Road Design and the Physical Environment: Appropriate Design Options for Steep Gradients; an example from Ghana

Dr Joseph Anochie-Boateng, CSIR, South Africa
Outline

• Overview of the Steep Gradients Project
• Project Key Objectives
• Project Site and Observations
• Design Options and Considerations
• Concluding Remarks
Project Management

PMU/Cardno - Dr Paulina Agyekum - AfCAP Technical Manager, West Africa)

Lead Consultant: CSIR South Africa
Local Consultant: BRRI Ghana

Major Stakeholders Ministry of Roads & Highways / Department of Feeder Roads

Project Team
Dr Joseph Boateng, CSIR, TL
Ing. Edmund Debrah, BRRI, LCE
Bernice Adjarolo, BRRI, LCET
Vincent Aquah-Bondzie, BRRI, LCET
ReCAP Project GHA2065

Phase 1: GHA2065A
Jan - May 2016
- Desk study
- Preliminary site evaluation
Main outcomes /output:
- Alternative surfacing options with preliminary cost analysis
- Scoping for the Phase 2

Phase 2: GHA2065B
Feb 2017 - Feb 2020
1. Design of alternative surfacing & pavement options (Year 1)
Main output: Design guidelines
2. Construction of demonstration sections (Year 1 & Year 2)
Main output: Construction guidelines
3. Monitoring of demonstration sections (Year 2 & Year 3)
Main output: Design and Construction specifications
Link to other projects

- Climate Adaptation: Risk Management and Resilience Optimisation for Vulnerable Road Access in Africa (Ethiopia, Mozambique and Ghana)
- Development of Low Volume Roads Design Manuals and Update of Standard Specifications and Detailed Drawings for Three AfCAP Member Countries in West Africa (Ghana, Sierra Leone and Liberia)
- On-going regional project on development of a materials database for use at national level
Key objectives

1. Conducting relevant research
   - Establish appropriate design and construction techniques for steep sections (gradient >12%)
   - Develop guidelines and construction specifications

2. Knowledge transfer and capacity building
   - Knowledge transfer (DFR, BRRI, other road agencies & research institutions in Ghana)
   - Assessment of capacity needs to be conducted - engagement with the selected agencies/institutions

3. Uptake and embedment
   - Implement the outcomes to maximise the impact of the project
   - Involves information sharing (meetings, presentations, workshops, technical discussions etc.)
Project road

- 3.5 km long road linking Akwesiho - Twenedurase villages in the eastern region of Ghana
- Located < 200 km north of Accra
- The third alternative route to major towns
- Sources of livelihood (Agriculture – cocoa, banana farming, food crops, etc.)
- Terrain is rolling to mountainous (gradients vary between 6 and 22%)
- Requires new pavement layer materials
Project road

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Topography
Project Site

October 2017
Site observations

- Several erosion gullies on the surface of the road exposing the underlying granitic residual soil
- Trees of varying sizes pose threat to the slope stability
Site observations

- Severe erosion issues
  - as a result of surface runoff washing placed materials
Site observations

- Several landslides - after a previous day heavy down pour of rains
  - Occurring in the conglomereration of silty-sand sandstone rock fragments formations
Rainfall

Annual Rainfall (2006-2016)

Year [2006-2016]
Temperature

<table>
<thead>
<tr>
<th>Year</th>
<th>Maximum temperature</th>
<th>Mean temperature</th>
<th>Minimum temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>+15°C</td>
<td>+20°C</td>
<td>+25°C</td>
</tr>
<tr>
<td>2010</td>
<td>+20°C</td>
<td>+30°C</td>
<td>+35°C</td>
</tr>
<tr>
<td>2011</td>
<td>+30°C</td>
<td>+40°C</td>
<td>+45°C</td>
</tr>
<tr>
<td>2012</td>
<td>+35°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>+35°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>+35°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>+35°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>+35°C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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General considerations

- Comparison of performance of alternative surfacing on the varying steep gradients
- Construction methods will vary (labour intensive and light equipment techniques)
- Pavement design method for the structural layers will vary
- Same materials will be used for underlying layers
- Significant use will be made of local resources—materials, contractors, labour & construction methods
Design considerations

- Materials and pavement designs are suitable for labour-based methods
- Mechanical stabilisation techniques to be applied to natural gravels that do not meet construction standards of base/subbase layers
- DFR would acquire capacity to supervise construction during implementation
Demonstration and control sections

<table>
<thead>
<tr>
<th>Control Section 1 (Chip Seal - S1)</th>
<th>Demonstration Section (Stone Paving)</th>
<th>Demo. Section (Interlocking Concrete Block Paving)</th>
<th>Control Section 2 (Chip Seal - S2)</th>
<th>Demonstration Section (Cold Mix Asphalt)</th>
<th>Demonstration Section (Thin Mesh Reinforced Concrete)</th>
<th>Demonstration Section (Rolled Compacted Concrete)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lined concrete drain</td>
<td>Curb with gutter</td>
<td>Road shoulder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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## Gradients - elevation profile

<table>
<thead>
<tr>
<th>Chainage [km]</th>
<th>1 + 600</th>
<th>1 + 850</th>
<th>2 + 130</th>
<th>2 + 410</th>
<th>2 + 660</th>
<th>2 + 940</th>
<th>3 + 220</th>
<th>3 + 500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surfacings Type</td>
<td>Surface Dressing</td>
<td>Surface Dressing (control 1)</td>
<td>Stone Paving</td>
<td>Interlocking Concrete Blocks</td>
<td>Surface Dressing (control 2)</td>
<td>Cold Mix Asphalt</td>
<td>Thin Mesh Reinforced Concrete</td>
<td>Rolled Compacted Concrete</td>
</tr>
<tr>
<td>Section</td>
<td><img src="image1" alt="Surface Dressing" /></td>
<td><img src="image2" alt="Surface Dressing" /></td>
<td><img src="image3" alt="Stone Paving" /></td>
<td><img src="image4" alt="Interlocking Concrete Blocks" /></td>
<td><img src="image5" alt="Surface Dressing" /></td>
<td><img src="image6" alt="Cold Mix Asphalt" /></td>
<td><img src="image7" alt="Thin Mesh Reinforced Concrete" /></td>
<td><img src="image8" alt="Rolled Compacted Concrete" /></td>
</tr>
<tr>
<td>Length (m)</td>
<td>1575</td>
<td>250</td>
<td>280</td>
<td>280</td>
<td>250</td>
<td>280</td>
<td>280</td>
<td>280</td>
</tr>
<tr>
<td>Elevation Profile (Not to Scale)</td>
<td><img src="image9" alt="Profile" /></td>
<td><img src="image10" alt="Profile" /></td>
<td><img src="image11" alt="Profile" /></td>
<td><img src="image12" alt="Profile" /></td>
<td><img src="image13" alt="Profile" /></td>
<td><img src="image14" alt="Profile" /></td>
<td><img src="image15" alt="Profile" /></td>
<td><img src="image16" alt="Profile" /></td>
</tr>
</tbody>
</table>

**Chainage km**
- 1 + 600
- 1 + 850
- 2 + 130
- 2 + 410
- 2 + 660
- 2 + 940
- 3 + 220
- 3 + 500

**Surfacings Type**
- Surface Dressing
- Surface Dressing (control 1)
- Stone Paving
- Interlocking Concrete Blocks
- Surface Dressing (control 2)
- Cold Mix Asphalt
- Thin Mesh Reinforced Concrete
- Rolled Compacted Concrete

**Section**
- Surface Dressing

**Length (m)**
- 1575
- 250
- 280
- 280
- 250
- 280
- 280
- 280

**Elevation Profile (Not to Scale)**
- 6%
- 14%
- 12%
- 13%
- 16%
- 16%
- 20%
- 22%
# 1. Stove paving

<table>
<thead>
<tr>
<th>Section</th>
<th>Section type</th>
<th>Chainage</th>
<th>Gradient</th>
<th>Subsection Chainage</th>
<th>Length</th>
<th>Description of variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Demo section: Stone paving [280 m]</td>
<td>1+850 to 2+130</td>
<td>12%</td>
<td>1+850 to 1+920</td>
<td>70 m / 50 m</td>
<td>Cobble stone – dressed stones (150 mm) laid on a bedding sand layer (30 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1+920 to 1+990</td>
<td>70 m / 50 m</td>
<td>Stone setts - roughly cubic (100 mm) stone setts laid on a bed of sand</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1+990 to 2+060</td>
<td>70 m / 50 m</td>
<td>Hand-packed stone - large broken stones (250 mm) with voids filled with sand</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2+060 to 2+130</td>
<td>70 m / 50 m</td>
<td>Mortared stone - selected natural stones (150 mm) laid on a bed of loose sand with the joints filled with sand-cement mortar</td>
</tr>
</tbody>
</table>
## 2. Interlocking concrete block paving

<table>
<thead>
<tr>
<th>Section</th>
<th>Section type</th>
<th>Chainage</th>
<th>Gradient</th>
<th>Subsection Chainage</th>
<th>Length</th>
<th>Description of variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Demo section: Interlocking concrete paving block, ICBP [280 m]</td>
<td>2+130 to 2+410</td>
<td>13%</td>
<td>2+130 to 2+200</td>
<td>70 m / 50 m</td>
<td><strong>ICPB Mix 1</strong>: 75 mm thick interlocking paving blocks made from OPC, natural sand and quarry stones</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2+200 to 2+270</td>
<td>70 m / 50 m</td>
<td><strong>ICPB Mix 2</strong>: 75 mm thick interlocking paving blocks made from PPC, natural sand and quarry stones</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2+270 to 2+340</td>
<td>70 m / 50 m</td>
<td><strong>ICPB Mix 3</strong>: Interlocking paving blocks made from OPC, sand, quarry stones (70%), screened laterite (30%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2+340 to 2+410</td>
<td>70 m / 50 m</td>
<td><strong>ICPB Mix 4</strong>: 75 mm interlocking paving blocks made from OPC, sand, quarry stones (30%), screened laterite (70%)</td>
</tr>
</tbody>
</table>
3. Cold mix asphalt

<table>
<thead>
<tr>
<th>Section</th>
<th>Section type</th>
<th>Chainage</th>
<th>Gradient</th>
<th>Subsection Chainage</th>
<th>Length</th>
<th>Description of variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Demo section: Cold mix asphalt, CMA [280 m]</td>
<td>2+660 to 2+940</td>
<td>16%</td>
<td>2+660 to 2+730</td>
<td>70 m / 50 m</td>
<td><strong>CMA Mix 1:</strong> 50 mm thick cold mix asphalt with base emulsion (K1-70 cationic type) with all quarry stones</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2+730 to 2+800</td>
<td>70 m / 50 m</td>
<td><strong>CMA Mix 2:</strong> 50 mm thick cold mix asphalt with emulsion (K1-70 cationic type) with blended quarry stones (70%) and screened laterite (30%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2+800 to 2+870</td>
<td>70 m / 50 m</td>
<td><strong>CMA Mix 3:</strong> 50 mm thick cold mix asphalt with modified emulsion (lime/cement additives) and 100% quarry stones</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2+870 to 2+940</td>
<td>70 m / 50 m</td>
<td><strong>CMA Mix 4:</strong> 50 mm thick cold mix asphalt with modified emulsion (with additives lime/cement) with blended quarry stones (30%) and screened laterite (70%)</td>
</tr>
</tbody>
</table>
4. Thin mesh-reinforced concrete

<table>
<thead>
<tr>
<th>Section</th>
<th>Section type</th>
<th>Chainage</th>
<th>Gradient</th>
<th>Subsection Chainage</th>
<th>Length</th>
<th>Description of variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Demo section: Cold mix asphalt, CMA [280 m]</td>
<td>2+660 to 2+940</td>
<td>16%</td>
<td>2+660 to 2+730</td>
<td>70 m / 50 m</td>
<td><strong>CMA Mix 1</strong>: 50 mm thick cold mix asphalt with base emulsion (K1-70 cationic type) with all quarry stones</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2+730 to 2+800</td>
<td>70 m / 50 m</td>
<td><strong>CMA Mix 2</strong>: 50 mm thick cold mix asphalt with emulsion (K1-70 cationic type) with blended quarry stones (70%) and screened laterite (30%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2+800 to 2+870</td>
<td>70 m / 50 m</td>
<td><strong>CMA Mix 3</strong>: 50 mm thick cold mix asphalt with modified emulsion (lime/cement additives) and 100% quarry stones</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2+870 to 2+940</td>
<td>70 m / 50 m</td>
<td><strong>CMA Mix 4</strong>: 50 mm thick cold mix asphalt with modified emulsion (with additives lime/cement) with blended quarry stones (30%) and screened laterite (70%)</td>
</tr>
</tbody>
</table>
## 5. Roller compacted concrete

<table>
<thead>
<tr>
<th>Section</th>
<th>Section type</th>
<th>Chainage</th>
<th>Gradient</th>
<th>Subsection Chainage</th>
<th>Length</th>
<th>Description of variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Demo: Roller-compacted concrete, RCC [280 m]</td>
<td>3+220 to 3+500</td>
<td>22%</td>
<td>3+220 to 3+290</td>
<td>70 m / 50 m</td>
<td>RCC Mix 1: 110 mm roller-compacted concrete from OPC, sand, quarry stones</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3+290 to 3+360</td>
<td>70 m / 50 m</td>
<td>RCC Mix 2: 110 mm roller-compacted concrete from PPC, sand, quarry stones</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3+360 to 3+430</td>
<td>70 m / 50 m</td>
<td>RCC Mix 3: 110 mm roller-compacted concrete from OPC, sand, quarry aggregate (70%), screened laterite (30%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3+430 to 3+500</td>
<td>70 m / 50 m</td>
<td>RCC Mix 4: 110 mm roller-compacted concrete from OPC, sand, quarry aggregate (30%), screened laterite (70%)</td>
</tr>
</tbody>
</table>
Design considerations

- Design is based on current practices of AfCAP and the DFR

- Demonstration sections have two lanes of 3.75 m wide (DC4, paved 6.5 to 7.5 m) per lane and 200 m long
  - Each demonstration section consists of four variable sections of 50 m long each. Shoulders (1 m on each side, paved)

- Design life for all pavement types is 15 years; analysis period is 25 years
Design considerations

- “Rigid” surfacings (TMRC & RCC) will be constructed on a two-layer system where the granular base/subbase material is constructed on a “proof-rolled” subgrade

- Expected traffic volume would potentially be higher than 300 vpd
  - Traffic growth is not expected to exceed 2%
Geometric design

- Cross-section elements
  - Carriageway width of 6.5 to 7.5m (8.0m)
  - Paved (single chip seal) shoulder width of 1 m
  - Roadway width of 10.0m
  - Cross-fall of 3%
Drainage

- Trapezoidal drains are proposed for the demonstration sections
  - steep nature of the embankment (weak/ unstable)
  - high rainfall in the project catchment area

- Interventions required to reduce the speed of water flowing down steep gradients
  - Failure to do so would likely result in erosion of embankments and clogging of the side drains

- Turnouts or mitre drains are needed along some portions of the project site
Drainage

- Cross-section of trapezoidal drain (units: m)
Materials

In-situ Rock Deposit

ESM Quarry Site
Materials

Processed aggregates from in-situ rock deposit

Aggregate from ESM Quarry

Screened Laterite Aggregate 1

Screened Laterite Aggregate 2
Total ADT = 433 (expected base-year traffic)

Traffic on the project road is projected to consist of 70% small vehicles (taxis and private cars); 27% medium vehicles (light and medium trucks – 20% and buses – 7%), and 3% heavy vehicles.
Uniform Section 1: 1.100 – 1.687 km

Uniform Section 2: 1.687 – 1.962 km

Uniform Section 3: 1.962 – 2.782 km

Uniform Section 4: 2.782 – 3.057 km
Structural design: in-situ vs required strength

<table>
<thead>
<tr>
<th>Pavement layer (mm)</th>
<th>Required DN value for TLC 1.0</th>
<th>DN values [@80\textsuperscript{th} percentile] for sections</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.100 – 1.687 km</td>
</tr>
<tr>
<td>0 – 150</td>
<td>DN ≤ 2.5</td>
<td>24.31</td>
</tr>
<tr>
<td>151 – 300</td>
<td>DN ≤ 4.0</td>
<td>26.99</td>
</tr>
<tr>
<td>301 – 450</td>
<td>DN ≤ 6.0</td>
<td>21.93</td>
</tr>
<tr>
<td>451 – 600</td>
<td>DN ≤ 13.0</td>
<td>24.25</td>
</tr>
<tr>
<td>601 – 800</td>
<td>DN ≤ 23.0</td>
<td>22.99</td>
</tr>
</tbody>
</table>

DCP design catalogue compliance key

<table>
<thead>
<tr>
<th>Inadequate (non-compliance) in-situ layer</th>
<th>Adequate (marginal compliance) in-situ layer(s) – need to be improved</th>
<th>Adequate (full compliance) in-situ layer(s)</th>
</tr>
</thead>
</table>
Pavement sections

- Shoulder (max width = 1.0m)
- 3% Crossfall
- Cobblestone surfacing (Quarry Produced)
- Slope 1 in 0.5

Details:
- SURFACING: 100mm size Cobblestones stacked in cement mortar
  
  Aggregate Source: Quarry produced

- DRAIN: Curb with Cutter

- BASE COURSE: Mechanically stabilized Lateritic gravel with 0-40mm stones, compacted to 95 - 98% mod. AASHTO (T180)

- SUBGRADE: 100 - 150mm Lateritic gravel proof rolled and compacted to 95% mod. AASHTO

- ROADBED: 150mm Natural Lateritic gravel Compacted to 95% mod. AASHTO

ACAP Project CHA20658
Alternative Surfacing for Steep Slopes]
Awasho - Twedahunse Road

Length: 70m
Chunage: 1+850 to 1+920

Designed by: Project Team
Drawing Prepared by: Project Team
Reviewed by: Project Team
 Approved by: MRT/DFR

Section not drawn to scale
Pavement sections

SURFACING: Interlocking Concrete Paving Blocks (ICP-1)
Dimension: 200mm x 100mm x 80mm

25 - 30mm thick Sand bed

400g/m² Waterproof Geotextile fabric

BASE COURSE: Mechanically stabilized latite gravel with 0-40 stones, compacted to 95 - 98% mod. AASHTO (T180)

SUBGRADE:
100 - 150mm latite gravel proof rolled and compacted to 95% mod. AASHTO

ROADBED:
150mm Natural latite gravel Compacted to 95% mod. AASHTO

AFCAP Project GHA20658
Alternative Surfacing for Steep Slopes
Akwasih - Twenebuduase Road

Length: 70m
Chainage: 2+130 to 2+200

Designed by: Project Team
Drawing Prepared by: Project Team
Reviewed by: Project Team
Approved by: MRH/DFR

Section not drawn to scale
Pavement sections

SURFACING: 50mm thick Cold Mix Asphalt
Type: CMA-1

BASE COURSE: Mechanically stabilized lateritic gravel with 0-40 stones, compacted to 95 - 98% mod. AASHTO (T180)

SUBGRADE:
100 - 150mm lateritic gravel
proof rolled and compacted to 95% mod. AASHTO

ROADBED:
150Mm. Natural lateritic gravel
Compacted to 95% mod. AASHTO

AfCAP Project GPA2065B
Alternative Surfacing for Steep Slopes]
Akwasho - Tweddle Road

Length: 70m
Chainage: 2+660 to 2+730

Designed by: Project Team
Drawing Prepared by: Project Team
Reviewed by: Project Team
Approved by: WRH/DFR

Section not drawn to scale
Pavement sections

- Shoulder (max width = 1.0m)
- 3% Crossfall
- Thin Meshed Reinforced Concrete (TMRC)
- Side slope 1 in 1
- Back slope 1 in 1
- 100mm thick W25 Lined Concrete Drain
- In-situ rock formation (Subgrade)

Surfacing: 70mm thick Thin Meshed Reinforced Concrete
Type: TMRC-1

Reinforcement Mesh (6mm Ø bars @ 200 c/c)
M10 Blinding Concrete

Base Course: Mechanically stabilized lateritic gravel with 0-40 stones, compacted to 95 - 98% mod. AASHTO (T180)

Roadbed: In-situ sandstone rock formation

ARCAP Project GHA2065B
Alternative Surfacing for Steep Slopes]
Akwasho - Twenedurase Road

Length: 70m
Channage: 24+940 to 34+010

Designed by: Project Team
Drawing Prepared by: Project Team
Reviewed by: Project Team
Approved by: MRR/DFR

Section not drawn to scale
Pavement sections

SURFACING: 110mm thick Roller Compacted Concrete
TYPE: RCC-1

BASE COURSE: Mechanically stabilized lateritic gravel with 0-40 stones, compacted to 95 - 98% mod. AMHTO (T180)

ROADBED: In-situ sandstone rock formation

AFCAP Project OHA20658
Alternative Surfacing for Steep Slopes
Akwasino - Tweduruwe Road

Length: 70m
Chainage: 3+220 to 3+290

Designed by: Project Team
Drawing Prepared by: Project Team
Reviewed by: Project Team
Approved by: MRH/DFR

Section not drawn to scale
Construction costs

- COBBLESTONE 1 (From Quarry Site)
- INTERLOCKING CONCRETE PAVING BLOCKS FROM PPC (Sand & quarry agg.)
- COLD MIX ASPHALT (Modified Emulsion with optimum lime/cement additive and all quarry stones)
- THIN MESHER REINFORCED CONCRETE FROM OPC (Sand & quarry agg. using Potland - Pozzolana 70/30 cement)
- ROLLER COMPACTED CONCRETE FROM PPC (Quarry dust & agg. using Potland - Pozzolana 70/30 cement)
Conclusions

1. Structural design
   - DCP-DN structural design applicability (Traffic volume > 300 vpd; ESA > 1 Million)
   - Conventional pavement design approach

2. Demonstration section
   - Adequacy of demonstration section lengths
   - Matrix composition
Conclusions (cont.)

3. Drainage
   – Safe and efficient discharging of surface runoff in side drains
   – Effects of sub-surface water action
   – Containment of ground water dripping from rock surfaces

4. Slope stability
   – Appropriate interventions (e.g. bioengineering, benching techniques)
   – Separate contract will be awarded for slope stabilization works

5. Construction
   – Government funded project
Thank you for your attention

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