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Prediction of paste backfill performance using artificial neural networks

La prédiction d'utilisation d'exécution de remblai de pâte réseaux neuronale artificielle

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ABSTRACT
Increasing regulations and social expectations of mines to minimize environmental impacts whilst ensuring a safe working environment and maintaining profitability has led to a higher degree of control throughout the mining and processing cycle. In recent years there has been an increasing trend with regards to the use of paste fill. Paste fill is defined simply as mine tailings (typically an effective grain size of approximately 5 µm) mixed with some form of binder. The tailings used to manufacture paste fill are unclassified; that is they are not graded or sized in any form. This lack of grading results in greater variation of the tailings and consequently the material characteristics. Traditionally, additional cement has been added into the paste fill blend to compensate for the variation of the grain size distribution and improve stability of fill exposures. Cement is the most expensive component of paste and can constitute between 15%-20% of the total cost of mining. Therefore, any reduction in the use of excess cement will result in obvious economic benefits. Within this study, artificial neural networks (ANNs) were applied to the prediction of fill strengths, and were based on the input parameters of cement content, solids content, curing time and grain size distribution. Correlations between the predicted and achieved strength of the paste for both Cannington mine and paste fill worldwide using ANNs were excellent. The use of ANNs as part of an integrated planning tool for the design of backfills has also been discussed in the paper.

RÉSUMÉ
Les règlements croissants et espérances sociales de mines pour minimiser des impacts écologiques pendant qu'assurant qu'un fonctionnement sûr environ-réparé et maintenir la rentabilité a mené à un plus haut degré de contrôle à travers l'extrait et le cycle de traitement. Dans les années récentes il y a eu une tendance qui augmente en ce qui concerne l'usage de pâte remplit. La pâte remplit est simplement définie comme extrait tailings (typiquement une taille de grain efficace d'approximativement 5 mm) a mélangé avec quelque forme de classeur. Le tailings a utilisé pour fabriquer la pâte remplit est non classifiée (pas gradué ou a calibré dans la forme). Ce manque de graduer a pour résultat la plus grande variation du tailings et par conséquent le charac-teristics matériel. Traditionnellement, le ciment supplémentaire a été ajouté dans la pâte remplit le mélange pour compenser la variation du GSD et améliore la stabilité de remplit des expositions. Le ciment est le composant le plus cher de pâte et peut constituer entre 15%-20 % du coût total d'extrait. Donc, n'importe quelle réduction dans l'usage de ciment supplémentaire aura pour résultat des avantages économiques évidents. Dans cette étude, ces réseaux neuronales artificielles (ANN'le s) ont été appliqué à la prédiction de remplit des forces, et ont été basé sur les paramètres d'entrée de contenu de ciment, le contenu de solides, guérissant le temps et la distribution de taille de grain. Les corrélations entre la force prédite et atteinte de la pâte pour la mine de Cannington et la pâte remplissent dans le monde entier utilisant ANN'le s était excellent. L'usage de ANN'le s comme la partie d'un outil de planification intégré pour la conception de remblais a été aussi discutée dans le papier.

1 INTRODUCTION

Since the mid 1990s, paste fill has gained rapid acceptance as an alternative backfill material to the conventional cemented hydraulic fills (Belem & Benzaazoua 2004, Rankine 2004, Naylor et al. 1997, Landriault 1995,). As mine stopes are removed, paste fill is used to backfill the voids. Paste fill provides substantial benefits to mining operations including an effective means of tailings disposal, improvement of local and regional rock stability, greater ore recovery and greatly reduced environmental impacts (Rankine & Sivakugan 2004, Bloss & Rankine 2005).

In order to provide stability, paste fill must remain stable during the extraction of ore and minerals from neighboring stopes. If the paste becomes unstable, the adjacent faces may relax and, as a result, displace into the open stope. In the past, considerably high cement quantities of up to 6% (typically 3 to 5% by wet weight) have been used to ensure the stability of backfilled stopes, especially during blasting. Filling costs for a mine typically represent in the vicinity of 20% of all mining costs, with binder costs constituting approximately 75% of that amount (Bloss & Grice 2001, Belem & Benzaazoua 2004). This high cost of cement has placed greater emphasis on the optimization of fill design for strength with respect to cement usage.

The use of artificial neural networks (ANNs) provides a new and immensely powerful opportunity to achieve this goal. ANNs were used within this study to predict the required strength of the paste fill and then to identify the most economical mix.

2 ARTIFICIAL NEURAL NETWORKS

ANNs are computer based models, which use and analyse historical data to develop solutions to complex, multivariate problems. Neural networks are comprised of a series of interconnected nodes or "neurons", which perform the same function as their biological namesakes. The neurons are interlinked by a series of connectors to form a series of layers. All networks have at least two layers - the input and output layers. Intermediate layers of neurons are not visible to neural network users and thus are commonly referred to as "hidden" layers.

There are two main features in an ANN - the architecture and learning algorithm. The architecture dictates the structural configuration of the networks, and the learning algorithm describes the method in which the networks are able to learn from the data. Learning may occur in either a supervised or unsupervised environment. The difference between these two types of networks is that unsupervised networks are trained without any output values, whereas supervised networks are trained with the outputs which are target answers (Dayhoff 1990). The latter of these network types is far more common. Unsupervised networks are usually confined to use in the classification of patterns into similar groups.

For the current research, a General Regression Neural Network (GRNN) was used with a feed-back supervised learning algorith. The GRNN has been shown to train quickly on sparse and incomplete data sets (Specht 1991, Abu Kiefa 1998). This algorithm was considered suitable for use in this study due to the data sets for backfills worldwide, and in particular paste fill, being rare and typically held in-house by mining companies with a high level of commercial interest tied into them.

3 AN INTEGRATED TOOL FOR BACKFILL DESIGN

Once placed, mine backfills need to satisfy certain dynamic and static loading requirements to ensure a safe underground working environment for all mining personnel. Dynamic requirments include the provision of resistance to liquefaction and stability during localised blasting or other seisimic events. Clough et al. (1981) identified an unconfined compressive strength of 100 kPa as the minimum strength required to resist mobilisation of cemented sands in earthquakes measuring up to M=6.5 on the Richter scale. This figure is widely accepted by the mining industry as providing adequate dynamic stabilty reistance within stopes. The primary static loading requirement is to provide a stable vertical face when exposed by the adjacent mining of stopes. This static requirement typically governs the design of backfilled stopes.

To identify the static stabilty requirements of underground fill stopes, numerical modelling using FLAC^{3D} was undertaken. The point which shows greatest stress concentration in the stope is at the centre of the base. Within this study, an inherently conservative approach to static stabilty was adopted with stability assumed to be satisfied, provided the uniaxial compressive strength (UCS) of the backfill used exceeded this value of maximum stress concentration. To provide a more representative figure of the internal stresses within a stope, taking into account the effects of arching, the stress at the mid-height of the stope was also identified. These stress profiles were identified for various base to height and width to depth ratios. Examples of the output are shown in Figures 1 and 2.

3.1 *Numerical modelling of backfill stress profiles*

Numerical modelling of backfilled stopes was undertaken using FLAC^{3D} . The constitutive models selected for simulating the paste fill and surrounding rock were Mohr-Coulomb and Elastic models respectively. The development and assumptions used by the numerical model are discussed by Rankine et al. (2001) and Rankine (2004).

A sensitivity analysis was conducted on the input paratemters for the numerical model and changes in stress development within the stope were observed. Values for each parameter were based on a reasonable variation which could be expected around typical values for each variable which is shown in Table 1. The material characteristics for cemented backfills included values typical of aggregate, sand and hydraulic fills as well as paste fill. This ensured that the ANN could be trained on data which encompasses the fills likely to be encountered in practice.

Vertical stress development has been shown to be primarily dependent on fill density and Poisson's Ratio. Low values of cohesion also contribute to increased vertical stresses within the stope by limiting the ability of the soil arch development.

The effect of stope geometry was also investigated using aspect ratios. Width to height (W:H) ratios of 1, 2, 3 and 5 with base widths (plan) of 18.75, 25 and 37.5m were investigated to determine the variation of vertical stress. Similarly the width to depth (W:D) aspect ratios were investigated for ratios of 1, 2 and 3. The typical outputs are depicted in Figures 1 and 2.

As expected, results showed that the vertical stress in stopes increases with increasing base dimensions and width:depth ratio.

The increased stress in the base of stopes with a larger plan dimension results from the increased distance required for the full development of the soil arch. This increased distance is caused through an increased load path distance, and causes reductions in the ability of stopes to transfer vertical loads through shear. An increase in vertical stress with W:D ratio was also observed. This increase is due to the transfer of the primary arching mechanism from a 3-D arch, to a 2-D arch.

A W:D ratio of 2 has been found to delineate the boundary between 2-D and 3-D arching. Figure 2 shows limited increase in the vertical stress, due to increased stope depth. This is because arching is considered to be almost exclusively 2-D in both cases.

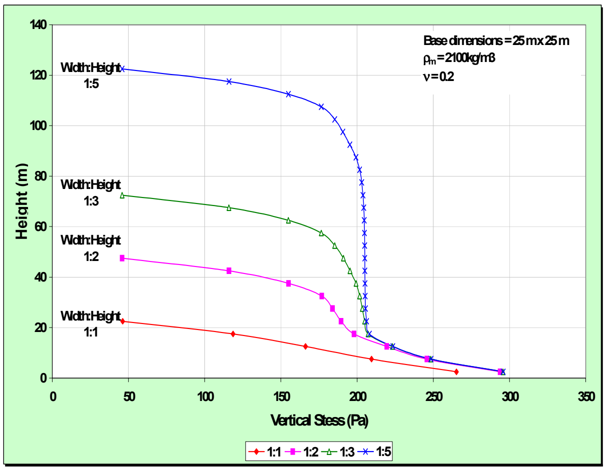

Figure 1 Vertical stress profile along the vertical centerline of stopes with variable width to height ratios (base dimensions = 25 m x 25 m)

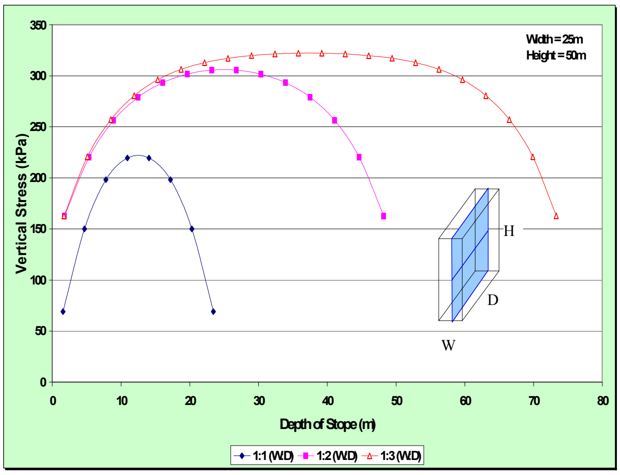

Figure 2 Vertical stress profile down the centre of stopes with variable width to height ratios (base dimensions = 25 m x 25 m)

Table 1 Input parameters for paste fill in the FLAC^{3D} model

Material Properties	Range	Units
Cohesion, c_u	100 - 1000	(kPa)
Density, ρ_m	1700 - 2300	(kg/m^3)
Friction Angle, ϕ	0 - 30	(deg)
Young's Modulus, E	1 - 250	(MPa)
Poisson's Ratio, ν	0.15 - 0.35	
Tensile strength, t	20 - 400	(kPa)
Dilation Angle, ψ	0 - 15	(deg)

Outputs for the maximum vertical stress at the base and mid-height of the stope were recorded for all the modelling combintions of stope geometry and material properties and entered into a database. This database was then used for input to the final integrated fill design tool to predict the required fill strengths for static stability (Fig. 3).

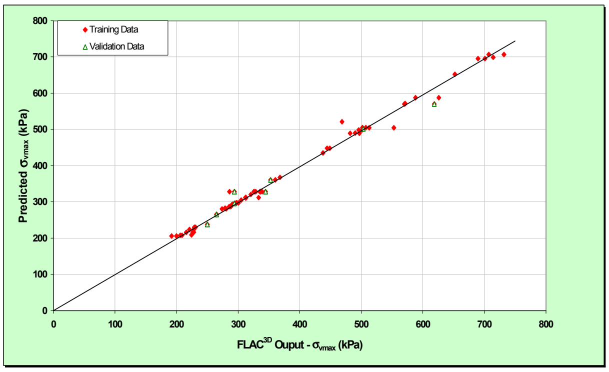

Figure 3 Results for ANN modelling of the predicted maximum vertical stress at the base of stopes

3.2 *Development and application of ANNs to the prediction of backfill strengths*

Currently there are a number of simplified methods available to relate physical properties to the UCS of backfills (Saliba 1996, Bloss 1992, Swan 1985, , Berry 1981). However, these methods are typically site specific and for specified types of fill. Therefore, they lack the robustness of a solution which is able to be applied to any general case. The ANNs available from within the Neuroshell(c) software package were used to predict backfill strengths. The ANNs trained the networks with the data provided and did not place any limiting assumptions on the analysis.

Data were collated from various sources, including tests conducted on Cannington paste fill as part of research by Rankine (2004) and also strength testing of paste fills reported in the literature. Table 2 summarises the data sets used for the ANN modelling and the parameters used in each analysis.

Table 2 Data set delineations.

Data Set	Description	Test Parameters	Data Points
1	Paste Fills – Cannington Model Name: "PFCAN"	Inputs: %C, %S, P80, Curing time Outputs: εf, E, UCS	170
2	Paste Fills – World wide Model Name: "PFVAR"	Inputs: %C, %S, P80, Curing time Outputs: UCS	89

The ANNs developed using the input test parameters are only valid for the range of values over defined within the training data. ANNs are used for interpolation of data and are not able to extrapolate. Table 3 shows the range of values for each of the ANNs.

Table 3 Range of values for input parameters

ANN model	% C	% S	D_{80} (µm)	Curing Time (days)
PFCAN	2 - 8	74 - 85	38 - 280	28 - 365
PFVAR	2 - 12	61 - 86	20 – 3700	28 - 365

Data sets for each of the ANN models were subdivided into two groups – "modelling" data and "validation" data. The modelling data were then further subdivided into a test set and training set (Fig. 4). Validation and test data differ in that the validation data are used to assess the predictive ability of the network on "unseen" data, whereas the "training set" is "seen" data used to calibrate the network during training. In each case, the division of data was conducted randomly.

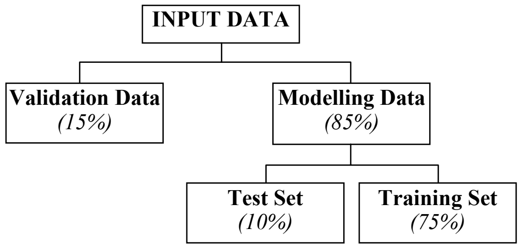

Figure 4. Division of data for ANN modeling

4 RESULTS

Once each of the models had been constructed, their individual performance and precision of the models were assessed using the coefficient of determination, r^2, between the predicted and measured data. The validation data were used to provide an indication of the predictive ability of the trained networks on unseen data.

Figures 5 and 6 depict predictions of fill strengths by the ANN models for paste from Cannington and for paste fill worldwide, respectively.

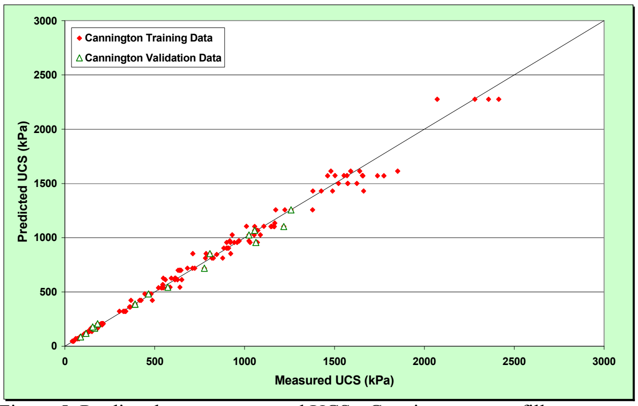

Figure 5. Predicted versus measured UCS - Cannington paste fill

The correlation coefficients for Figures 5 and 6 were 0.991 and 0.901, respectively. A higher r^2 value was obtained for the ANNs developed for Cannington Mine "PFCAN". This higher value resulted from having a large database of unconfined compressive strengths available to train the ANN. There is also a higher degree of control over the manufacturing process of paste concistency of the characteristics of the mill feed used to make the paste.

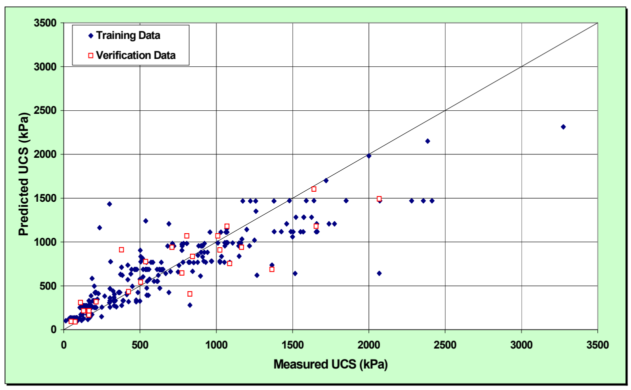

Figure 6. Predicted versus measured UCS - Paste fill from various sources worldwide

The r^2 value of 0.901 for the ANN predictions of the paste fill strengths from worldwide sources is significant. This indicates that the factors of cement content, solids content, curing time and grain size of the paste can be used to predict the likely stregth of the paste – with a moderately high degree of confidence. Previously, the best predictive tool for backfill strengths was that of the binder number concept – introduced by Swan (1985). This method had an r^2 value of approximately 0.8, and therefore it is suggested that the use of ANNs may provide a better generalised solution.

5 INTEGRATED DESIGN TOOL FOR BACKFILL PERFORMANCE USING ANNS

By integrating the use of ANNs to predict the required backfill strength and UCS of the paste, the engineer is able to define an array of paste fill mixes to satisfy the defined criteria. To find the lowest cost paste fill option, the user is prompted for the input variables of: solids content, D_{80} (the size in μm of which 80% of the tails will pass) and curing time.

The highest solids content that can be reticulated to the stope is also defined. Yield stress, and thus the ability to reticulate paste underground, is governed by solids content (Clayton 2002). The grain size distrubution, nominally identified by the D_{80}, can be identified using sieve analysis and the curing time before exposure determined through investigation of the proposed mining sequence.

An EXCEL program, PASTEC, generated by the first author (Rankine 2004), integrated the use of these ANNs, was used to back analyse a previously filled stope at Cannington mine. By comparing the historical fill records with the output from the PASTEC model, it is evident that an overcompensation of approximately 10% in the cement content of the paste existed. Calculated for a single year, if a reduction in cement of 10% had been adopted, the saving for Cannington Mine alone would have been in the order of between $AUD 700,000 and $AUD1,000,000. Therefore, if applied as a generalised tool on a global scale, the integrated design tool would provide enormous commerical savings potential for the mining industry.

6 DISCUSSIONS AND CONCLUSIONS

The use of ANNs is a new area with enormous potential for application in the field of geomechanics and mining. Its use in the prediction of backfill strengths and vertical stress profiles based on user defined inputs has provided a tool which is able to predict very accurately the required outputs. By using the two ANNs, an integrated model has been developed, which provides enormous commerical potential for local mines or the global mining community.

This integrated model approach to backfill design provides the most holistic and complete method of backfill design to date. It presents a method for the determination of optimum cement content for each paste fill mix, depending on the user defined input parameters for the stope geometry, material bulk density, curing time available to each exposure (1^{st} to 4^{th}) and solids density. The solids density information is expected to result from the rheological requirements for the reticulation of the paste to the stope.

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