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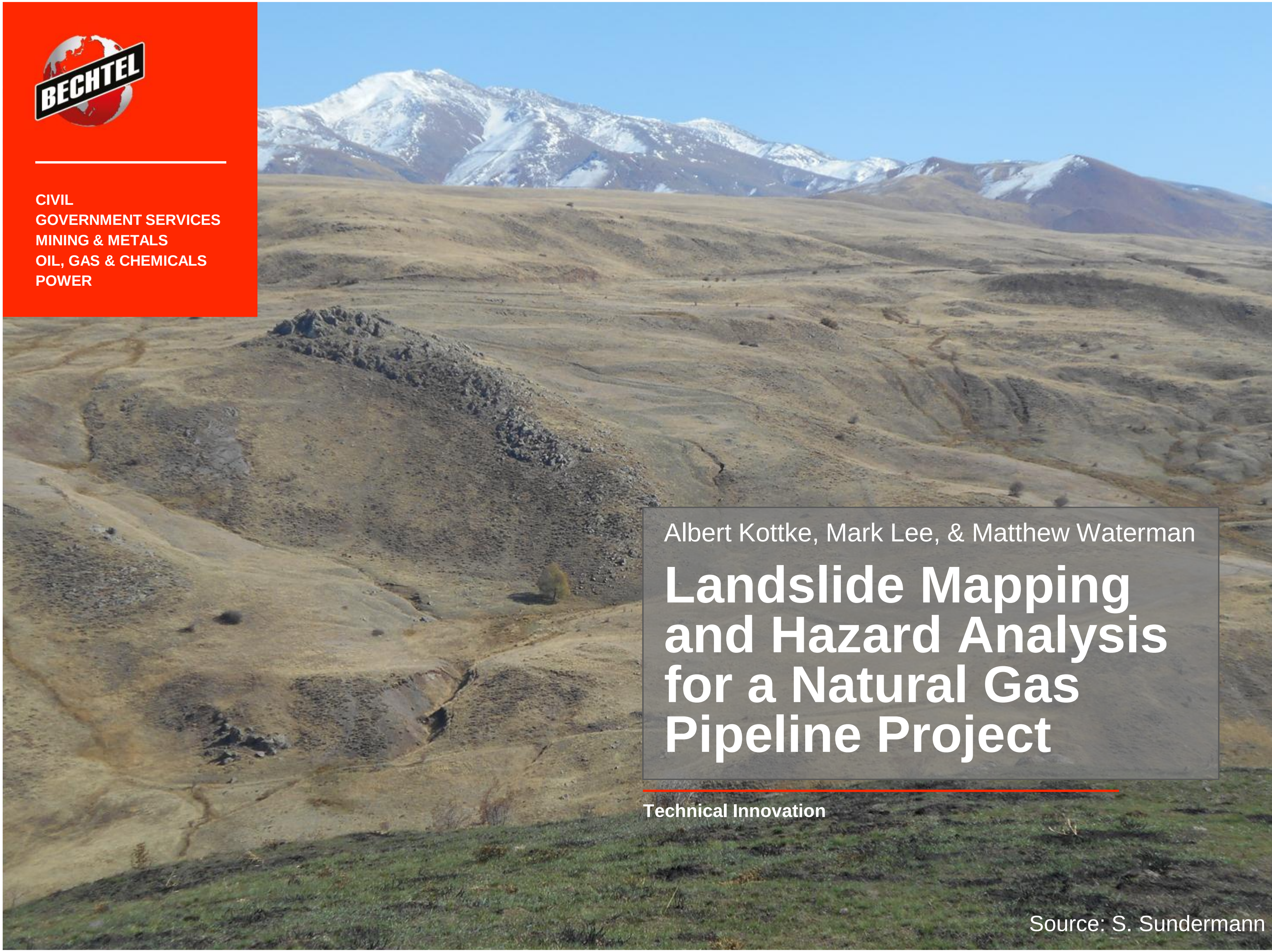


Albert Kottke, Mark Lee, & Matthew Waterman

Landslide Mapping and Hazard Analysis for a Natural Gas Pipeline Project

Technical Innovation

Source: S. Sundermann

Project Overview

- Route selection, evaluation, and preliminary design of an 1850 km natural gas pipeline
- Route crosses wide range of conditions:
  - Elevations ranging from sea level to over 3,000 m
  - Varied geology
  - Multiple geohazards:
    - Active faults
    - Karst
    - Liquefiable soil
    - Landslides
- Avoidance is the primary method for addressing geohazards – requires accurate identification

View along the alignment (Source: A. Kottke)

Prior Work

- Client's geologists performed identification and characterization of geohazards:
  - Desktop review of geohazards using Google Earth
  - Supplemented with site visits to specific areas to confirm desktop review and propose re-routes
- Work relied on:
  - Ability to identify geohazards from remote imagery and topography
  - Knowledge of local areas with significant geohazards
- No systematic program of field verification
- Identified ~1800 suspected landslides within 500 m of alignment

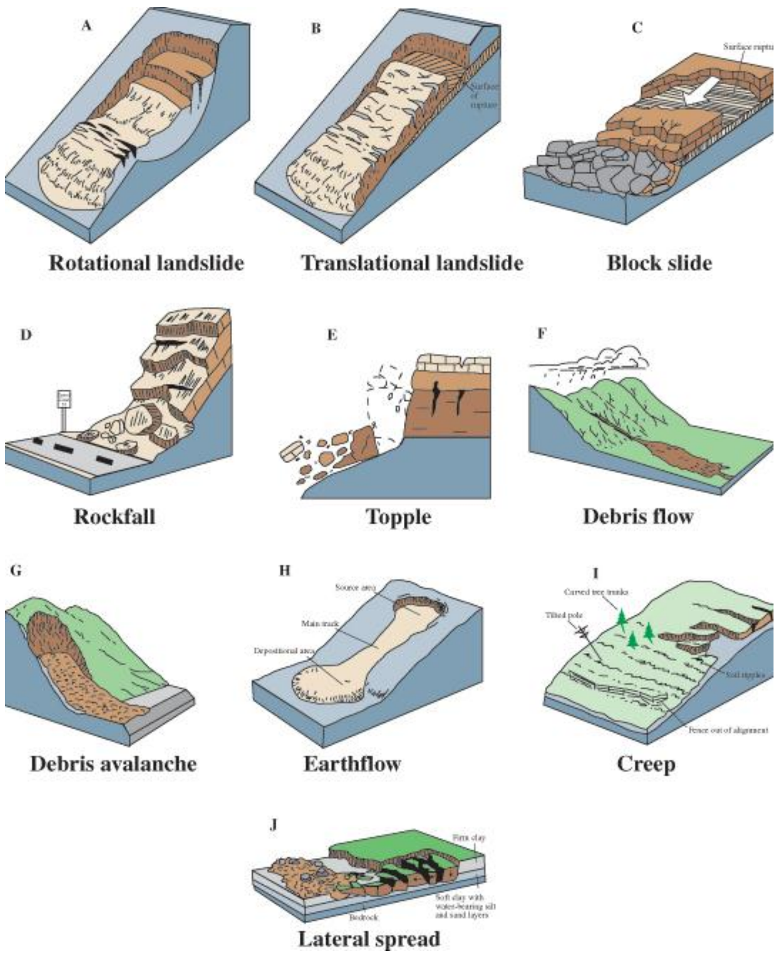
Aerial imagery with topography with landslide feature

Pre-Field Work Planning (Logistics / Hardware)

- Used digital geologic mapping with tablet PCs running ESRI ArcPad:
  - Allowed for seamless integration with project GIS system
  - Incorporation of data from multiple sources
  - Referencing multiple maps (topographic, orthophoto, geographic, etc.)
- Divided the alignment into five zones:
  - Each zone was mapped by teams of geologists
  - Specific areas were visited by subject matter experts

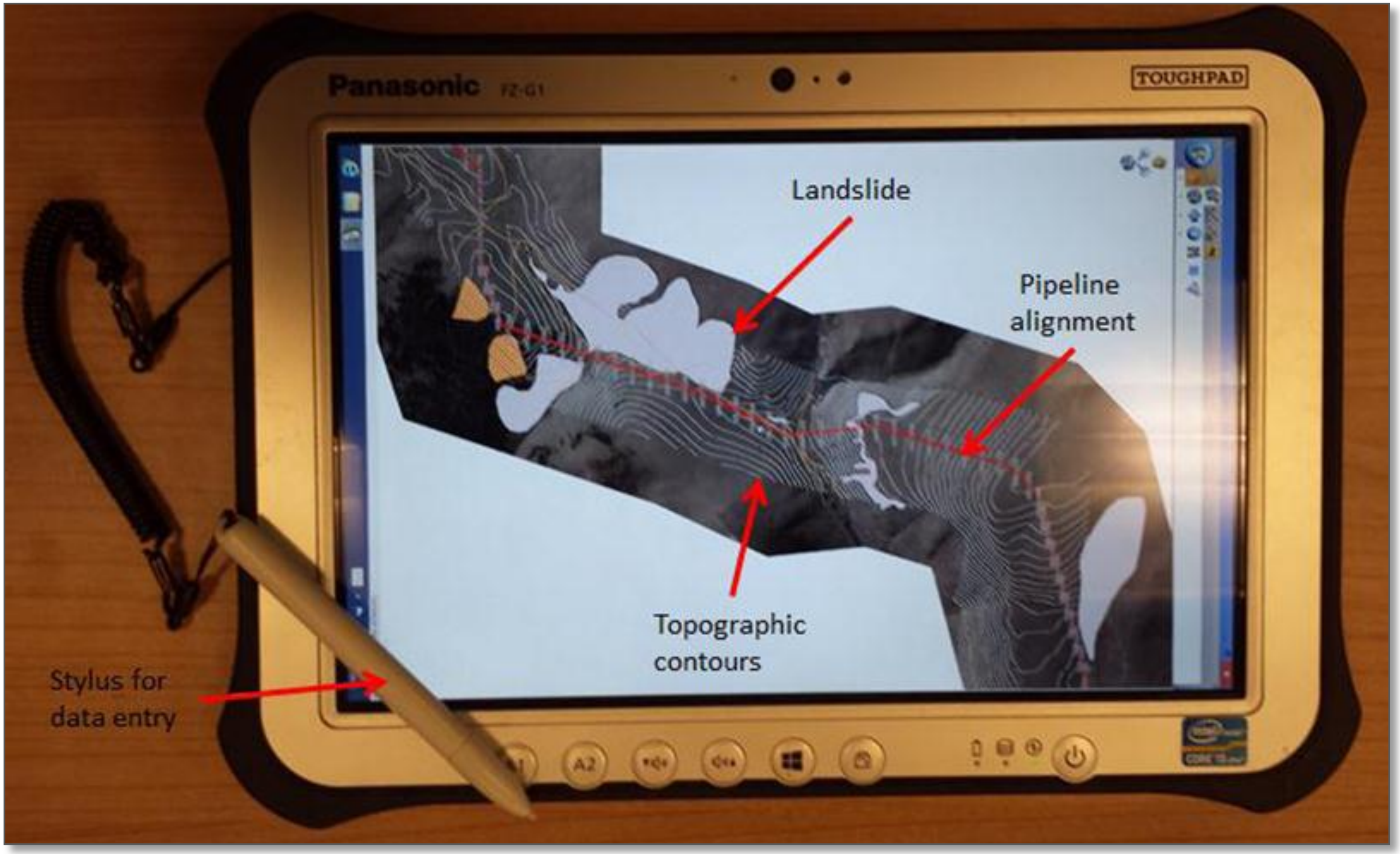
Landslide Classification

- Considered all potential slides within 200 m of alignment
- Mapped spatial area of the landslides and classified landslides for risk assessment
- Classified previously identified and newly mapped landslides
  - Mechanism
  - Type (Cruden and Varnes, 1996)
  - Activity State
  - Estimated thickness



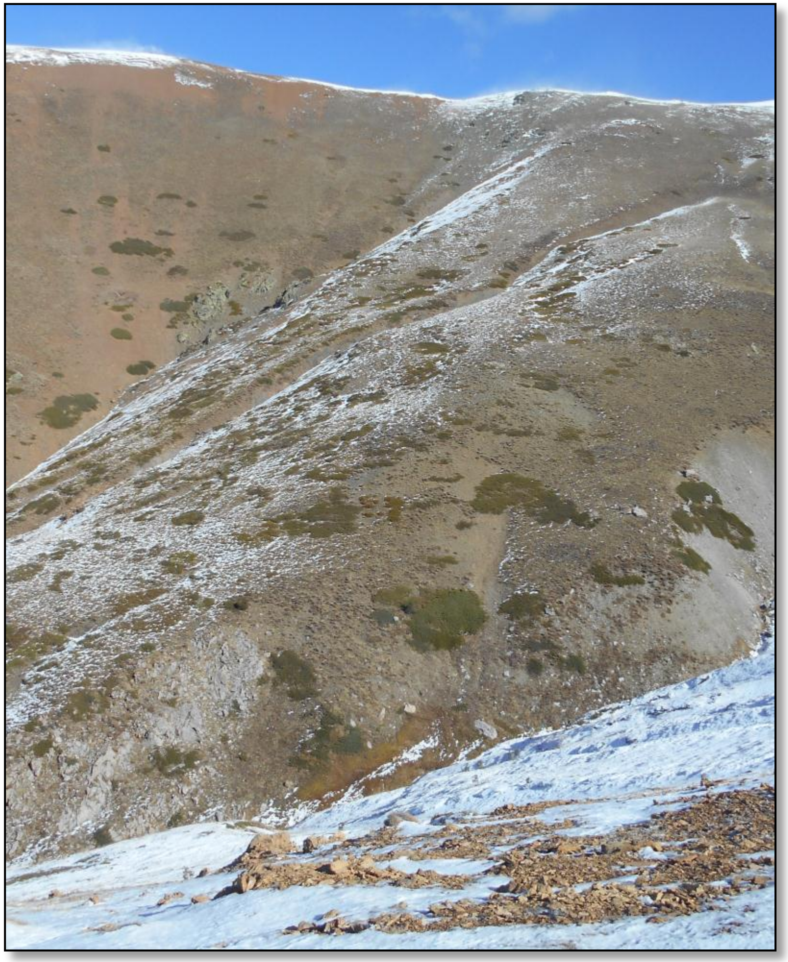
From USGS Facto Sheet 2004-3072 July 2004
http://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html

Fieldwork / Data Collection



Source: M. Waterman

Fieldwork / Data Collection



Sources: A. Kottke and S. Sundermann

Post Processing of Landslide Data

- Combined mapped geohazards from all geology teams
- Review each landslide:
  - Presence based on field and updated desktop mapping
  - Unified the classification scheme for all landslides
  - Incorporated preliminary results of field exploration program
- Developed a register of landslides within 50 m of alignment:
  - 298 features (88 sites added by field mapping) at 309 locations
  - Each of these features was re-examined to ensure correct landslide type and boundary delineation

Example of mapped landslide from multiple sources

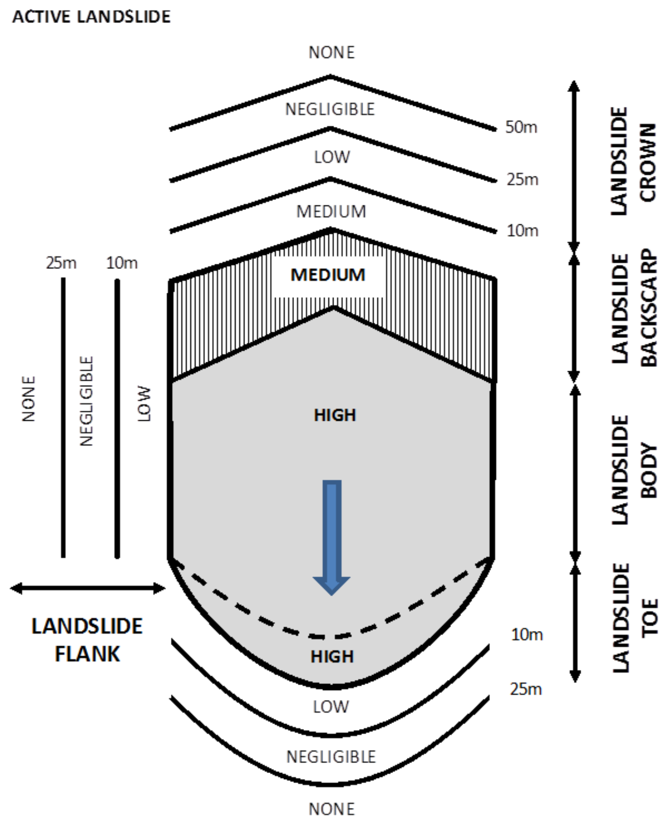
Updated Landslide Classification

- Final register is dominated by translational slides of debris and earth
- Includes:
  - Meters of creeping earth
  - Kilometers of sliding debris
- Need to relate presence of landslide to potential for pipeline rupture

Mechanism	Landslide Type	Rock	Debris	Earth
Falls	Fall	23	0	1
	Topple	1	0	0
Slides	Single Rotational	0	37	0
	Multiple Rotational	3	0	0
	Translational slide	5	105	57
	Mudslide	0	0	33
	Creep	0	0	10
Flows	Channelised flows	0	3	0
Complex	Rock slide complex	3	0	0
	Rock and debris	0	3	0
	Debris slide	0	13	0
	Earth slide (mudslide)	0	0	1

Landslide Hazard Assessment

- Hazard classes based on judgment:
  - None: No credible threat
  - Negligible: Rupture only under exception circumstances
  - Low: Rupture unlikely to occur during lifetime of the project
  - Medium: Rupture could potentially occur
  - High: Rupture should be expected to occur
- Developed a set of criteria based on:
  - Proximity to alignment
  - Relative position
  - Activity state
  - Thickness



Hazard classes relative to landslide body and proximity to pipeline (M. Lee 2013)

Landslide Hazard Mitigation

- Majority of sites had hazard levels of negligible or none
- 20 sites had medium and high hazard levels
- Mitigation efforts are to be handled on a case-by-case basis:
  - Rerouting of the alignment is preferred
  - Deep burial is a potential solution but requires detailed field investigations and engineering

Hazard Class	Number of Sites
High	6
Medium	14
Low	43
Negligible	79
None	167
TOTAL	309

Final Design

1. Field Investigations:
   - A LiDAR survey should supplement the field work described in this presentation
   - Additional borings and/or trial pits should be planned at locations of landslides where rerouting may not be an option, to help determine deepest potentially active slip plane depth
   - During construction geologists should be present to identify additional geohazards not previously identified due to obstructions of right-of-way
2. Field Reconnaissance:
   - Geohazard reconnaissance to identify gaps resulting from pipeline reroutes and relocation of compressor stations or other supporting equipment
3. Geohazard Analyses:
   - Interpretation of LiDAR survey for identification of landslides
   - Evaluation of engineering solutions (stabilization measures) for locations where residual risk for landslides exists after rerouting
   - Hazard assessment for seismic triggering of landslides

Conclusions

1. Aim of work was to identify sections of the alignment where landslides presented an unacceptable level of hazard to operation of the pipeline
2. Results of field and desktop studies were used to develop a landslide hazard register which ranked landslides according to their hazard level
3. The primary mitigation strategy has been to reroute the pipeline to avoid as many high and medium hazard landslides as possible, but it is not possible to remove exposure to low and negligible hazard sites
4. Predominant landslide areas can be identified by circuitous rerouting to avoid these features
5. Where it is not feasible to avoid being in close proximity to mapped landslides and residual risk is unavoidable given routing through mountainous, landslide prone terrain, this risk may be mitigated through engineering solutions.