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Empirical design and rock mass characterization

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ABSTRACT: We suggest some ground-rules for empirical design and discuss the approach needed for rock mass characterization on which these empirical procedures are based. This characterization can be assisted by the image analysis procedures recently developed, not only fragmentation measurements, but also measurements of joint orientation, spacing and roughness, and of overbreak and underbreak. Some examples are given of applications.

1. INTRODUCTION

Predictions based on first principles of fracture mechanics and physics of comminution add to our understanding of blasting processes. However, in spite of advances in analytical procedures in recent years, we are still unable to model "from scratch" the complex fragmentation process sufficiently well for practical applications. Empirical and observational methods continue to be used almost exclusively for practical blast design as in most other rock engineering applications. Although empirical methods are often looked down on as "unscientific", there is no reason why scientific method cannot be applied: an example of this is the statistical approach taken by Aler, Du Mouza and Arnould, and briefly reviewed in this paper.

2 EMPIRICAL DESIGN

2.1 Design methodology

Empirical design is based on the premise that each rock formation has a unique "character" that controls its behaviour in engineering works. Different kinds of rock mass react differently, and if one can adequately characterize the rock mass to be blasted, one can also optimize the methods and obtain reliable predictions. An empirical design comprises the following steps, as shown in Figure 1:

(a) Description of "ground quality" by a quantitative classification system, to allow a reproducible means of transferring to future projects the experience gained globally working in ground of many different qualities.
(b) Quantitative definitions of the "techniques" to be optimized. In the context of blast optimization this includes geometry of the blast (spacing, burden, hole diameter, etc.); explosives type and distribution, and initiation sequence and delays.
(c) Quantification of optimum "results". In the case of blast optimization this may include parameters descriptive of fragmentation efficiency, costs of blasthole drilling and explosives, secondary breakage and handling requirements, overbreak and wall damage, and safety and environmental considerations such as control of vibration levels.
(d) Correlation of ground quality and technique with performance. Trends are established by compilation and comparison of results from many blasts over a full spectrum of ground conditions. Correlations can be shown graphically and/or by means of predictive equations ("models").

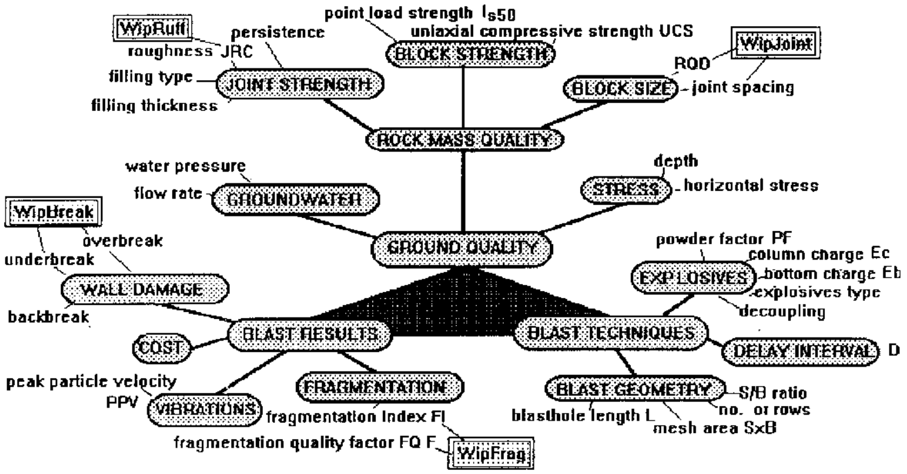

Figure 1: Steps in empirical blast design.

2.2 Calibrating the models

The data set on which correlations and predictions are based usually takes years to compile. Bieniawski, for example has been collecting data to correlate RMR with underground stability of mine openings for the last 20 years. However, blast data are more readily obtained than case histories of tunnel collapse, particularly with the benefit of the improved methods for measuring fragmentation. One characteristic of empirical predictions is that useful results can be obtained initially with quite few data, and the predictions improve with time.

The required correlations correspond to the edges of the central triangle in Fig. 1, such that having defined any two of the triangle's apices, the third can be determined. Three types of prediction are possible:

(a) blast results can be predicted from techniques and ground quality;
(b) techniques can be selected to give specified results in any given set of ground conditions;
(c) changes in ground quality can be detected from changes in results (e.g. fragmentation), if the blast techniques are defined or remain unchanged.

The potential benefits of feedback between fragmentation measurements and blast design are obvious, and a number of predictive models have been proposed, tested, and found to be useful. However establishment of the necessary correlations in blasting models requires a great many measurements to cover an adequate range of ground conditions and blasting methods, even for open pit blasting, let alone underground. The introduction of practical methods for measuring fragmentation, should greatly facilitate the calibration and testing of blast optimization models, increasing their reliability and range of application.

The alternative models differ in the ways in which they define rock quality, blast technique, and required results. Most take into account only bench blasting or cratering, and define "good blasting" in terms of fragmentation alone. Further research is needed to quantify correlations with improved definitions of variables and adaptations to underground as well as open pit blast design.

2.3 Image analysis measurements of rock mass quality

Alternative (b) above is the most common way in which empirical blasting models are employed, where blasting techniques are selected according to ground quality conditions and desired results. However, alternative (c) is equally valid, in which the blast model is worked backwards to detect and quantify changes in rock quality from measured changes in fragmentation. This is best achieved by maintaining the blast unchanged until adjustments become necessary as the quality of the rock improves or deteriorates. Muckpile measurements of fragmentation are likely to prove quite sensitive to changes in rock quality, and more reliable than direct measurements of in situ joint spacings and pre-blast block sizes. Image analysis methods of block size measurement are hampered by the oblique angles of photography imposed by the narrow confines of underground drifts. These difficulties can be overcome to some extent by merging of image data and by tilt corrections for scale variations within the image. However, a more difficult if not insoluble problem with direct measurements of joint spacing and block size is the unknown amount of "plucking" of the rock face.

The "plucking" problem can best be illustrated by comparing a smooth-blasted face with one that has been over-blasted in the same rock. Joints with apertures of microns are almost invisible on a smooth rock face unless accentuated by groundwater seepages or artificially by dye penetrants. They become visible only by virtue of the removal (plucking) of pyramid-shaped rock blocks that occurs to a greater or lesser extent depending on the energy of the blast. Image analysis relies on a faceted face. Measurements of joint orientations are unaffected, but for measurements of block size, the more the plucking, the more joints that are identified. Each triangular pyramid removed by blasting exposes three facets and three joint edges. Block size therefore tends to be over-estimated, and by an unknown amount, unless the face is heavily over-blasted. Measurements of sizes in the muckpile do not suffer from this problem.

The potential use of muckpile fragmentation measurements as indicators of rock mass quality opens the door to a number of interesting possibilities, including use of blasting results to classify rock quality not only for fine-tuning of the blast, but also for all the other uses of rock mass quality classifications, including dimensioning of openings and determination of requirements for support or reinforcement. These measurements may also provide a measure of joint persistence. Only a few years ago it was tacitly assumed that blocks in the muckpile are bounded by freshly generated fractures produced by blasting. Now it appears that many, perhaps most fragments are bounded by preexisting joint facets, or at least by geological planes of weakness that separate when blasted (Aler et al, 1966). Joint persistence or impersistence has long been recognised as one of the most difficult properties to quantify, yet one of the most important. Time and again stability analyses of rock excavations lead to a conclusion that with 100% persistent joints, the rock face is unstable, yet with 98% persistence it is quite safe. Measurements of blast muckpile fragmentation and comparisons with measurements on faceted rock faces might afford some possibility of quantifying joint persistence. Often there is a visible difference in colour or texture between a preexisting joint facet and a freshly generated fracture. Even an approximate estimate would be superior to the present lack of information.

3 ROCK MASS CHARACTERIZATION

3.1 Classification principles and parameters

Rock mass classifications tend to become entrenched and applied regardless of their evident limitations. In the context of selecting a method of rock mass characterization suitable for empirical blast design, it is worth taking a fresh look at the fundamentals of classification systems. As with image analysis techniques, classification methodology has been explored in other disciplines, and the broad literature on the subject can suggest alternative approaches.

Classifications can be based on one or several attributes. Before the advent of more "advanced" (complex) classification systems in rock engineering, the single parameter RQD was widely and quite successfully used on its own to characterize rock and predict its behaviour in engineering works. Sonic velocity measurements continue to be employed by some heavy equipment manufacturers as the single measure of rock quality for selection of appropriate rippers and excavators.

The more attributes included in a rock mass classification, the better the correlation obtained with rock mass behaviour. However, whereas just one parameter is probably insufficient for an adequate prediction, there is a practical limit and classifications based on four or more attributes are probably too complex. A law of diminishing returns applies, such that if the few key properties that are included are well-chosen, the addition of each subsequent property increases the work, while adding little to the predictive power of the classification.

A survey by the ISRM Commission on Rock Mass Classification suggested that three attributes of the rock mass are found, in one form or another, in all commonly used geomechanics rock mass classifications (ISRM, 1981a):

(a) Block size, or RQD, both of which are a measure of joint intensity or spacing;
(b) Block strength, which can be quantified by any of several available strength tests, all of which are closely intercorrelated. Point load strength is suggested because of its speed and simplicity;
(c) The shear strength of the joints that form the faces of blocks. This can be measured by shear strength testing or represented in the classification by related index properties.

The strength of unweathered joints depends on the combination of joint persistence, joint roughness (JRC), and the strength of the interlocking roughness asperities (JCS) which for unweathered joints is identical to the intact block strength. If the joints are weathered or filled, information on filling type and thickness is also required.

Tests and observations whose purpose is to indicate (point the way to) a given attribute such as rock mass quality are termed "index observations". Some basic considerations in selecting index observations are that they should be:

(a) as little correlated as possible, to avoid duplication and unintentional double or multiple weighting;
(b) sufficiently simple for many measurements to be completed, preferably in situ, so as to adequately characterize the variation in the property they are meant to represent;
(c) relevant and make an important contribution as a predictor;
(d) quantitative on a continuous scale rather than discrete or descriptive and should cover the full range of the attribute being measured;
(e) reproducible with a dispersion of results far less than the range of the property being measured.

For example, in selecting a test to represent intact strength, the point load test satisfies all five criteria, whereas uniaxial compressive strength fails to satisfy criterion (b) and Schmidt rebound hardness fails according to criteria (d) and (e).

3.2 Quantification of "ground quality"

Blast design has lagged behind other branches of rock engineering design in coming to recognize the importance of joints and other forms of "discontinuity" in controlling behaviour of the rock mass. Joints limit the strength of rock and also control bulk modulus of deformation and flow of groundwater. In the context of blasting, they have little or no tensile strength, and so tend to arrest propagation of cracks, and to reflect, refract, and attenuate elastic waves, particularly those of short wavelength. They provide preferred directions of breakage, also absorb and waste a disproportionate amount of blast energy, and act as channels for the dissipation of gases generated by the blast.

In the search for an appropriate way to represent the contribution of rock properties to fragmentation by blasting, existing rock mass classifications that relate mainly to the "static" behaviour of rock in tunnels and to a lesser extent mines are probably not ideally suited. However, it makes sense to consider use of existing classifications where possible, to avoid the proliferation of yet further classifications without good reason.

There is no single accepted rock mass classification but the two in most common use are the Rock Mass Rating (RMR) of Bieniawski (1973, 1989) and the Norwegian "Tunnelling Quality Q" system of Barton et al (1974). RMR, is the sum of six properties: uniaxial compressive strength, RQD, joint spacing, quality of the joints, groundwater conditions, and joint orientation. Barton's "Tunnelling Quality Q" also includes six parameters combined as the product of ratios:

$$Q = (RQD/Jn)\ (Jr/Ja)\ (Jw/SRF)$$

The first ratio is related to "block size" and the second accounts for the shear strength of joints, whereas the third is unrelated to the rock itself, representing the ambient conditions of stress and groundwater, which change seasonally and with excavation. The numerical values of Q range from 0.001 for exceptionally poor quality squeezing ground, up to 1000 for exceptionally good quality rock which is practically unjointed.

The Q and RMR systems, are based on much the same properties, and so are highly correlated and can be predicted one from the other. Various authors give a relationship in the form:

> RMR = A log Q + B,
> where A is typically in the range 9-14, and B is in the range 35-55.

Because of this close correlation, it might make sense to combine existing systems into a "unified classification" as exists for soils, at the same time reconciling some of the discrepancies in each system, but in the interim, most engineers using these classifications as a basis for empirical design continue to calculate both Q and RMR, and to compare the results. Butler et al (1990) describe a computerized, knowledge-based expert system called Classex which facilitates calculation of Q, RMR, and RQD ground classification systems. RMR in particular has been redefined through five or six publications since it first appeared, and without the help of an expert system approach it is difficult to keep track of these modifications and to take advantage of the clarifications by others adapting them for a variety of uses.

Research into rock characterization and index testing during 1965-70, led to the development of a "size-strength" classification (Franklin, Broch and Walton, 1970; Franklin, 1986). While this ignores the third factor joint wall strength, which is an important omission for highly weathered or sheared joints, a size-strength representation, particularly in medium to high strength rocks free from clay-filled joints, probably accounts for most of the variation in rock mass character.

In conclusion, as illustrated in the upper part of Figure 1, we suggest that the three characteristics block size, block strength and joint strength be included in the rock characterization part of an empirical blast model. Point load strength provides a convenient index for block strength and joint wall strength in the case of unfilled joints. Image analysis procedures are available to assist in quantifying block size and joint roughness. These are outlined in Section 4 below.

3.3 Quantification of blast results.

Quantification of blast "performance" or "success" is considered schematically in the lower left apex of the Figure 1 triangle. What we mean by "successful blasting" depends on the application. In civil engineering works, the focus is usually on preserving the rock walls intact with a minimum of reinforcement, on reducing underbreak, overbreak and fly rock, and on maintaining vibration levels below acceptable limits. In mines and quarries, the objectives include fragmentation efficiency (size, uniformity, shape), maximum yield with minimum dilution, and minimizing production costs for drilling, explosives, secondary breakage and materials handling. The objectives have been converging with the recognition that wall control can be cost-effective even in a production blasting context.

In the absence of measuring methods there was no great urgency in defining exactly what was meant by good fragmentation. The new measuring capability is leading as might be expected to new and more precise definitions of "efficient blasting". Aler and colleagues at the Paris School of Mines propose defining fragmentation efficiency of a blast relative to the preexisting "geological fragmentation" caused by jointing (Aler et al, 1995 & 1996). They determine the initial size distribution of the rock mass by applying stochastic three-dimensional modelling to in situ measurements of joint spacing. The sizes present in the blast rockpile are measured using the Fragscan image analysis system. A Rosin-Rammler probability distribution function is fitted by the least-squares method to each of these two data sets to determine the Rosin-Rammler characteristic size Xc and uniformity coefficient N before and after blasting.

Aler et al define a Fragmentation Index FI = Xcr/Xcp, as the ratio of Xc values before and after blasting. This gives the reduction in characteristic size achieved. A second index, the Fragmentation Quality Factor FQF = Nr/Np indicates how uniformly the blast energy has been distributed among the full range of in situ block sizes. FQF = 1.0 indicates that the blast energy has been equally effective in reducing all sizes of preexisting block, whereas a value less than 1.0 indicates that the larger blocks have been fragmented more than the smaller ones.

The proposed fragmentation indexes should prove useful as measures of blasting efficiency. However, "normalization" by dividing the R-R parameters by pre-blast values introduces a further potential source of error and dimensionless ratios are perhaps less meaningful to stone users and purchasers than actual sizes expressed in centimetres or inches. Also, we should avoid moving from a situation where fragmentation is ignored in the assessment of blast efficiency to one where it becomes the predominant or only factor. Questions arise concerning how best to take into account the combination criteria as different as drilling and explosives costs, wall damage, and fragmentation. Since cost is often the bottom line, it would be of interest to translate measurements of fragmentation efficiency in terms of cost benefit.

3.4 Quantification of blast technique

It is in quantifying the third apex of the Figure 1 triangle, blast techniques, that Aler and colleagues have made a major contribution by using multivariate statistics to select the optimum combination of classification parameters from among a confusing proliferation of alternatives. Techniques such as factor analysis and discriminant analysis have been successful in resolving complex data sets in medical, biological and geological applications. However, this is perhaps the first application to blast design, even to empirical design in rock engineering.

The first step in their analysis is to apply a preliminary multiple regression analysis to reduce the complexity of the blast geometry data set to a more manageable number. They retain four of the least-correlated blast geometry variables, eliminating six that "can be sufficiently represented by other variables with which they are closely correlated". The four retained are:

Blasthole length L (representing vertical dimensions of the blast);
Mesh area S x B, (representing horizontal dimensions);
Spacing-to-burden ratio S/B (representing interaction between horizontal and vertical dimensions)
Number of rows R (representing the size of the blast).

Principal-component analysis (PCA) was then applied to the selected four variables of blast geometry plus four parameters related to the explosive energy:

Powder factor, PF;
Delay interval, De;
Bottom charge, Eb;
Column charge, Ec.

The results indicate that geometrical components of blast design, notably the spacing-to-burden ratio and the size of blast, have the greatest influence. Fragmentation was found to improve with larger blasts, also with an increase in spacing-to-burden ratio, with a decrease in the mesh area, and with an increase in the delay interval. Fragmentation was found to increase linearly with increasing block size, indicating that utilization of blast energy becomes more efficient in more massive rocks, probably as a result of less energy being lost through open fracture networks. Surprisingly, changes in powder factor had little effect on fragmentation. Discriminant analysis was then employed to formulate a fragmentation prediction tool using the parameters that the principal component analysis had indicated to be the most significant.

4 IMAGE INPUT FOR BLASTING OPERATIONS

As indicated schematically in Figure 1, image analysis techniques can assist in various ways to quantify rock quality for purposes of blast design as well as in measuring blast performance. Further applications such as quality control of quarried products and pit wall stability analysis, although peripheral to the main theme of this workshop, may be considered sufficiently relevant to justify a brief account of the methods and their applications.

4.1 Joint roughness measurements

Joint Roughness Coefficient (JRC) measurements are required for rock mass classification using the Q system, and also for estimating the shear strength of joints for pit wall stability calculations.

The method of shadow profilometry (Maerz, Franklin and Bennett, 1990) was devised in response to a request by Noranda Mining Technology Division, who require JRC values for rock mass classification and empirical design underground. Roughness is determined from the irregular edge of a shadow cast by a straightedge onto the joint surface. A video camera captures an image of the shadow. WipRuff software then isolates and measures the shadow edge, making a correction for angle of illumination, given by the length of shadow cast by a "sundial" post of known height in the field of view. Roughness is represented in terms of centreline average, mean square value, fractal number and several other statistics. JRC is determined from a correlation established between the measured roughnesses and Barton's "typical roughness profiles" (ISRM, 1981b).

The system was tried out during June 1987 at Noranda's Hemlo Mine. JRC was measured for each of 250 images. Comparisons with visual estimates showed that the human eye has difficulty in distinguishing between different degrees of roughness, whereas the shadow profile method gives JRC within 5 to 8 per cent. The results were found to correlate well with shear strengths measured by Noranda in the laboratory.

4.2 Overbreak and underbreak measurements

Overbreak quantities are often in dispute as to whether they are caused by bad rock or bad blasting. Photographs and video tape usually are relied upon to provide a permanent record, which is more fully utilized if quantitative measurements are made.

These techniques were employed in 1986, at an early stage in their development, to help resolve a contract dispute in connection with open excavations for a hydroelectric generating station in Manitoba. The owner and contractor had different opinions on whether wedge slides and a loose, unstable face in the powerhouse excavations were the result of inadequate blasting or unavoidable geological factors which included intersecting clay-filled joints. Jointing measurements were taken both manually by climbing the face, and from photographs. Direct measurements in the lower part of the face could then be extrapolated to inaccessible locations. The angles of inclined clay-filled joints were compared with those of regional principal stresses and the directions and the orientations of faults recorded on geological maps.

A "light sectioning method" for overbreak measurement was subsequently developed for use in tunnels. This was a logical extension of the shadow profilometry method for joint roughness measurement, but at a larger scale and applied to the curved surface of a tunnel or mine drift. A plane of light is projected perpendicular to the tunnel axis using a tripod-mounted flashlight and conical mirror. The illuminated profile is recorded by video camera, and the image digitized, enhanced and measured by image analysis software. The measured tunnel cross-sections are then compared with a computer-generated design profile to give the distribution and amounts of overbreak and underbreak around the perimeter. These overbreak diagrams can be compared with geological structure to determine causes and modify the blasts accordingly.

After initial tests in Noranda's Ansil mine in Quebec, the method was evaluated during construction of three irrigation and hydroelectric tunnels in Mexico (Franklin et al, 1989; Ibarra et al, 1996). Correlations were established between overbreak and underbreak quantities and both rock quality (Norwegian Q system), and blast energy (Perimeter Powder Factor). They allowed optimization of blast design to give a balance between overbreak and underbreak costs in any given quality of ground.

4.3 Quality control of in-place rockfill

Image analysis appears to be the only practical way to evaluate in-place gradations of rockfill and stone performance and degradation as a result of weathering over prolonged periods. Measurements can include gradations and block shapes, measurements of homogeneity and segregation, and also, with customized software, monitoring of embankment spread and settlement. The photographic record is also useful for documenting the amount and type of stone deterioration.

The trend in breakwater design has been to replace large, difficult to obtain and expensive armour stone blocks by more readily available and much less expensive stone of moderate size. Gradation is a key factor in design of these "rubble breakwaters", and has to be closely controlled. Rockfill degradation during handling and placement can result in segregation into coarser and finer fractions. In marine works, segregation creates pockets of undersized materials that are easily eroded, and concentrations of large blocks that are transparent to wave action and provide windows for internal erosion. Image analysis can help diagnose and correct these problems.

Fragmentation measurements with portable video camera input can provide a quick and convenient method for quality control of rockfill, rip rap and armour stone at every stage from quarry source selection through blasting, transportation of stone, embankment construction and monitoring of in-place embankment performance.

4.4 Pit wall stability and slope design

In large open pit mines, which reach diameters of kilometres and depths of several hundred metres, a difference of a degree or two in pit wall angle can mean millions of dollars in gained or lost ore. Even for mining and quarrying operations of more modest size, depending on configuration of the resource and thickness of overburden, slope angle affects to a greater or lesser extent the stripping ratio and hence mining profits.

At the feasibility study stage, prior to the start of mining, measurement of large-scale lineaments visible in air photographs and satellite images backed by ground reconnaissance has been found helpful in determining directions of faults, major joints and geological contacts critical to pit wall stability.

Conservatively stable angles often present no problem in the early stages of mining, and the walls can be steepened as they approach final limits. This allows the information on joint orientations and roughnesses needed for slope design to be obtained from image analysis and outcrop measurements of exposures in the pit walls, which is more reliable and a lot easier and less expensive than measurements on drill core.

For identification and remediation of existing instability problems, the first step is to identify the hazard mechanisms which may include ravelling, toppling, as well as slab and wedge sliding. A photographic record can assist in identifying potential hazard mechanisms, assigning rock mass quality ratings according to RQD, size-strength, Q or RMR systems, measuring volumes of potentially hazardous rock, assessing the degree of hazard, and selecting the most appropriate treatments.

Photoanalysis has been used as an aid to rock hazard evaluation and specification of treatments for highway rock cuts along the Niagara Escarpment in Hamilton, the Trans Canada Highway in Ontario, the Cabot Trail in Cape Breton, Nova Scotia, and the Great Falls hydroelectric generating facility in Bathurst, New Brunswick.

Sliding and to a lesser extent toppling mechanisms are amenable to stability calculations using the limit equilibrium method. The data needed on joint orientations and shear strengths can be obtained with the help of image analysis. Roughness measurements by the shadow profile method have been used with the Barton non-linear shear strength criterion on a number of projects involving slope stability assessment. This approach avoids the sometimes considerable cost of direct shear strength testing (several thousand dollars each for large-scale in situ shear strength tests). In situations where joints in each set vary in roughness and filling characteristics, it is better to explore the full range of roughnesses and fillings to estimate the variation (range) of shear strengths than to measure strength more precisely on a limited number of joint surfaces that may not be representative.

Most hazard rock situations involve ravelling, freeze-thaw and other mechanisms that are not amenable to quantitative stability calculations. These can be assigned a hazard rating based on rock mass quality classification, taking into account not only the likelihood of slope failure, but also the volume of the potential fall, the capacity of ditch or catch fence, the probability of falling rock causing damage or injury, the methods and costs of remediation alternatives, and other factors. These assessments frequently can benefit from image analysis measurements and rock mass classification. The methodology has been programmed into an expert system for a current contract to assign treatment priorities to 120 potential rock hazard locations along highways in northern Ontario (Franklin, Senior and Peck, 1997).

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