				4/1 -2	4/1 -2								5/1 -2	5/1 -2	5/1 -2				
Embankments																				
Erosion								5/1									3/1			
Protection works																				
Slope stability																				
Cut stability																				
Fill stability	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Construction																				
Overall finish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Erosion protection works																				
Maintenance																				
Quantity	3/4	0	5/4	5/4	5/4	5/4	4/4	5/4	5/4	5/4	5/4	5/4	5/4	5/4	5/4	5/4	5/4	5/4	5/4	5/4
Quality	2/5	2/5	2/5	2/5	2/5	2/5	2/5	2/5	2/5	2/5	2/5	2/5	2/5	2/5	2/5	2/5	2/5	2/5	2/5	2/5

COMMENTS:
1. Culvert silted at inlet
1. Needs culverts

Supporting Photos

Assessment Item: Erodibility - Side drains, unlined

Distress: Severe erosion of side drains

Chainage: 300 m to 400 m

Degree: 4 Extent: 5

Assessment Item: Drainage (in reserve) – Side drains

Distress: Blockage of side drains by landslide debris

Chainage: 700 m to 800 m

Degree: 5 Extent: 3

Assessment Item: Drainage (in reserve) – Side drain

Distress: Damage to erosion protection in side drain

Chainage: 1 600 m to 1 700 m

Degree: 2 Extent: 1

Assessment Item: Drainage (stream) - Erosion

Distress: Erosion of river bank and damage to protection works

Chainage: 700 m to 800 m

Degree: 5 Extent: 1

<table>
<tr>
<td>


Assessment Item: Drainage (in reserve) – Side drains
Distress: Poor maintenance of lined side drain
Chainage: 700 m to 800 m
Degree: 5 Extent: 3
</td>
<td>


Assessment Item: Drainage (streams) – Erosion of approach fills
Distress: Poor control of water next to road leading to erosion of bridge approach fill
Chainage: 1 600 m to 1 700 m
Degree: 3 Extent: 1
</td>
</tr>
<tr>
<td>


Assessment Item: Drainage (in reserve) - Shoulders
Distress: Poor shoulder maintenance
Chainage: 300 m to 400 m
Degree: 4 Extent: 3
</td>
<td></td>
</tr>
</table>

ANNEX B: Problem soil causes and identification

B.1 Expansive clays

B.1.1 Causes

Expansive clays are widespread internationally and of major economic significance. Typical damage to roads includes longitudinal unevenness and bumpiness, differential movement near culverts and longitudinal cracking. The presence of trees alongside the road often results in localised moisture extraction by their roots with the development of sporadic subsidence and arcuate cracking. Expansive clay damage to roads usually affects their serviceability more than their structural integrity, provided cracking and surface distress are timeously and effectively repaired. Damage is generally restricted to areas that have significant seasonal rainfall or poor surface water drainage.

Expansive soils are those containing smectite (montmorillonite) clays, which are mostly derived from the chemical weathering of basic rock forming minerals. Probably the worst expansive clays occur on deeply weathered gabbros, basalts and dolerites in tropical and sub-tropical areas. Expansive clays are also commonly found in transported soils derived locally or from some distance from weathered basic igneous rocks. Smectites can also form from the alteration under alkaline conditions of other silicate minerals low in potassium, as long as calcium and magnesium are present and leaching is impeded. Although the expansive potential of a soil can be related to many factors, it is primarily controlled by the quantity of smectite minerals.

Volume changes in expansive soils are confined to the upper few meters of a soil deposit where seasonal moisture content varies due to drying and wetting cycles. The zone within which volume changes are most likely to occur is defined as the active zone. The active zone can be evaluated by plotting the in situ moisture content with depth for samples taken during the wet and dry seasons. The depth at which the moisture content shows no seasonal variation is the limit of the active zone. This is also referred to as the lower depth of seasonal moisture change. However, with the anticipated ***changes in precipitation and temperatures***, the length and characteristics of the dry season are expected to change, resulting in greater moisture movements in this critical depth zone. These are expected to cause more extensive expansive clay damage to roads.

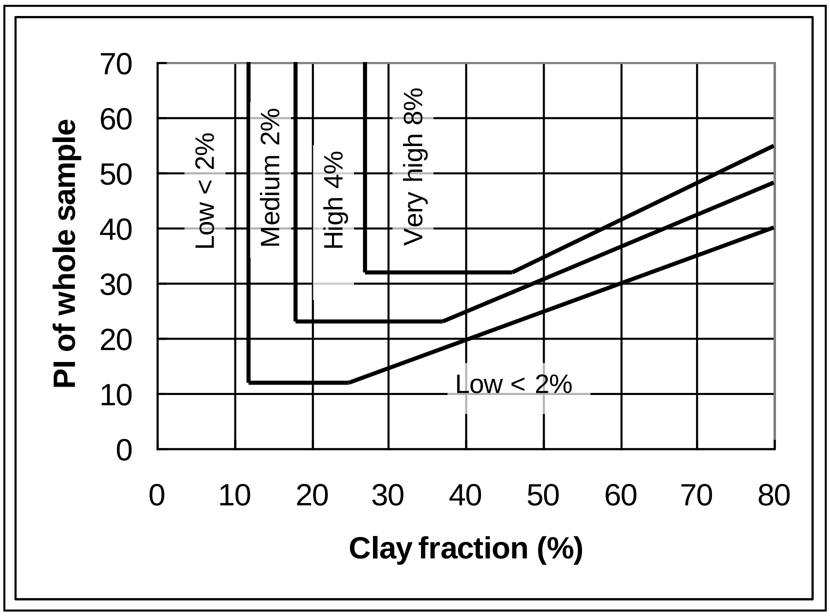
B.1.2 Recognition of expansive clays

The simplest way of identifying the presence of expansive soils is through field observations where the surface expression of cracking in dark grey, black or sometimes red soils is evident as shown in Figure B.1. However, the presence of a thick non-expansive transported or topsoil cover can sometimes mask these cracks and excavation of a test pit, in which cracking and slickensiding of the material will be observed is necessary. The identification of smectite in subgrade soils is best done using X-ray diffraction.

Figure B.1 Typical evidence of the presence of expansive clay soils

By their nature, smectite clays will tend to be more plastic than other clay minerals and a measure of the plasticity index, or better still the activity (ratio of plasticity index to clay fraction) is a good indication of the presence of smectites. This is one of the earliest methods of indicating potentially expansive soils using Figure B.2 based on the clay fraction of the soil (minus 2 µm) and the standard Plasticity Index (PI). It should be noted that the estimates for the degree of swell using this technique do not consider the initial moisture content of the material, assuming that they move from a state of dryness normally used in the laboratory to wet. It is known that an equilibrium moisture content develops under a road structure and the moisture fluctuation in this zone is minimal. However, from beneath the outer wheel track of roads with unsealed shoulders to the edge of the fill, significant and variable moisture fluctuations occur. It is unlikely that the initial moisture content in these zones is, however, particularly dry.

Figure B.2 Identification of expansive clay soils and estimate of expansion (Van der Merwe, 1976)



An indication of potentially expansive soils can also be obtained from land type soil maps where materials identified as "vertic" soils will always have expansive characteristics, while soils with a high base status (or "eutrophic") and clay content should be investigated more thoroughly, as they have the potential to be expansive.

B.2. Dispersive/erodible/slaking materials

B.2.1 Causes

Dispersive, erodible and slaking materials are similar in their field appearance (highly eroded, gullied and channelled exposures), but differ significantly in the mechanisms of their actions. Fortunately for road builders, only the (probably less common) dispersive soils present problems of any consequence. Figure B.3 shows a typical dispersive soil with definite evidence of piping.

Figure B.3 Dispersive soil showing formation of "pipes"

Dispersive soils are those soils that, when placed in water, have repulsive forces between the clay particles that exceed the attractive forces. This results in the colloidal fraction going into suspension and in still water staying in suspension (Figure B.4). In moving water, the dispersed particles are carried away. This obviously has serious implications in earth dam engineering, but is of less consequence in road engineering except when used in fills. Dispersive soils often develop in low-lying areas with gently rolling topography and relatively flat slopes. Their environment of formation is also usually characterised by an annual rainfall of less than 850 mm.

Figure B.4 Dispersive soil in water (crumb test) showing suspension that does not settle out

Erodible soils will not necessarily disintegrate or go into dispersion in water. They tend to lose material because of the frictional drag of water flowing over the material that exceeds the cohesive forces holding the material together.

Slaking soils disintegrate in water to silt, sand and gravel sized particles, without going into dispersion. The cause of this process is probably a combination of swelling of clay particles, the generation of high pore air pressures as water is drawn into the voids in the material and softening of any incipient cementation.

Slaking and erodible soils when occurring as subgrades or even when used in fills are unlikely to cause significant problems unless water flows through the fill or subgrade. Problems are thus mostly associated with poor culvert and drainage design. The inclusion of dispersive soils in the subgrade or fill on the other hand has been seen to lead to significant failures through piping, tunnelling and the formation of cavities in the structure. It is therefore important to identify dispersive soils timeously.

B.2.2 Recognition

The testing and recognition of dispersive soils requires various soil engineering and pedological laboratory tests. These include:

- Determination of the Exchangeable Sodium Percentage (ESP)
- Cation Exchange Capacity (CEC)
- Crumb test[19]
- Double hydrometer test, and
- Sodium Absorption Ratio (SAR) and the pH.

The crumb test on undisturbed lumps of material (placed in pure water) is usually the simplest first indication, but is not always definitive. Dispersive soils tend to produce a colloidal suspension or cloudiness over the crumb/lump during the test, without the material necessarily disintegrating fully. Disintegration of the crumb in slaking soils is very rapid and forms a heap of silt, sand and gravel. Erodible soils do not necessarily always disintegrate in the crumb test as they require a frictional force of moving water to loosen the surface material, without any of the loose material remaining in suspension.

It is not very important (or even possible in many cases) to quantify the actual potential loss of dispersive material from subgrades and fills as the process is time related and given enough time, all of the colloidal material could theoretically be dispersed and removed, leading to piping, internal erosion and eventually loss of material on a large scale. It is, however, important to identify the presence of dispersive soils, and their differentiation from erodible and slaking materials, so that the necessary precautions can be taken if they will affect the constructed pavement. With expected ***increased drying out of soils during extended drought periods*** followed by ***intensive storms***, damage of roads including dispersive soils can be expected to be significant.

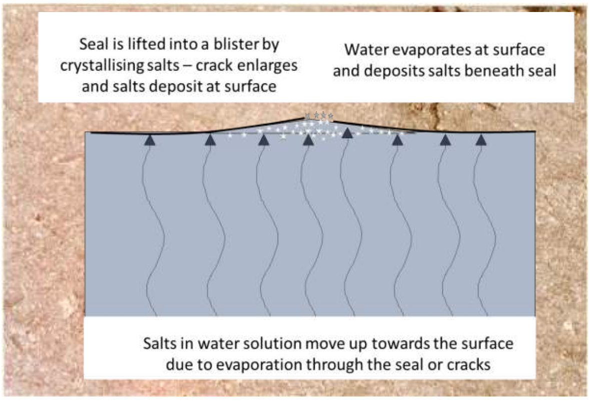
B.3 Saline soils

B.3.1 Causes

Unlike dispersive soils that are affected by the presence of excessive cations of sodium attached to clays, saline materials are affected by the combination of specific cations and anions in the form of soluble salts, independent of clays. These can be a major problem on road projects where migration of soluble salts to beneath bituminous surfacings (Figure B.5) leads to weakening of the upper base and blistering and disintegration of the surfacings. Soluble salts, particularly sulphates, and their acids can also have a serious detrimental effect on the stability/durability of chemically stabilized materials and concrete.

[19] The Emerson crumb test (2002) has been found to be applicable for low volume roads. Rain water can be used for the test in the absence of distilled or “bottled” water. The test has been found to be reliable for the prediction of dispersive behaviour of soils with the pinhole test.

Figure B.5 Mechanism of soluble salt damage to bituminous surfacings



Soluble salt damage to roads has been reported primarily from arid, semi-arid and warm dry areas. Salts can originate from the in situ natural soils beneath the structures as well as from imported material for the pavement layers or from saline construction water. Only the presence of soluble salts in subgrade materials is considered in this Guideline as the materials for other layers can be controlled provided the problem is identified timeously.

Subgrade materials in areas where the land surface shows some depression resulting in seasonal accumulation of water are particularly prone to the accumulation of salts leached from the surrounding areas. In other flat areas, capillary rise of groundwater and precipitation in saline soils can result in the upward migration of salts to or near the soil surface. With the expected climate change, increasing aridity and changes in sea-level are expected to increase soluble salt problems if the necessary precautions are not taken.

B.3.2 Recognition

In some cases, the visible presence of crystallised salt deposits at the soil surface is a certain indication of the need for additional investigation for possible salt problems. This is often associated with the presence of animals licking the soil surface. In most other cases, the presence of salt is best confirmed by using laboratory test methods.

In the conventional road engineering context, the identification of possible soluble salt problems is based on the pH and conductivity of the materials. It should be noted that the results of the electrical conductivity and pH tests can vary significantly depending on the pre-treatment, the moisture content at which the measurements are made and particularly on the material size fraction tested.

Limits for the use of saline materials are generally based on work in specific countries and their applicability to other areas is unknown. In general, an electrical conductivity on the passing 6.7 mm fraction more than 0.15 Sm^{-1} (or an electrical resistance of less than 200 Ω on the minus 2 mm fraction) should raise concern and indicate the need for further investigation. Similarly, soluble salt contents more than 0.5 per cent should be a cause for possible concern and lead to additional investigations.

B.4. Soft clays

B.4.1 Causes

Widespread problems, mostly in coastal estuarine (lagoon) and marshy areas result from the presence of very soft alluvial clays in these areas. Deep soft clays in estuarine areas are formed mostly because of periodic fluctuations in seal level. Inland soft clays tend to be much shallower having been deposited in marshy areas. Soft clays are generally, but not necessarily saturated and normally consolidated to lightly over-consolidated (because of fluctuating water tables). The materials thus have low shear strengths, are highly compressible and their low permeabilities result in time-related settlement problems. In addition, the frequent occurrence of organic material in the clays affects their behaviour and the determination of their properties.

As noted above, the presence of these materials is predominantly in the coastal areas although they can also be associated with large mature river systems. The shear strength of these clays would normally be between 10 and 40 kPa, making them impossible to difficult to walk on. Soft clays are seldom uniform with depth and are usually interlayered with silts and sands, which provide more permeable drainage paths than would be determined from oedometer testing of undisturbed clay samples. However, the depths and strengths of the materials are such that inspection of the materials in test pits or auger holes is not recommended.

Potential future rising of sea-level is likely to introduce larger areas of soft clays and lead to increased road construction problems in coastal areas.

B.4.2 Recognition

The in situ condition of these materials is one of their most important properties that need to be considered – testing of disturbed samples will usually provide results that are meaningless. It is thus better to use in situ test methods such as Standard Penetration Testing (SPT), vane shear or Cone Penetration Testing (CPT) to determine the depths, presence of silt or sand layers, strengths and if possible, permeabilities. If these can be identified with a reasonable degree of confidence, estimates of the quantity and rate of settlement and the potential stability of embankments over the materials can be made.

B.5. Wet areas/high water tables

B.5.1. Causes

It is possible that some non-clayey areas have a water table close to the natural ground surface, which makes the placement of road structures difficult and can affect their structural integrity. Unlike the clay areas, the problem is not the low strength or settlement potential, but the effect of the water (and high pore-water pressures under traffic loading) on the pavement structure.

High water tables result in a steady, high in situ moisture but it is also possible that fluctuating high moisture content conditions within the pavement sub-structure may occur because of seasonal precipitation and longer-term climate change characteristics. A good understanding of the moisture conditions and environment needs to be defined during any investigation involving subgrade materials.

Various moisture indices such as Thornthwaite’s Moisture Index or water surplus maps can provide very useful information on potential problems in this regard. It should be borne in mind, however, that the climatic zones on such maps may change as ***precipitation and evaporation increase or decrease*** with time. Many of the problems encountered in roads are common to specific moisture zones, and these have been highlighted under their respective headings in this Guideline.

B.5.2 Recognition

It is usually easy to recognise potential wet conditions, which are characterised by areas of standing water, specific types of vegetation (reeds, papyrus grasses, etc.), localised muddy conditions and often the presence of crabs and frogs. However, with the changes in climatic conditions, particularly increases in periods of extreme storm events, roads constructed at or near natural ground level could become impassable for longer periods of time.

B.6. Collapsible soils

B.6.1. Recognition

Collapsible soils result from a unique condition in which “bridges” of fine materials (usually clays or iron oxides) within a framework of coarser and harder particles (mostly quartz) become weak when wet and collapse under load. The important condition is that the material must be in a partially saturated condition and then wetted up and loaded simultaneously, which is a common situation beneath road structures. They tend to be more prevalent in drier areas.

Collapsible materials can occur on both residual and transported materials. Many granites and feldspathic sandstones when weathered result in the feldspar altering to kaolinite with the quartz particles staying intact. This forms a honeycomb type of structure, which, when wetted up and loaded, results in shearing or “collapse” of the clay bridges and a settlement or reduction in volume of the material. Certain basalts and dolerites with dry densities of 1200 to 1300 kg/m^3 have also shown collapse potential.

Indications of the possibility of collapsible materials are:

- A very low density, because of the large number of voids separating the quartz framework
- Densities of less than about 1600 kg/m^3 (mostly in the range 1000 to 1585 kg/m^3)
- The presence of “pinholing” or voiding observed during the soil profiling
- Usually more than 60% of the mass of the material lies in the 0.075 to 2 mm range and less than 20% is finer than 0.075 mm
- When the material excavated from a pit is insufficient to fill the pit again (the collapse structure will be disturbed and the material will decrease in volume).

The expected climatic scenario of ***longer drought periods*** followed by potentially ***extreme storm events*** will have a major impact on unidentified or un-engineered collapsible soil areas. Wetting of the subgrade after extended drought periods followed by the application of traffic loads is expected to result in significant road surface deformation. The result of collapse of the subgrade is mostly manifested by the development of a deeply rutted and often uneven road surface and significant deterioration of the riding quality of the road (Figure B.6).

Figure B.6 Typical manifestation of collapsible subgrade