The Dharan-Dhankuta Road, Koshi Zone: overview of engineering performance and lessons learned during the first 40 years

Outline

1. DDR background
2. Geohazards & preventive/remedial works since the 1970s:
   - landslides & slope erosion
   - storms & flooding
   - earthquakes
3. Case study: remedial works after 1988 earthquake
4. DDR performance by mountain zone:
   - Zone 2
   - Zone 3
   - Zone 4 (including hairpin stacks)
   - Zone 5
5. Lessons learned
6. Concluding comments

Acknowledgements

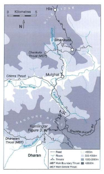
Logistics:

- the late Ishwar Sunwar (Roughton & Partners, & independently, for >20 years 1988 - 2011)
- Roughton & Partners (many staff from maintenance team on site at various times 1985-2002, especially John Howell, Jane Clark, Robin Workman, Tony Murphy)
- Indu Dhakal
- Shuva Sharma
- Sumit Dagar

Information/Photographs/Data:

- Ishwar Sunwar
- Shuva Sharma
- Indu Dhakal
- Sumit Dagar
- John Howell
- Robin Workman
- Tony Murphy

Koshi Highway Evolution including DDR

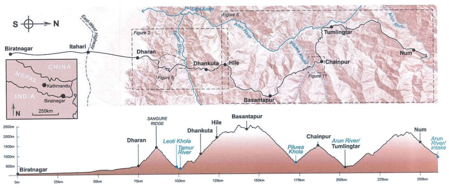


Koshi Highway, National Route H 08: access to

- Dhankuta c.1981
- Hile c.1982
- Basantpur c.1985
- Tumlingtar c.2001
- Num c.2012

UK Govt/Nepal Govt DoR collaboration

World Bank/Nepal Govt DoR/Nepal Electricity Authority collaboration



Hearn (2017)

DDR: chronological summary

Feasibility Studies:

- Coalma route 1973-74
- RPT route 1974-75

Investigations, Topographic Survey, Preliminary Design 1975-76

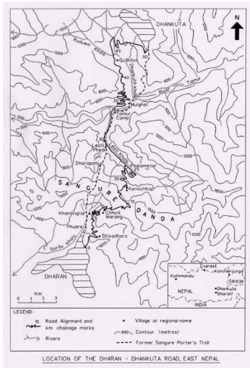
Detailed Design, Construction 1977-1982:

- RPT site design team
- UK Govt's Property Services Agency (PSA) managing contractor

Official opening: 15.3.1984 by late King Birendra

Maintenance:

- Roughton & Partners/Roughton International 1984-2002
- DoR 2002 - present



DDR: Geology & terrain conditions

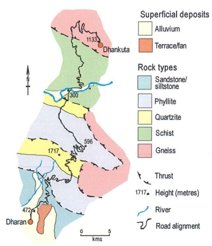
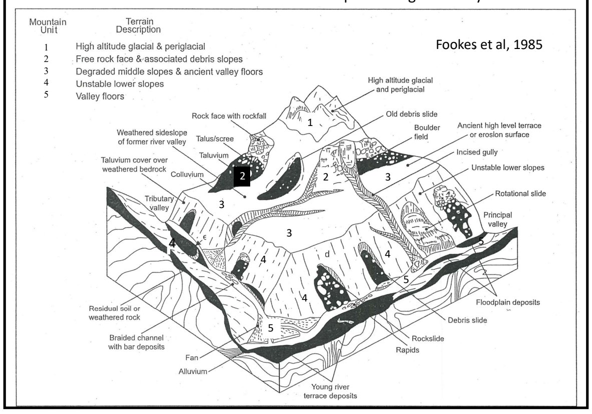


Figure CS7.1.2 Geology of the Dharan-Dhankuta area (from Fookes & Marsh, 1981).

Potential deep rock weathering and crushed/sheared rocks around faults and thrusts already known during feasibility studies

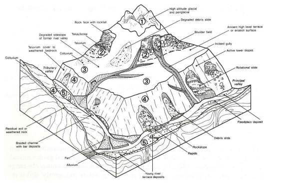
Major potential natural landslide (up to sub-catchment-scale instability) and flood hazards well appreciated at feasibility & reconnaissance stages

Terrain Framework: mountain model developed during feasibility studies

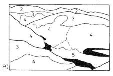


Fookes et al, 1985

DDR: alignment selection & design philosophy w.r.t. mountain model



Alignment selection: make height in Zone 4 via relatively stable climbing corridors, make distance in Zone 3



Mountain model: view from the DDR looking south across Tamur River valley to Sangure Danda

Cross-section design:

- Zone 2, generally full cut, but avoid 'joint-controlled' rock cutting where possible
- Zone 3, balanced earthworks
- Zone 4, minimise earthworks as far as possible with careful balancing, make use of sound rock at depth, accept extensive use of walls and revetments
- Zone 5, just above max FL, avoid full embankment or retained fill at constrictions (e.g. gorges and other sites with potential for high debris impact and deep scour), cross alluvial fans at throat where possible

DDR: design standards & construction statistics

DDR design standards – a 'mountain motorway' relative to other Nepal hill roads at the time?

Item	Standard	Remarks
Carriageway width	5.50m	Widening on bends, up to 9 m at hairpins, in according with AASHO standards
Shoulder width	0.5 - 1 m	
Design speed	30 km/h	
Maximum gradient	9 - 11 %	Maximum 3 % at hairpins ± 20 m from start/end of curve. Maximum length of gradient >9% limited to <1000m
Minimum curve radius	25 m	Decreased to minimum 9 m at hairpins
Maximum superelevation	8 %	For curve radius of 20 m or less

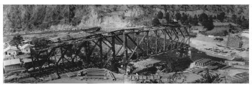
Approximate construction data

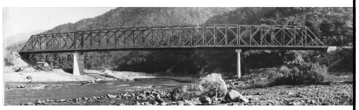
Item	Quantity/Unit	Remarks
Peak Labour Force	c. 15,000	Around mid 1978
Average Labour Force	5,000-10,000	From about mid 1977 – mid 1980
Total Rock and Soil Excavation	c. 4,100,000 m3	Derived from the total construction costs for Earthworks, Retaining Walls, River Training, Drainage and Area Drainage items.
Total Embankment/Soil Fill Material	c. 700,000 m3	
Total Gabion Retaining Walls/ Revetments/Protection Structures	c. 280,000 m3	
Total Masonry Retaining Walls/Culvert Abutments / Revetments / Protection Structures	c. 30,000 m3	
Number of Bridges	12	1 200 m-long steel truss (Tamur), 2 32 m-long concrete arches, 9 concrete slabs or T-beams of length 8 – 40 m.
Number of Culverts	c. 330	About 50% masonry abutments with concrete slabs up to 5 m x 5 m in size, 50% steel Armco up to 2 tubes of 1.4 m diameter.
Total Construction Cost	£15.4 Million	1981 prices, comprising c. £10.9 M on construction items and c. £4.5 M for inflation, design and management fees.

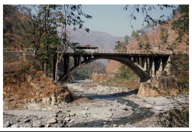
DDR: major structures

Ruduwa Khola Bridge, 32m

Tamur River Bridge, 200m



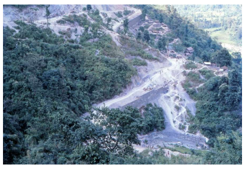




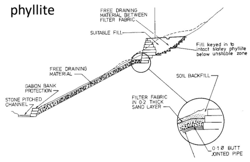
Leoti Khola Bridge, 32m

Geohazards & Preventive/Remedial Works - landslides & slope erosion

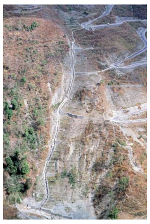
c.10,000m³ rockslide during construction, - buffer zone & bund built at toe after debris clearance, with local realignment



Retaining wall & downslope drainage to cross existing slump failure in fractured phyllite

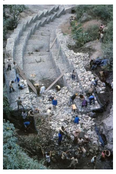


Extensive hillside support & 300m-long stepped masonry cascade to control erosion from side drain exits on hairpins

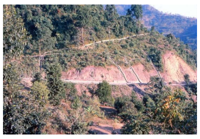


Geohazards & Preventive/Remedial Works - landslides & slope erosion

Gabion mattresses & cascades below culvert outlets for gully protection

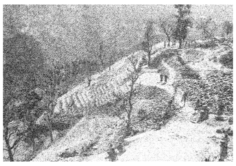


Collapsed access track from surface runoff replaced by gabion wall with deeper foundation



Trench & filter drains in areas with seepage and surface distress

Geohazards & Preventive/Remedial Works - landslides & slope erosion

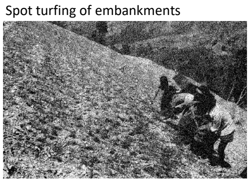


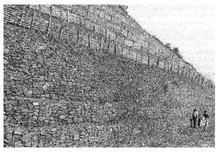
Terracing of spoil tips

Major effort by PSA IOWs & site support staff to control loose spoil tipping during construction

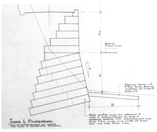
Brushwood barriers on tipped spoil (above); wooden fences on erodible high cut slope (below)

Spot turfing of embankments



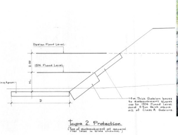


Geohazards & Preventive/Remedial Works - storms & flooding

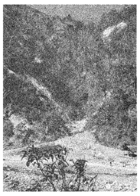

Original construction of gabion walls (above) and embankment protection (below), with flexible 'falling apron' mattresses into scour holes

Wall and embankment collapses and washouts from Leoti floods

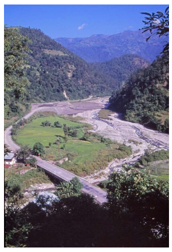




Geohazards & Preventive/Remedial Works - storms & flooding

New alluvial fans from catchment instability in tributary valleys, causing bridge blockage

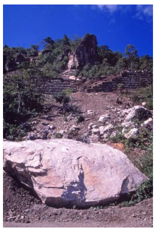
Example of Garjuwa Khola: minor fan build-up in 1974 (left) during reconnaissance walkover, c.6m bridge deck clearance judged acceptable. Massive new tributary catchment landsliding & erosion completed inundated bridge in <20 years (right, fan in middle distance in 1998)



Geohazards & Preventive/Remedial Works - earthquakes

Cracking & displacement of carriageway and adjacent slopes, undermining and collapse of retaining walls



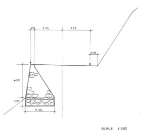
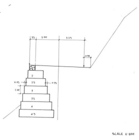


Road blockage from rockslides in high rock cuts, rockfall from natural rock outcrops between roadlines


1988 Earthquake Case Study Background (1)

2km-long hairpinning section of road built 1977/78; severely damaged by M=6.6 earthquake in 1988

Undesirable lengths of masonry retaining wall up to 7m high founded on soil were designed and built in 1978 because of materials supply issues (lack of gabion wire on site, when gabion walls were the preferred wall type)

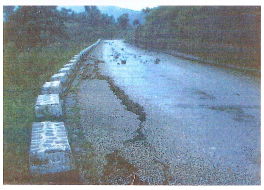
1988 Earthquake Case Study Background (2)

40m-long section of masonry wall failed by lateral displacement and rotation

Other sections settled and displaced outwards by up to 3.0m at crest

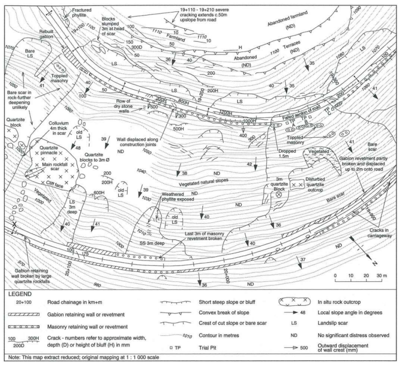
Ductile gabion walls in adjacent sections up to 10m high deformed by bulging and settlement on non-yielding foundations.

No complete failures, maximum outward displacement c.400mm at crest



1988 Earthquake Case Study Background (3)

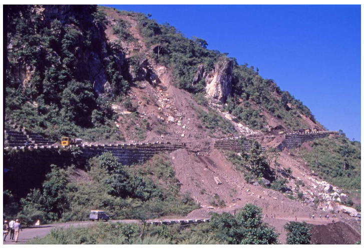
Extensive cracking of natural hillside, formed in colluvium and weathered phyllites, was observed and mapped above and between the roadlines



Martin, 2001

1988 Earthquake Case Study Background (4)

Two short sections on lower road line supported by gabion walls up to 8m high destroyed by rockfalls from quartzite rock pinnacles – largest rockfall blocks up to 300 tonnes

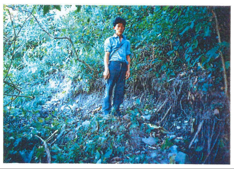


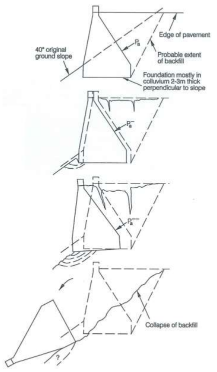
1988 Earthquake Case Study
Key Issues Requiring Engineering Judgement

1. Rebuild damaged roadline, or abandon it and realign new section of road on adjacent hillside?
2. If rebuild, what type of retaining wall and cross-section to use for failed lengths of masonry wall?
3. Demolish and rebuild other displaced (but not completely failed) masonry walls?, or attempt to repair them?
4. Attempt to stabilise large rock pinnacles against future earthquake–generated rockfalls?

1988 Earthquake Case Study – Decision on Key Issue 1

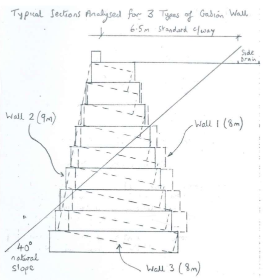
Rebuild roadline, not realignment. Critical field observation from mapping of distress on hillside – cracking was generally superficial, <300mm deep, judged insufficient to promote further instability to undermine whole roadline; plus inferred mechanism of masonry wall collapse was due mainly to inadequate original toe embedment and high toe bearing pressures, not deep-seated instability under whole roadline.





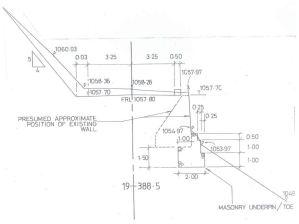
1988 Earthquake Case Study – Decision on Key Issue 2

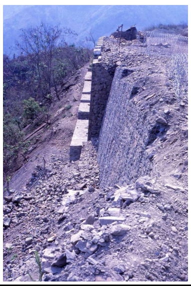
Rebuild failed sections with battered gabion walls sloping at 5:1 into hillside, after trial analysis of 3 wall shapes



1988 Earthquake Case Study – Decision on Key Issue 3

Salvage and repair displaced masonry walls wherever practicable by underpinning and/or buttressing. (Demolition of displaced blocks of masonry walls in units 6m long and up weighing up to c.250 tonnes was a major logistical constraint for reconstruction).





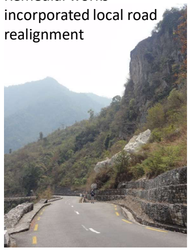
1988 Earthquake Case Study – Decision on Key Issue 4

Accept future earthquake-generated rockfalls as tolerable risk. Full-scale stabilisation of rock pinnacles judged to be beyond scope of reasonable improvement works.

Footnote: repetition of very similar damage in <25 years, is this 'tolerable risk'?

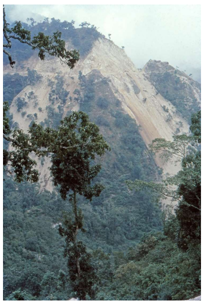
Rockfall damage in Sept 2011 M6.8 earthquake

Remedial works incorporated local road realignment



Summary of DDR performance over 40 years: zone 2

Secure alignment.
- No significant collapses
- Occasional blockage from cut slope failures.
- Problematic spoil disposal during construction, >10 years for some slopes to revegetate



Brittle quartzites susceptible to rockslides during earthquakes

Unbalanced earthworks, large excess cut material unavoidable- significant spoil disposal issues during construction

Summary of DDR performance over 40 years: zone 3

Very secure alignment.
- no significant collapses
- occasional rebuilding of deformed gabion walls across drainage lines required soon after construction

Balanced earthworks, modest use of retaining walls

Reconstruction of deformed gabion wall – due to poor stone packing & inadequate supervision during original construction

Summary of DDR performance over 40 years: zone 4

Generally secure alignment.
- No major collapse of multiple stacked hairpins
- Some major damage to relatively short sections during major earthquakes;
- Frequent cut slope failures and occasional collapses during construction, and occasional failures during maintenance period:
- Significant gully erosion below culverts and side drain outlets at hairpins required extensive offsite erosion control by checkdams and cascades.

Checkdams in eroding gully

Rebuilding failed section of gabion revetment

Long erosion scar below hairpin side drain exit (left) and extensive hillside repair work (right)

Summary of DDR performance : zone 4 (continued)

Good performance to date from major hairpin stacks, aided by full linings of gullies between roadlines & below side drain exits for erosion protection

Khamlingtar hairpins under construction (1978) and on completion (1982)

Masonry & gabion cascades between culverts

Mulghat hairpins under construction (1979)

Summary of DDR performance over 40 years: zone 5

Alignment generally insecure over c.3k of 5k Leoti River length.
- Repeated loss of roadline by flood impact and scour at several sections 30-200m long (up to 5 times at same location 1984 - 2014). <u>Impact increased by minor horizontal realignments towards river during construction 1978/79</u>
- 1 bridge across tributary valley completely buried by alluvial fan debris within 15 years after construction
- 3 other bridges requiring regular excavation of fan debris to reinstate original bridge deck
- Occasional failures in high rock cuts causing blockage during construction, and during maintenance period

Long retained fill section protected by toe aprons and groynes on completion (1982, left), undermined by scour and flood damage (1988, right)

Summary of DDR performance: zone 5 (continued)

Bridge and initial downstream training walls to encourage sediment flushing (right) completely buried under further fan buildup (left)

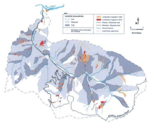
Other bridges requiring regular clearance of fan debris to reinstate bridge decks

DDR Performance: Summary of known major damage & downtime

Year	Major Hazards	Downtime	Comments on Damage
1984	Flood	several days	400m road, 1 tributary bridge, several groynes destroyed. Road maintenance camp buried in sediment
1985	Flood	?	?
1987	Flood	?	?
1988	Earthquake, Landslides (Aug), Landslides, Flood (Sept)	4 days no traffic, then light vehicles only 3 weeks, full clearance 2.5 months	Road collapse or breakage by rockfall at 3 locations in hill section, plus 14 other complete road blockages. Road destroyed by flood impact at 4 locations in river section. 2 tributary bridges blocked/overtopped. Large increase in alluvial fan debris due to major new landsliding in tributary catchments
2002	Flood	?	?
2003/4	Flood	?	Loss of >100m road
2011	Earthquake	1 day?	Road destroyed by rockfall at same location as in 1988
2012	Flood	1 or 2 days?	?
2013	Flood	?	?
2014	Flood	?	80m of same section lost in 2012 destroyed

Key Lessons Learned: alignment selection & design

- Great care needed at feasibility stage to select appropriate climbing corridors for hairpins in zone 4



Leoti catchment landslide comparison 1984 & 2015 (Hearn, 2017)

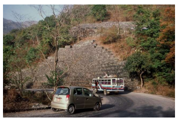
- Avoid fully-embanked or retained fill cross-sections in gorge constrictions and outsides of meander bends in zone 5

- Avoid rigid retaining walls on soil foundations in seismically active terrain

Key Lessons Learned: retaining and drainage structures

- Much attention to design detailing and construction sequence needed in hairpin stacks, to minimise risk of progressive failure during construction

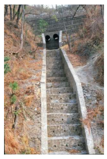
- Quality of stone & workmanship during construction critical for secure performance of high gabion retaining walls & revetments



Key Lessons Learned: retaining and drainage structures

- Build at-grade culverts along gully floors wherever practicable – minimise use of 'drop' outlets through retaining walls (for reduced erosion/scour below and risk of culvert breakage/cracking during in-service wall deformation)

- Generally poor performance of inclined mattresses, masonry and stone-pitched linings along vulnerable drainage lines – needed replacement by heavier stepped cascades or closely-spaced checkdams

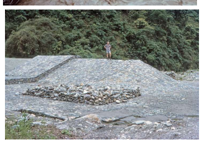


Key Lessons Learned: flood & scour protection

- Under-estimation of flood damage and scour potential, leading to inadequate designs for protection of embankments and walls subject to direct flood impact

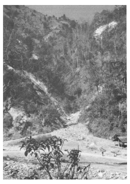
- Inadequacy of designed 'falling aprons' against scour

- Indaequacy of designed groynes and 'river training'/bank protection walls to prevent major flood and scour damage

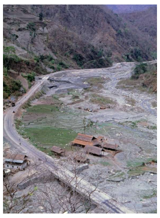


Key Lessons Learned: alluvial fan crossings

- More focus needed to assess instability in tributary catchments and potential locations of fan accumulation at feasibility stage



- Put horizontal alignment as close to fan throat as possible. Increase vertical clearance of bridge decks at fan crossings as far as practicable



DDR performance over 40 years: concluding comments

- Hill sections (c.44km) : overall good performance, little downtime except for significant disruption during 1988 earthquake affecting 1.5km-long section at Karkichhap
- Leoti River section (c.6km): overall poor performance, greater damage than anticipated during design and construction. But downtime limited due to relative ease in forming temporary access in river bed, pending remedial works
- Unwise (in hindsight) small adjustments to horizontal alignment outwards into Leoti river bed during construction in 1978/79, to speed up access for building the Tamur Bridge
- Major hairpin stacks (Khamlingtar, Mulghat) worked well so far, but vulnerable to progressive erosion and blockage, especially at culverts and along gullies between road legs – deserves focus in ongoing maintenance
- Uncertainty in assessing/predicting cycles of natural landsliding & erosion relevant to road design and construction
- Excessive 'mountain motorway' design standards?: road would be more secure with less generous widening, minimum curve radius, and maximum gradient – fewer hairpins in climbing stacks, reduced heights of retaining walls, less excavation & filling, etc.

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