

IPC04-0390

THE ROLE OF AERIAL PHOTOGRAPH INTERPRETATION IN NATURAL HAZARD AND RISK ASSESSMENT

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ABSTRACT

Aerial photograph interpretation is an accurate and economical method of assessing terrain conditions and natural hazards affecting pipelines and other linear facilities. Completed in advance of vehicle and helicopter-based reconnaissance, it provides a comprehensive site overview that cannot be obtained at ground level. Aerial photograph interpretation helps construct and confirm preliminary hazard and stream-crossing inventories, understand hazard mechanisms, and estimate hazard volume and activity. Time series photo interpretation uses several sets of aerial photographs taken of the same area in different years to track changes in terrain, stream patterns and land-use over time. In addition, aerial photographs are superior navigation tools in the field.

These points are illustrated using examples from pipelines in British Columbia and Alberta. This work will be of interest to managers of pipelines throughout western Canada, and to those involved with pipeline route selection through mountainous regions.

(Keywords: British Columbia, Alberta, pipeline, landslide, hazard, risk, vulnerability, geotechnical, hydrotechnical, airphoto).

INTRODUCTION

Hazard identification is the first step in systematic and defensible risk management [1,2]. Natural hazard and risk management methodologies and databases rely on an accurate geographic base for the inventory of geotechnical and hydrotechnical hazards affecting the pipeline [3-5]. A partial inventory of hazards affecting the pipeline is contained in reports of inspection or maintenance to the utility. Field

investigation can identify hazards that are visible on the ground. However, the resulting list of hazards compiled with these techniques will be incomplete unless accompanied by, and referenced to, a systematic, spatial examination of terrain.

Aerial photograph interpretation of the pipeline corridor is a cost-effective and practical technique for establishing a geographic inventory of hazards and conducting regional and large-scale hazard assessments. Although not explicitly a part of risk calculations, information from aerial photograph interpretation can be used to approximate hazard magnitude and frequency, spatial variations in risk, and pipeline vulnerability.

This paper describes the role of aerial photo interpretation in natural hazard and risk management using examples from pipelines in British Columbia and Alberta.

BACKGROUND

Natural Hazard and Risk Assessment involves quantifying risk using probabilities and mathematical equations. A review of some standard risk terminology and principles [1,2] is required to understand the role of aerial photo interpretation during the hazard identification and risk analysis stages of the methodology.

Hazard refers to a condition with the potential to cause an undesirable effect on the pipeline. A natural hazard or geohazard is a geotechnical (i.e. landslide) or hydrotechnical (bank erosion) event. When quantified, hazard is the annual probability of a hazard of a certain magnitude (a.k.a. energy) occurring in a certain location.

Risk is a measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by the product of probability and consequences. In the context of risk analysis for pipelines, risk is commonly defined as the product of P, the probability of a hazard

impacting the pipeline, and C, the consequences of the impact.

$$R = P \times C \quad (1)$$

Probability and consequence can be subdivided into more specific terms as follows;

$$R = P(H) \times P(S:H) \times P(T:H) \times V \times E \quad (2)$$

where R is the risk to the pipeline; P(H) is the annual probability of a hazard of a certain magnitude (a.k.a. energy) occurring in a certain location; P(S:H) is the probability of spatial impact given the hazard has occurred; P(T:H) is the probability of temporal impact given that spatial impact has occurred. V is the vulnerability of the pipeline to the hazard; it is the proportion of loss suffered when the hazard impacts the element, and is expressed as number between 0 (no loss, damage, or injury) to 1 (total loss, complete destruction, or death). E is the population, buildings, and engineering works, economic activity, public services utilities, infrastructure and environmental features in the area potentially affected by the hazards.

The goal of risk analysis is to define, within the limits of the project resources, the above terms as accurately as possible. Aerial photograph interpretation plays an important role in defining the terms P(H), P(S:H), and V:

P(H) – Hazard frequency-magnitude relationships are explored using single or time series evaluation of aerial photographs to estimate the hazard type, volume, and frequency of occurrence. For example, landslide volume can be estimated from the dimensions and aspect ratio of the landslide observed in the aerial photographs, or using the approximation Volume $\sim A^{3/2}$, where A is the area of the landslide [6]. Rates of landslide movement or bank erosion can be estimated from time series photo interpretation.

P(S:H) – The likelihood of spatial impact can be evaluated using air photo interpretation [7]. After locating all hazards along the right-of-way, the likelihood of a landslide impacting the pipeline can be assessed by evaluating the runout from the three-dimensional view of terrain seen in the aerial photographs.

V – The vulnerability, or degree of loss, can also be assessed from aerial photographs [7] by identifying the hazard type, and estimating the magnitude and velocity. Buried pipelines are not often damaged from small rock falls or slides, yet they are highly susceptible to damage, and even rupture, from large rock falls and soil slides [8]. Air photo interpretation can also be used to evaluate potential damages in the immediate area and downstream of a pipeline rupture and site access for emergency response and mitigation strategies.

ENGINEERING GEOMORPHOLOGICAL MAPPING

Engineering geomorphological mapping identifies the distribution, form, origin, drainage, and other geotechnical terrain characteristics of a site or region under investigation [9,10]. The mapping techniques used are flexible and can be tailored to specific project objectives, such as slope stability, route selection, or in this case, natural hazard and risk management. Aerial photograph interpretation is a basic component of most in-office engineering geomorphological studies. Despite significant advancement in satellite-based

digital imagery, aerial photographs have superior resolution and are easier to use in the office and the field (Table 1).

Established terrain mapping standards and landslide classification schemes should be followed as closely as possible to facilitate accurate description and communication among engineers and geoscientists, and to facilitate the integration of data into risk management databases [3,11]. The terrain mapping legend most often used by the authors is the British Columbia Terrain Classification System [12,13], which describes surficial material, landform, geomorphological processes, and other terrain characteristics. The symbology includes labels, for polygons delineating areas with similar characteristics, and site symbols, for point and line features, such as landslides, stream, springs, ground fractures and beaver dams. Landslides types are classified as rock, debris or earth movements after Cruden and Varnes [6].

Standard schemes are used, wherever possible, to express the volume or frequency of landslides. If hazard frequency cannot be determined using aerial photo interpretation due to insufficient or no historic photograph editions, the terms active, inactive, dormant, historic, and others, may be used as a proxy for frequency [6,14].

Table 1 Comparison of aerial photograph (AP) and satellite imagery resolution (adapted from [9]).

Image Type	Pixel Size (GRC) ¹ (m)	Minimum Object Size ² (m)	Largest Useful Scale
Landsat TM, ETM	30	200 x 200	Regional
SPOT colour	20	135 x 135	Regional, Medium
SPOT B&W	10	65 x 65	Regional
IKONOS	1	7 x 7	Detailed
1:50 000 AP	1	7 x 7	Detailed
Quickbird	0.63	4 x 4	Detailed
1:15 000 AP	0.30	2 x 2	Detailed
1:10 000 AP	0.20	1.3 x 1.3	Detailed
1:5 000 AP	0.10	0.7 x 0.7	Detailed

¹ground resolution cell; = image scale/(1000 x line pair/mm), assuming 50 line pairs/mm for aerial photographs.

²45 GRCs needed to interpret an object in high contrast (high quality) imagery.

PROCEDURES FOR AERIAL PHOTOGRAPH INTERPRETATION

The typical procedure for completing air photo interpretation of pipeline corridors starts with obtaining stereo aerial photograph coverage of the right-of-way of interest. Pipeline routes can range from a few kilometres to over 1000 km in length. The best scale to use depends on the level of detail required, the length of corridor of interest, and budget constraints. Table 2 relates the stages of risk management to study scale, size and spatial accuracy [15].

Throughout much of North America, complete aerial photograph coverage is available at a cost of \$7-10 per photograph. Table 3 shows minimum costs for obtaining government-published aerial photograph coverage. In cases where government surveys are unavailable, incomplete, or of insufficient scale or quality, dedicated air photograph surveys

can be commissioned from airborne remote sensing service providers. Custom surveys will be more expensive. Their cost will depend on service provider, geometry of the pipeline, photo scale, and final deliverable.

For Stage 1 and Stage 2 hazard assessments, and for routes that exceed a few hundred kilometres in length, regional-scale photographs (1:50 000 to 1:40 000-scale) are preferred. These 'high-level' photographs provide a broad view of the corridor and allow interpretation of a wide swath of land on either side of the utility. Using a larger-scale series of air photos, such as 1:15 000 to 1:20,000 scale photographs, results in a greater number of stereo pairs to examine and increases the labour and materials costs. In addition, in 'low-level' photographs less ground is imaged, thus additional stereo pairs covering either side of the right-of-way will be required to observe terrain conditions away from the pipeline. This effect has not been taken into account in the tabulation of costs for large map scales in Table 3. An experienced geomorphologist equipped with stereo glasses capable of magnification often can identify as much hazard-related information on the 'high-level' photographs as is evident on the 'low-level' editions.

Table 2 Stages of risk management [9,15]

Stage	Class	Map Scale	Study Area (km ²)	Spatial Accuracy (m)
1	National	< 1:1,000,000	> 1000	> 500
1	Regional	1:50,000 to 1:500,000	< 1000	+/- 50 to 250
2	Medium	1:15,000 to 1:50,000	< 500	+/-8 to 25
3	Large	1:5,000 to 1:15,000	< 50	+/- 5 to 8
4	Detailed	1:500 to 1:5,000	< 5	+/-0.025 to 2.5

Once obtained, the photographs are organized in order of increasing chainage (i.e. kilometre or mileage post). One of each stereopair is annotated with a line representing the location of the pipeline right-of-way, which is marked off with the kilometre posting (KP). KP's are taken from pipeline route maps or alignment sheets. Stream crossings are indicated by arrows drawn along rivers, streams or gullies that cross the right-of-way. Streams that parallel, and are in proximity to, the pipeline are also indicated because they represent potential encroachment or avulsion/outflanking hazards. Other geographic information, such as towns, highways and valve stations can be labelled on the photographs as needed. Mapping is done using a mirror stereoscope or pocket stereoscope, with annotations on every other photograph (usually the right one of a pair if right-handed). India ink pens are preferred over wax pencils for their fine lines.

Detailed geomorphological mapping is done along the corridor in a swath centred on the pipeline. All locations of active or inactive geomorphologic processes, including landslides and streams, are mapped and classified using a combination of site symbols and labelled terrain polygons. Surficial material, surface expression, and other terrain characteristics as the risk algorithm demands, are mapped along

the entire right-of-way. The interpreter must take care to examine terrain conditions along either side of the right-of-way, preferably up to the height of land on both sides of the surrounding valley. Hazards may initiate in tributary valleys and travel some distance to impact pipelines or other linear facilities in the main valley (Fig. 1).

Table 3 Budget parameters for stereo aerial photographic coverage of pipeline routes.

Aerial Photograph (AP) Scale	AP Distance per 1 km of Pipeline, (cm)	# AP Pairs per 100 km of Pipeline ³	Cost of AP Coverage for 100 km of Pipeline ⁴
1:50 000	2	12	\$192
1:40 000	2.5	14	\$224
1:30 000	3.33	17	\$272
1:20 000	5	28	\$448
1:15 000	6.7	37	\$592
1:10 000	10	56	\$896

³ assuming straight route with standard AP overlap of 60% and mapping over central 18 cm of every other AP.

⁴ assuming a cost of \$8 per photograph.

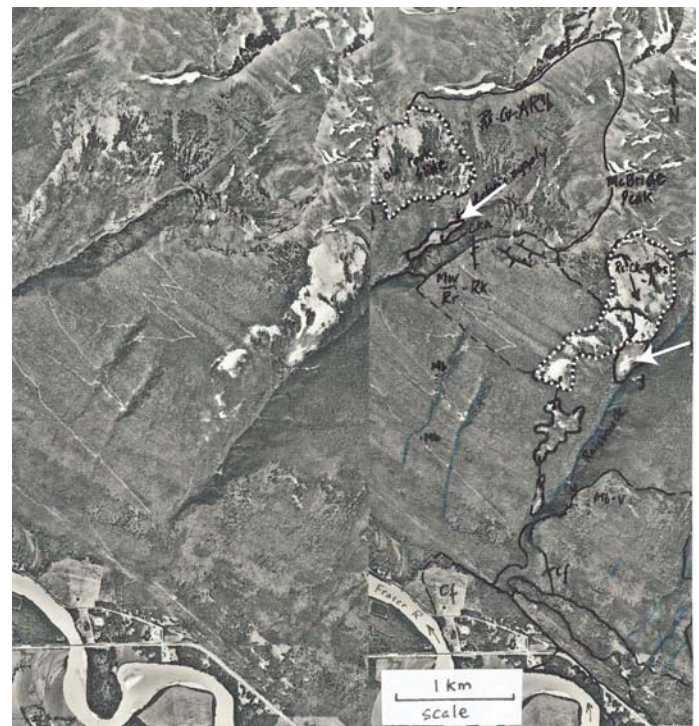


Figure 1 Stereogram of tributary watersheds along Robson Valley near McBride, B.C. Active rock fall (dotted) and abundant colluvium (arrow) in tributary valleys may contribute to debris flows or other hazards, which can travel downstream to impact facilities in the main valley.

The last step in engineering geomorphological mapping for hazard and risk analysis and database development is the transfer of information from aerial photographs to a computer

database. This requires the tabulation of terrain characteristics, landslides, stream crossings and encroachment locations keyed to pipeline KP. The information fields required will vary according to the project design [3,11].

HISTORICAL PHOTO INTERPRETATION

Aerial photographs are accurate records of historical terrain conditions. Historical photo interpretation, or time series analysis, involves viewing several sets of aerial photographs of the same region to document changes in terrain conditions, stream patterns, and land use through time. In Canada, commonly 5 or more editions of aerial photography are available for many areas going back 50 years or more. Early photographs may be oblique instead of vertical with inferior focus, cloud conditions, or overlap inconsistencies. Despite these shortcomings, their record of terrain conditions in the first half of the century is invaluable.

For Stage 3 and 4 studies, time series photo interpretation is used to advantage in tracking the progress of stream erosion or encroachment. The technique can lead to estimates of rates of erosion and channel migration. Forest harvesting, road and bridge building, or road deactivation can be tracked over time to monitor the effects of these activities on riverbank erosion and degradation. In addition, time series photo interpretation may provide evidence of past hazards that were not on record.

BUILDING A GEOTECHNICAL HAZARD INVENTORY

Aerial photograph interpretation of the right-of-way is an integral step in building a complete geotechnical inventory [3,11]. Using photo interpretation, one can identify all hazards and conditions affecting the pipeline including those not visited or readily accessible in the field (Fig. 1), and those places where signs of instability are not evident on the ground (Figs. 2, 3). For example, landslides of probable early post-glacial age along the northern shore of Wabamum Lake, Alberta illustrate the potential for similar failures along the right-of-way that are not immediately visible during field inspection (Figs. 2, 3).

At a minimum the hazard location relative to the pipeline, hazard type, area, estimated volume, and activity should be assessed and recorded by the interpreter. This is the minimum information required to identify the hazard, estimate the likelihood of occurrence and potential vulnerability of the pipeline to the hazard. Maximum velocity, runout, and potential damage can be inferred from these minimum requirements. Stage 3 and 4 assessments require more details than those listed above.

BUILDING A HYDROTECHNICAL HAZARD INVENTORY

The first step in assessing hydrotechnical hazards affecting the pipeline is the development of a complete inventory of streams crossings and encroachment areas. Aerial photograph interpretation is an important tool for compiling a comprehensive tabulation of all river, stream and gully crossings. This preliminary inventory will help determine the scope of the field inspections, help with field navigation, and identify activities and features affecting the flow regime that are located beyond the immediate hazard site.

Many streams are not identified on topographic maps or commonly available thematic maps, and a pipeline company may not have a complete list of stream crossings. Inevitably, a

detailed photo interpretation survey will result in a long list of crossings, many of which will not match with the records of the pipeline company. Many of the new, previously untabulated crossings might be glaciofluvial meltwater channels or other ephemeral gullies that are unlikely to contain significant flow. Ephemeral streams are confirmed in the field and some are retained in the inventory.



Figure 2 Top: Stereogram of pipeline (dashed) near Wabamun Lake, 90 km east of Edmonton, Alberta, showing large areas of landsliding along the shore of the lake (dotted). Star shows location of Figure 3.

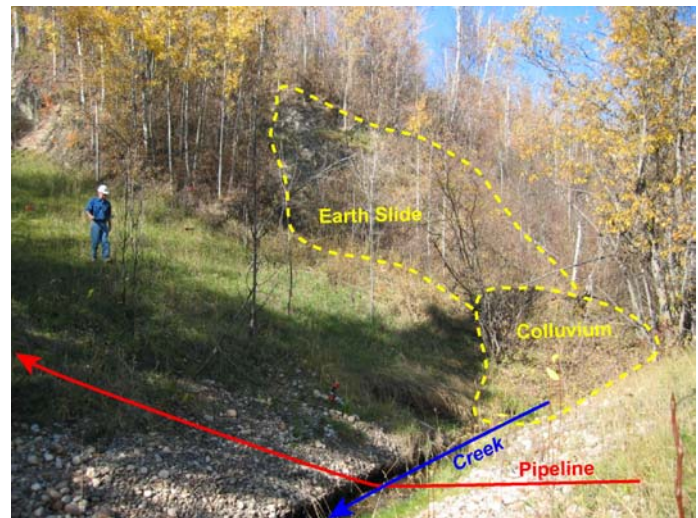


Figure 3 A small earth slide was observed at the stream crossing at KP 91 (Fig. 2 star). No indication of the greater extent of landsliding visible on the aerial photographs.

The interpreter can tabulate other terrain characteristics as required by the database design, for example the presence of defences such as berms, control structures or rip rap. These features are best seen at low stage or on large-scale photographs.

HAZARD FREQUENCY-MAGNITUDE RELATIONSHIPS

Defining the frequency-magnitude relationships for a hazard type in a given area, $P(H)$ in Eq. 2, is a necessary but often difficult undertaking. If a frequency-magnitude curve can be constructed for a region then a more accurate estimate of $P(H)$ will be known. Time series analysis of aerial photographs by a qualified geoscientist can help document the historical progress of hazards, estimate how often slides occur, and estimate the hazard volumes and extents within the study area. A minimum number of hazards are required to do this effectively. Aerial photograph interpretation can also provide insight into the causes of the slides and the spatial relationships between the hazards and other features such as road, culverts, bridges, etc.

DEFINING THE LIKELIHOOD OF SPATIAL IMPACT

The likelihood of spatial impact, $P(H:S)$ in Eq. 2, can be assessed using aerial photo interpretation to evaluate the current and potential travel distance of the hazard.

Regional photo interpretation studies of pipelines throughout British Columbia reveal a relationship between the position of the pipeline and the suite of geotechnical and hydrotechnical hazards affecting it. Hydrotechnical hazards are the most common and frequent hazard for pipelines, as these occur with greater spatial frequency and are more dynamic than most landslides. For example, in terms of spatial frequency, for approximately 2000 km of pipeline traversing a variety of terrain in British Columbia, on average, 1 geotechnical hazard site has been recorded for every 25 km of pipeline, while hydrotechnical hazard sites occur every 2 km. Temporal frequency is more difficult to quantify due to gaps in the period of record and inconsistencies in reporting. However brief inspection of shorter periods of record for transmission pipelines indicate that a geotechnical hazard may rupture a pipeline in British Columbia on the order of once every 4 years per 1000 km while hydrotechnical hazards may expose a pipeline twice per year per 1000 km.

Throughout British Columbia and in other glaciated areas of relief, pipelines located on river floodplains or the floor of river valleys (Fig. 4) are subject to greater hazard exposure than those located on benches or terraces (Fig. 5) above the valley floor, or those located on highlands and plateaus.

In terms of constructing a comprehensive hazard inventory, the advantages of aerial photo interpretation over ground-based methods of site characterization include the speed of work achieved by experienced geomorphologists, and the low cost and high accuracy of data. Prior to field investigation, the most comprehensive inventory will be obtained if air photo interpretation is conducted in concert with a review of hazards documented by the pipeline company. This adds to the hazard database and allows the identification of adverse conditions and hazards that might otherwise be missed on aerial photographs due to scale or vegetation. Nonetheless, ground truthing by engineers and geomorphologists is an essential step in the process of hazard identification and inventory.

Despite the accuracy and resolution of aerial photographs, field visits are still needed to check interpretations and identify features that are obscured or are too small to resolve on the photograph. In addition, terrain may have changed since the air photograph being studied was taken. Aerial photographs can help field inspectors decide in advance of the field work whether the site should be approached by vehicle or by helicopter. Finally, aerial photographs are superb navigation tools in the field.

DISCUSSION

Aerial photograph interpretation is a powerful technique for assessing terrain conditions but it does have limitations. Chief among these is the fact that forest cover obscures details of terrain and may hide small landslides (Fig. 2). Additionally during Stage 1 and 2 studies, there may be insufficient resolution in small-scale aerial photographs to properly assess the effectiveness of various defences that may influence the exposure of a pipeline to a hazard. For example, berms, rip rap, and other modifications may be difficult to discern given the scale of most commonly available air photos. Their identification also will depend on river stage and degree of forest cover. If using aerial photographs of 1:15 000 scale or larger, these modifications can be discerned in most cases.

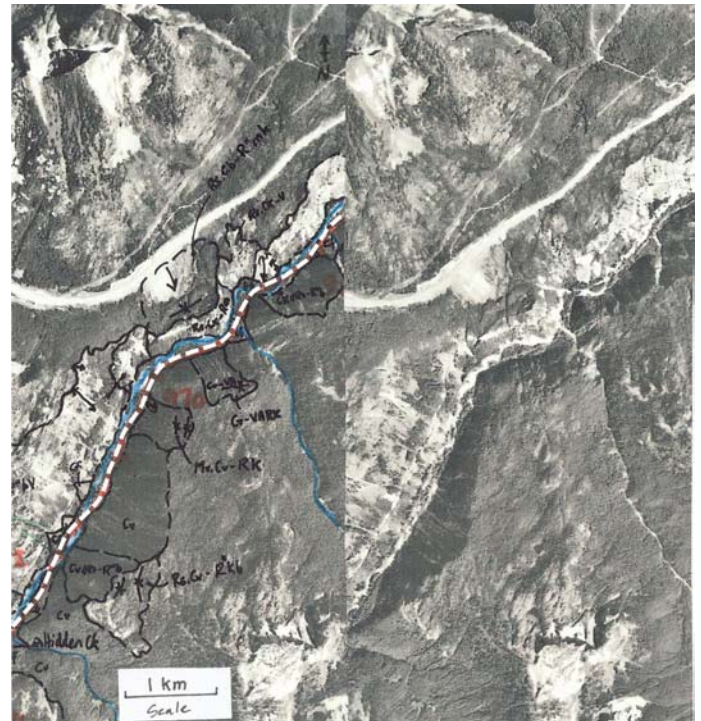


Figure 4 Stereogram of a pipeline (dotted) along Coquihalla River canyon located northeast of Hope, B.C. In this region, the pipeline is exposed to a multitude of geo- and hydrotechnical hazards.

CONCLUSIONS

Despite the advancements in digital remote sensing products such as high-resolution satellite imagery, aerial photograph interpretation still remains an accurate, practical, and cost-effective method of obtaining a comprehensive tabulation of geotechnical and hydrotechnical hazards affecting

pipelines. Aerial photograph interpretation provides a comprehensive site overview that cannot be obtained at ground level without significant expense. It also provides a first order estimate of parameters that go into qualitative risk analysis such as hazard type, volume, frequency, velocity, and likelihood of spatial impact.

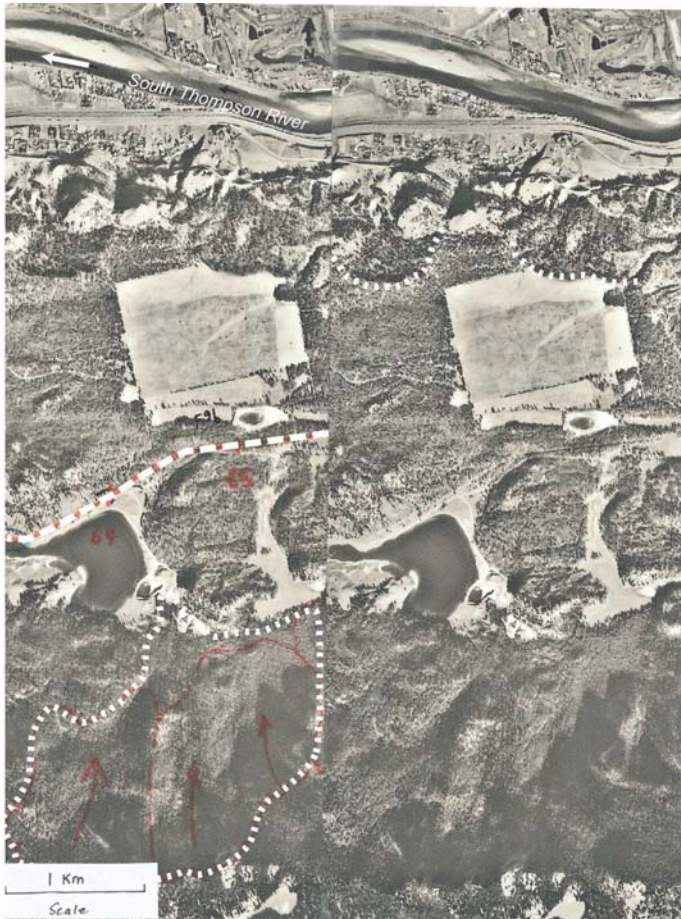


Figure 5 Stereogram of a pipeline (red line) traversing a bench in the South Thompson River valley east of Kamloops, B.C. The pipeline follows a relatively hazard-free route that is set back from the influence of downslope headward erosion, and upslope rock fall.

ACKNOWLEDGMENTS

BGC would like to acknowledge Terasen Pipelines Inc. and Northwest Hydraulics Consultants Ltd for technical and business contributions to the ideas expressed in this paper.

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