A Model to Predict The Performance of tunnelling Machines Under Stressed Conditions

N. Bilgin, H. Tunçdemir, C. Balci, H. Çopur, Ş. Eskikaya

Istanbul Technical University, Mining Eng. Dept. 80626, Maslak, Istanbul-TURKEY

SYNOPSIS

One of the most important factors in determining the economic efficiency of rapid excavation systems for tunnel and mining activities is the prediction of the cutting performance of these systems. In the past, different models were developed based on site observations, laboratory small- and full-scale cutting tests. However, it is important to note that none of these models takes into account the rock stresses for machine performance prediction. Within NATO TU-Excavation Project supported by Science for Stability Programme, a detailed research study was carried out using a numerical modelling software (Franc 2D/L) and a small-scale rock cutting rig. Experimental samples were prepared using cast plaster and concrete blocs, which were later stressed by the aid of hydraulic pistons. A shaping machine, a triaxial piezo electric transducer and a data acquisition system were used to record the cutter force in three orthogonal directions and the specific energy value under stressed conditions. Previously described cutting performance models for roadheaders were re-evaluated using the results of numerical modelling and data of cutting test results under stressed conditions.

1. INTRODUCTION

A practising engineer is always interested in predicting the machine performance prior to starting a project that will definitely define the excavation economy. Roadheaders have been widely used both in mining and civil engineering applications since 1960s. The main advantages compared to classical excavation methods are mainly, high advance rates, safety, less labour and less strata disturbances. The past few research works were focused on the prediction of the performance of roadheaders or TBMs from laboratory cutting tests. The work originated in Newcastle upon Tyne University dealt with the correlation of in situ data with the results of core cutting tests[1,2]. In that study, the specific energy obtained from small scale cutting test was the main factor in the machine performance prediction. A more realistic model was developed by using full-scale rock cutting test results in Earth Mechanics Institute of Colorado School of Mines[3]. Another approach developed by Bilgin is purely based on the statistical evaluation of field data[4,5,6,7,8]. However, none of these models take into account the field stress. One of the main objectives of this paper is oriented into understanding of this phenomenon.

2. PREVIOUS CUTTING PERFORMANCE MODELS FOR ROADHEADERS

The prediction of the cutting performance of any mechanical excavator (continuous miner, roadheader etc.) for any mineral or rock formation is one of the main concerns in determining the economics of a mechanised mining method. There are several methods for this and it is strictly advisable to use more than one method to have more realistic approaches. These methods are core cutting or small-scale cutting tests, full scale cutting test and empirical approaches, which will be discussed below.

2.1 Small scale cutting test

This cutting test is discussed in details by McFeat and Fowell[1,2]. A core of 7.6 cm. in diameter or a small rock sample of 20 x 10 x 10 cm is fixed in a table of a shaping machine and cut by a chisel pick having a rake angle of –5 degrees, a clearance angle of 5 degrees, tool width of 12.7 cm and a cutting depth of 5 mm. The tool forces in three orthogonal directions are recorded using a force dynamometer and the specific energy in MJ/m^3 or kWh/m^3 is calculated by dividing the mean cutting force FC by the yield Q (the volume of rock or mineral obtained by unit distance of cut). The test results, which may be classified as index values, are evaluated according to previously accumulated field performance data.

2.2 Full-scale cutting test

This method is the most realistic approach, since a block of 70 x 50 x 50 cm. in size is cut in the laboratory with an actual size cutter (point attack tool, chisel picks etc.). The cutting force, normal force, sideways force and specific energy values are obtained with different depth of cut and tool spacing and the production rate of a given mechanical excavator is calculated by the following formula[3]:

$$ICR = 0.8 \frac{P}{SE} \tag{1}$$

In this formula ICR is instantaneous production rate in m^3/h, P is cutting power of the mechanical excavator in kW and SE is optimum specific energy in kWh/m^3.

2.3 Empirical approach

The empirical approach defined by Bilgin predicts the instantaneous production rates of axial and transverse type cutting headed roadheaders and is based on the in situ observation of many tunnelling and mining projects[4,5,6,7,8]. The cutting performance is formulated below.

$$ICR = 0.28 \times HP \times (0.974)^{RMCI} \quad (2)$$

$$RMCI = UCS \times (RQD / 100)^{2/3} \quad (3)$$

In these formulas:

ICR= Instantaneous cutting rate, m^3/h
HP= Cutting power, HP
RMCI = Rock mass cuttability index
UCS= Uniaxial compressive strength, MPa
RQD= Rock quality designation, percent

3. CUTTING TOOL BEHAVIOUR UNDER STRESSED CONDITIONS

From rock cutting mechanics science point of view, it is generally accepted that in majority the ground stresses has a little effect on the tool cutting forces. First cutting experiment carried out by Pomeroy in different coal samples showed that a modest level of stress can close up the cleats in coal, making it more difficult to cut[9]. Figure 1 shows clearly how the lateral pressure affects the normal force in coal cutting. However it is reported by Roxborough and Phillips[10] that experiments undertaken on a rock which was largely free of discontinuities, confining stress up to 200 kg/cm^2 was found no measurable effect on cutting force, normal force and specific energy. These studies are pioneering in their field and limited in number and only to unrelieved cutting conditions. During realisation of the NATO TU-Excavation Project sponsored by NATO Science for Stability Programme, it is decided that some laboratory rock cutting experiments under stressed conditions should be carried out in order to make clearer this phenomenon. A numerical model should also be run to support the findings of rock cutting experiments under stress conditions.

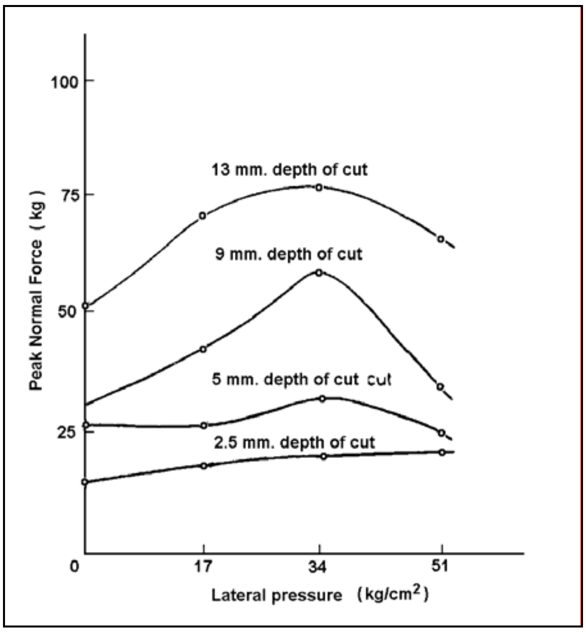

Figure 1. Effect of lateral pressure on peak normal force for a coal specimen (After Pomeroy)

Several samples were needed for relieved and unrelieved cutting experiments. Two artificial materials, plaster and concrete were used during experiments to keep constant the homogeneity characteristic of the test material. Mechanical properties of plaster and concrete are shown in Table I.

Table I. Mechanical properties of plaster and concrete

	Plaster	Concrete
Compressive Strength (kg/cm^2)	81	230
Tensile Strength (kg/cm^2)	13	24
Elasticity Modulus (kg/cm^2)	24420	260000
Poisson Ratio	0.18	0.18

3.1 A numerical model for stress analysis

The stress analyses were performed using software ‘Franc2D/L’[11]. It is a crack propagation simulator for two-dimensional layered structures. The finite element method is used in Franc2D/L to compute the stresses and displacements in an arbitrary structure subjected to arbitrary boundary conditions. The material is assumed to be linear elastic. Franc2D/L needs a pre-generated (initial) mesh. The initial meshes were developed using software ‘Casca’[12], which is distributed together with Franc2D/L.

Three models were developed for concrete based on unrelieved and relieved (for spacing values of 10 mm and 15 mm) cutting conditions. Six-nodded triangular elements were used for mesh generation. Plain strain condition was applied with 1 mm plate thickness in all models. Elasticity modulus of 260000 kg/cm^2 and poisson ratio of 0.18 were used as concrete’s material properties. A pressure of 220 kg/cm^2 was applied in all models to simulate the normal force (cutter force) acting on the concrete. In addition, the lateral pressure was applied in five different magnitude levels (0, 10, 20, 50 and 150 kg/cm^2) in all models. All of the pressures were applied as normal and constantly distributed along the surface.

The depth of cut was 5 mm for all models. The cutter width was 12.5 mm for all models. The meshes and the geometry for the models are presented in Figures 2, 3 and 4. In these figures, the displacements are constrained along both the X- and Y-axis in the ‘Line AB’ (length of 7.5 cm) and along only the Y-axis in the ‘Line BC’ (length of 15 cm). The lateral pressure is applied along the ‘Line CD’.

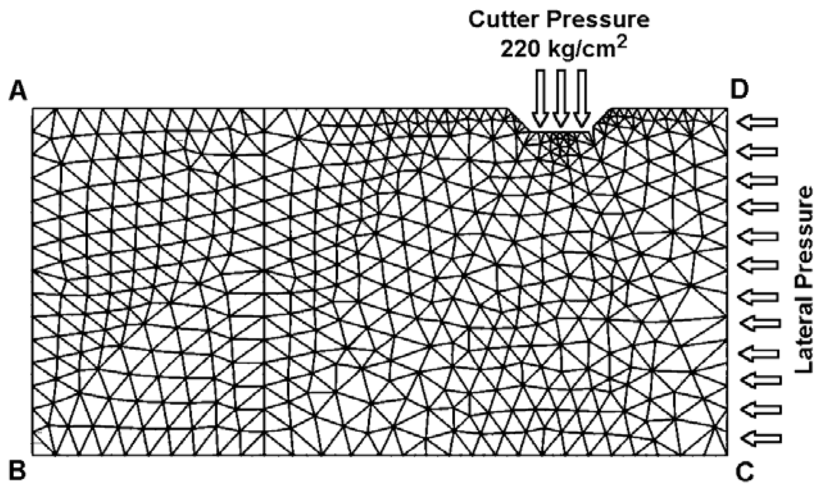

Figure 2. Model geometry for unrelieved cutting.

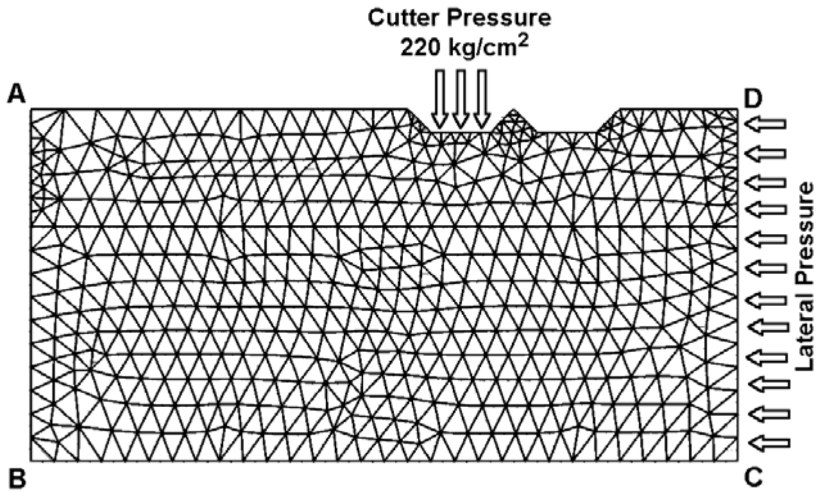

Figure 3. Model geometry for relieved cutting (spacing = 10 mm) .

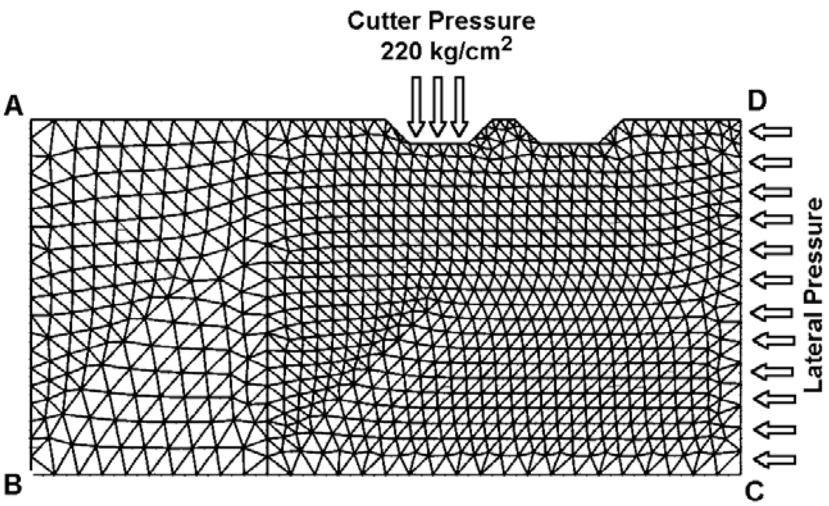

Figure 4. Model geometry for relieved cutting (spacing = 15 mm).

The stress distributions along the Y-axis (σ_{yy}) around the cutter-concrete contact area are presented as contour map in Figures 5, 7 and 9 for all models. It should be noted that the compressive stress is (-) and the tensile stress is (+) in these figures. Figures 5a, b, c, d, e show σ_{yy} stress distribution for unrelieved cutting, lateral stress being kept at 0, 10, 20, 50 and 150 kg/cm^2. It is clearly seen from these figures that lateral stresses decrease tensile stresses dramatically around the cutting tool or cutting groove up to a certain level of lateral stresses, in this case, a lateral stress of 1/5 or 1/4 of sample compressive strength in magnitude. It is obvious that a decrease in tensile stress around cutting tool will have an increasing effect in tool forces. Since breakage of chips occurs as tensile failure, decreasing tensile stress concentration would mean more difficult chipping of material and necessitate increasing cutter forces to generate tensile fractures. On the other hand, applying lateral pressure generates a confinement within the sample. It is known that breakage of a multi-axially loaded material is more difficult than uniaxial loading case. The interpretation of σ_{yy} stress distribution for unrelieved cutting as a hypothetical curve is given in Figure 6. This figure may be summarised as there is a critical lateral stress of 1/4 or 1/5 of rock compressive strength causing an increase of around 60 percent in cutter force.

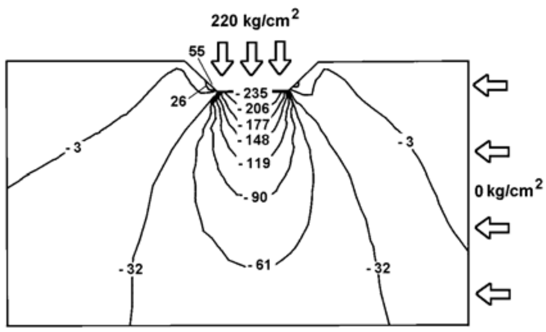

Figure 5a. σ_{yy} stress distribution for unrelieved cutting, lateral stress = 0 kg/cm^2

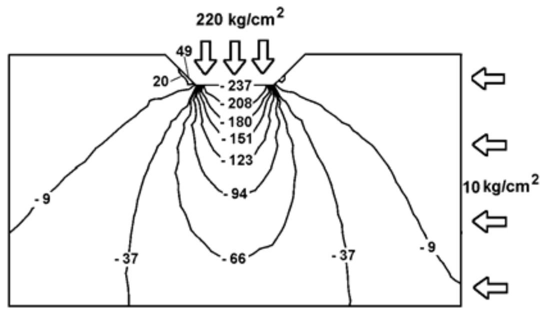

Figure 5b. σ_{yy} stress distribution for unrelieved cutting, lateral stress = 10 kg/cm^2

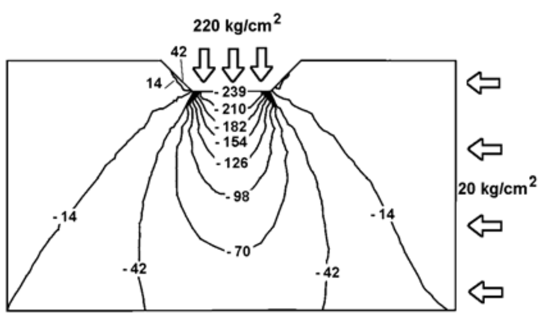

Figure 5c. σ_{yy} stress distribution for unrelieved cutting, lateral stress = 20 kg/cm^2

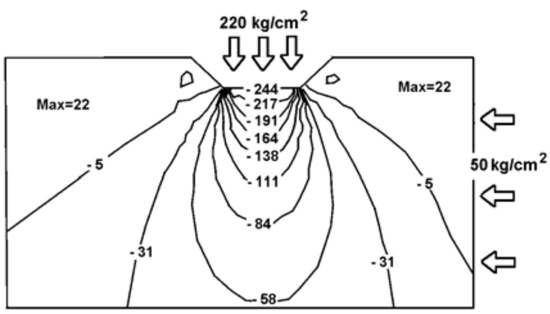

Figure 5d. σ_{yy} stress distribution for unrelieved cutting, lateral stress = 50 kg/cm^2

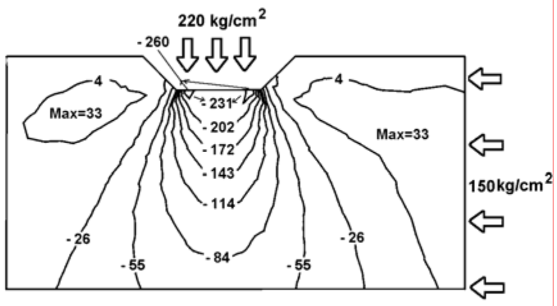

Figure 5e. σ_{yy} stress distribution for unrelieved cutting, lateral stress = 150 kg/cm^2

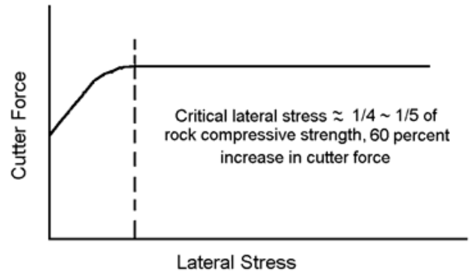

Figure 6. Interpretation of σ_{yy} stress distribution for unrelieved cutting, hypothetical curve

It is important to note that relieved cutting mode should be considered in practical situation, since the cutting tools interact each other in a cutting head of an excavation machine. There is always a free cutting groove next to an adjacent cutting tool effecting cutting performance of this tool. Figures 7 and 9 show σ_{yy} stress distribution for relived cutting for different lateral stresses. Cutter spacing of 10 mm and 15 mm are taken for numerical modelling, cutter spacing being measured from one edge of the cutter to the edge of the next cut. Figures 8 and 10 give the interpretation of σ_{yy} stress distribution for relieved cutting with tool spacings of 10 and 15 mm, respectively. These figures justify also the fact that a critical lateral stress up to 1/4 or 1/5 of compressive strength increases cutter force, however, this time not as high as in unrelieved mode. This is mostly because the effect of confinement on the current cut groove would decrease due to the previously generated relief cuts.

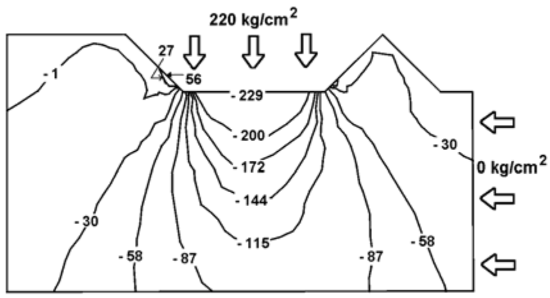

Figure 7a. σ_{yy} stress distribution for relieved cutting, s=10 mm, lateral stress = 0 kg/cm^2

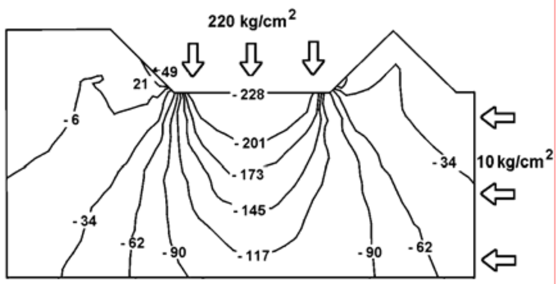

Figure 7b. σ_{yy} stress distribution for relieved cutting, s= 10 mm, lateral stress = 10 kg/cm^2

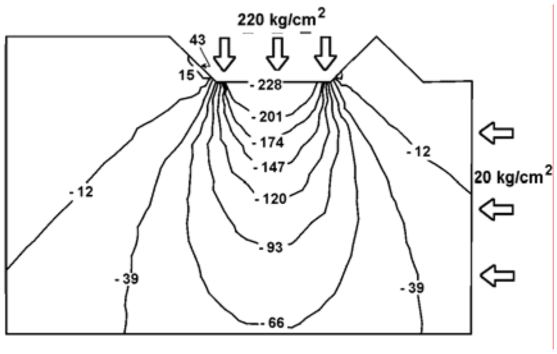

Figure 7c. σ_{yy} stress distribution for relieved cutting, s= 10 mm, lateral stress = 20 kg/cm^2

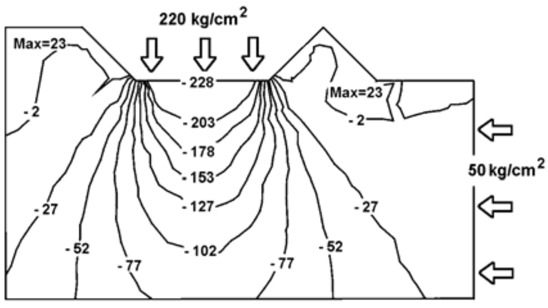

Figure 7d. σ_{yy} stress distribution for relieved cutting, s= 10 mm, lateral stress = 50 kg/cm^2

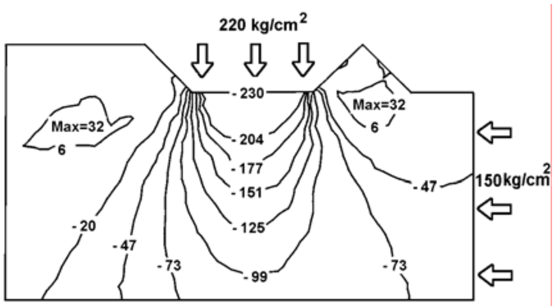

Figure 7e. σ_{yy} stress distribution for unrelieved cutting, s=10 mm, lateral stress = 150 kg/cm^2

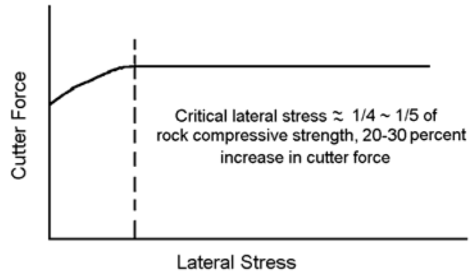

Figure 8. Interpretation of σ_{yy} stress distribution for relieved cutting,s=10 mm, hypothetical curve

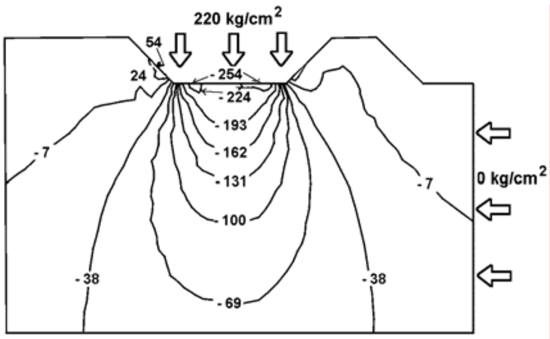

Figure 9a. σ_{yy} stress distribution for relieved cutting, s=15 mm, lateral stress = 0 kg/cm^2

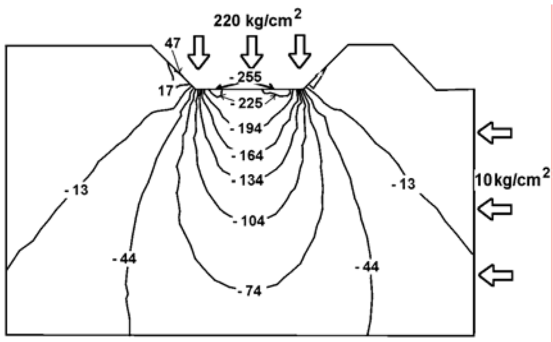

Figure 9b. σ_{yy} stress distribution for relieved cutting, s= 15 mm, lateral stress = 10 kg/cm^2

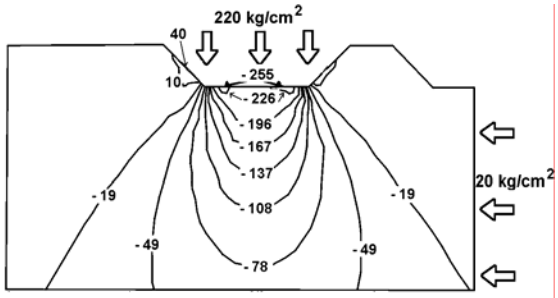

Figure 9c. σ_{yy} stress distribution for relieved cutting, s= 15 mm, lateral stress = 20 kg/cm^2

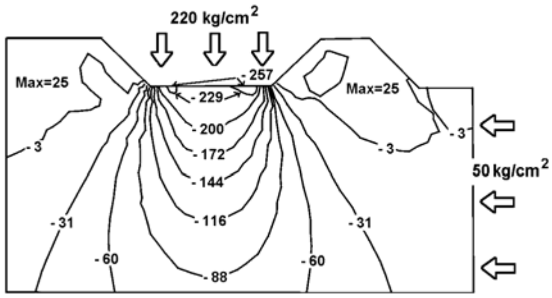

Figure 9d. σ_{yy} stress distribution for relieved cutting, s= 15 mm, lateral stress = 50 kg/cm^2

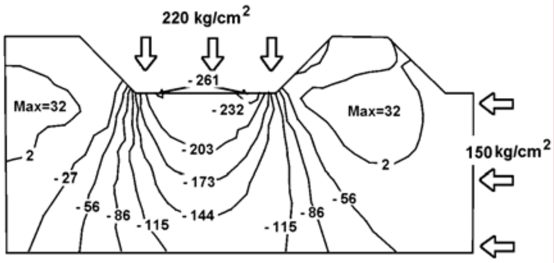

Figure 9e. σ_{yy} stress distribution for unrelieved cutting, s=15 mm, lateral stress = 150 kg/cm^2

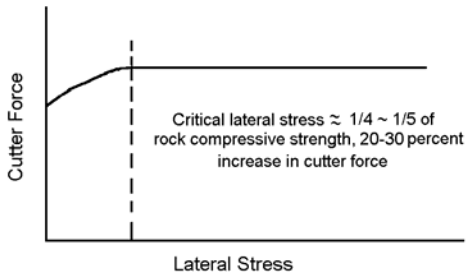

Figure 10. Interpretation of σ_{yy} stress distribution for relieved cutting,s=15 mm, hypothetical curve

3.2 Experimental set-up and test procedure for modelling the ground stresses

A shaping machine equipped with a chisel pick having a rake angle of -5° and width of 12.5 mm is used as a cutting rig. Tool cutting, normal and side force are measured using a triaxial piezoelectric, a charge amplifier and a data acquisition system. Specific energy values are found dividing the mean cutting force (in KN) to the yield (in m^3/km). All cutting parameters are defined in Figure 11. Lateral stresses are given to cutting samples with the aid of hydraulic pistons. Deliberately small increments of lateral forces were applied to cutting samples in order to check the findings of numerical modelling. A great attention was paid to prepare standard plaster and concrete samples for cutting tests. The mechanical properties of the cutting samples were already given in Table I.

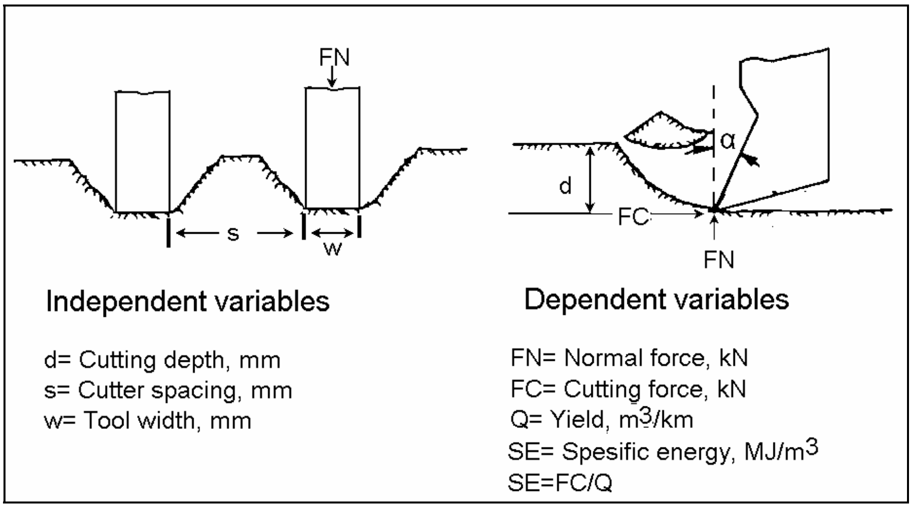

Figure 11. Definition of dependent and independent variables in rock cutting experiments

The effect of lateral stress on mean normal force for relieved and unrelieved cutting of concrete and plaster samples are given in Figures 12 and 13. These figures justify the findings of numerical model described above. For moderate lateral stresses and unrelieved cutting, normal forces increase almost up to 60 percent, and for relieved cutting up to 25 percent. As shown in numerical modelling, this increase in normal force is expected to be levelled off after a critical lateral stress having a magnitude of 1/4 or 1/5 of sample compressive strength.

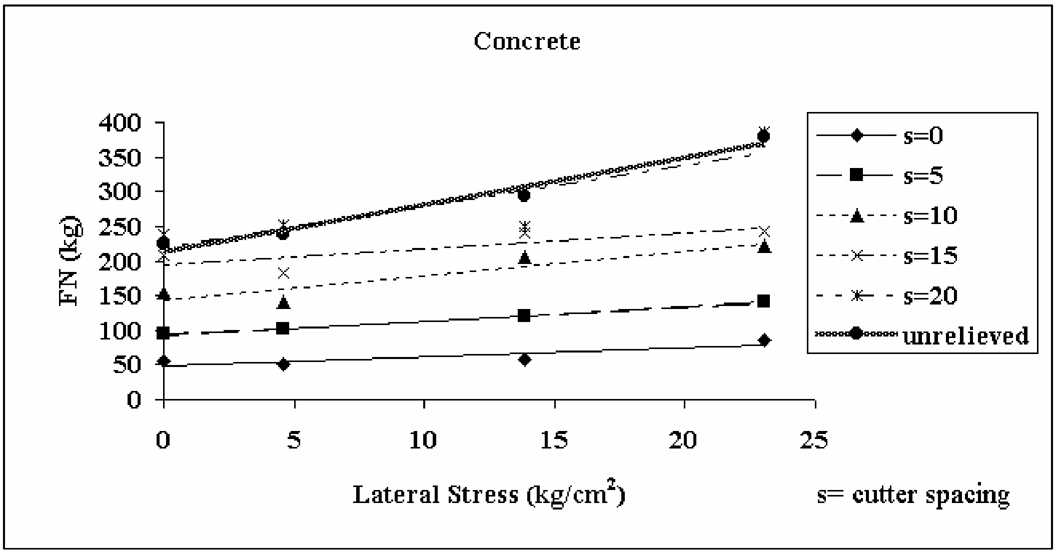

Figure 12 The effect of lateral stress on mean normal force for concrete for relieved and unrelieved cutting.

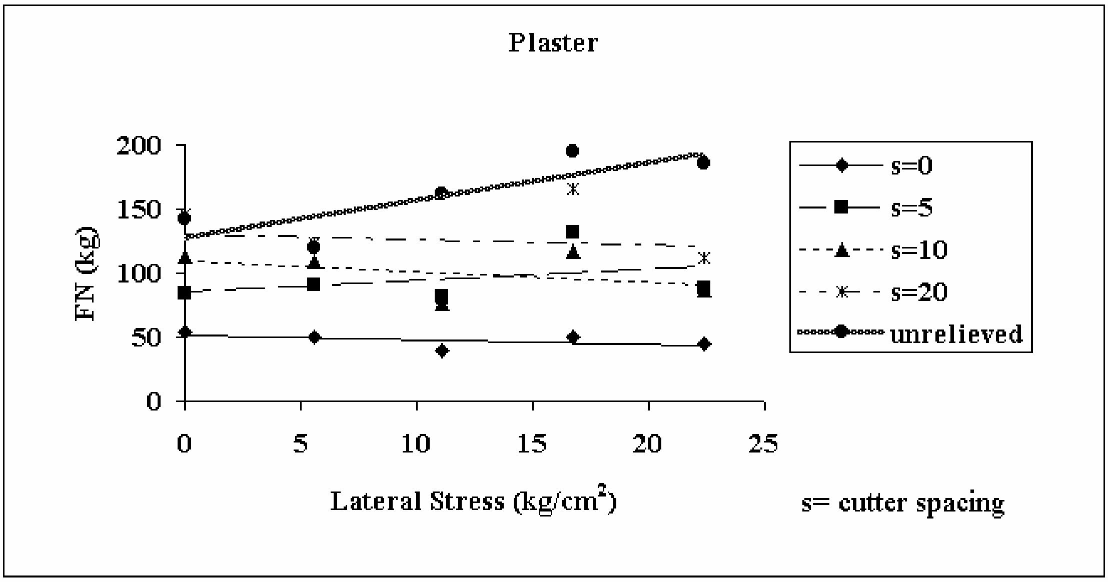

Figure 13 The effect of lateral stress on mean normal force for plaster for relieved and unrelieved cutting.

It is well known from rock cutting mechanics that tool-cutting force is directly related to normal force. Figures 14 and 15 show that cutting force is also effected by lateral stress as much as normal force.

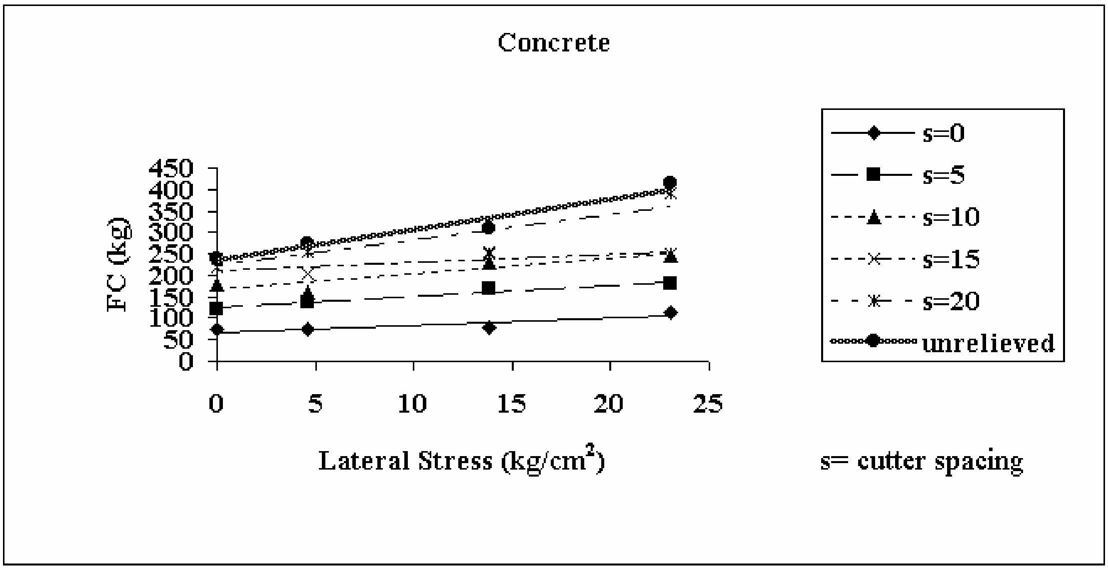

Figure 14 The effect of lateral stress on mean cutting force for concrete for relieved and unrelieved cutting.

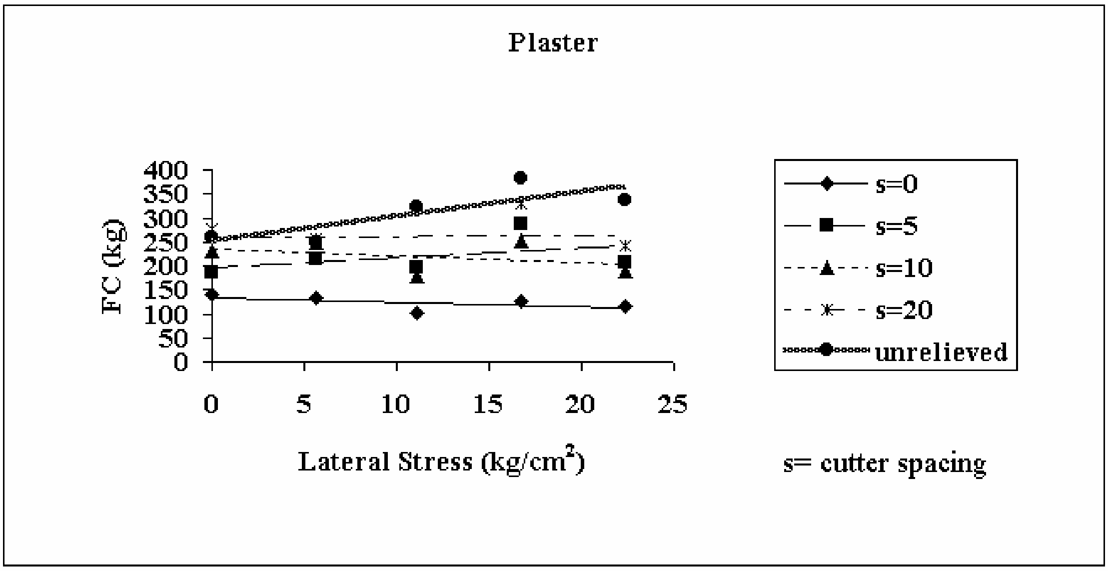

Figure 15 The effect of lateral stress on mean cutting force for plaster for relieved and unrelieved cutting.

Figures 16 and 17 show the effect of lateral stress on specific energy for relieved and unrelieved cutting of concrete and plaster samples. The effect of lateral stress in concrete is more apparent with an increase of 60 percent in unrelieved mode and 25 or 30 percent in relieved mode. These results emphasise that the full-scale cutting test results used in machine performance prediction should be re-evaluated. It is recommended that specific energy values found in full scale relieved cutting tests, should be multiplied at least with a factor of 1.3 in performance prediction models, if tunnels under stresses are considered.

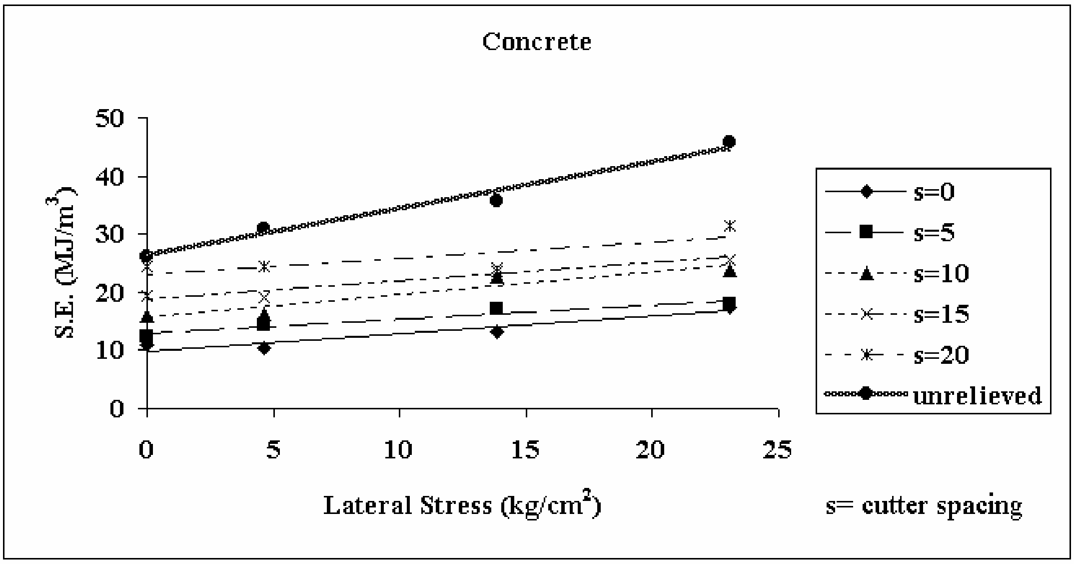

Figure 16 The effect of lateral stress on specific energy for concrete for relieved and unrelieved cutting.

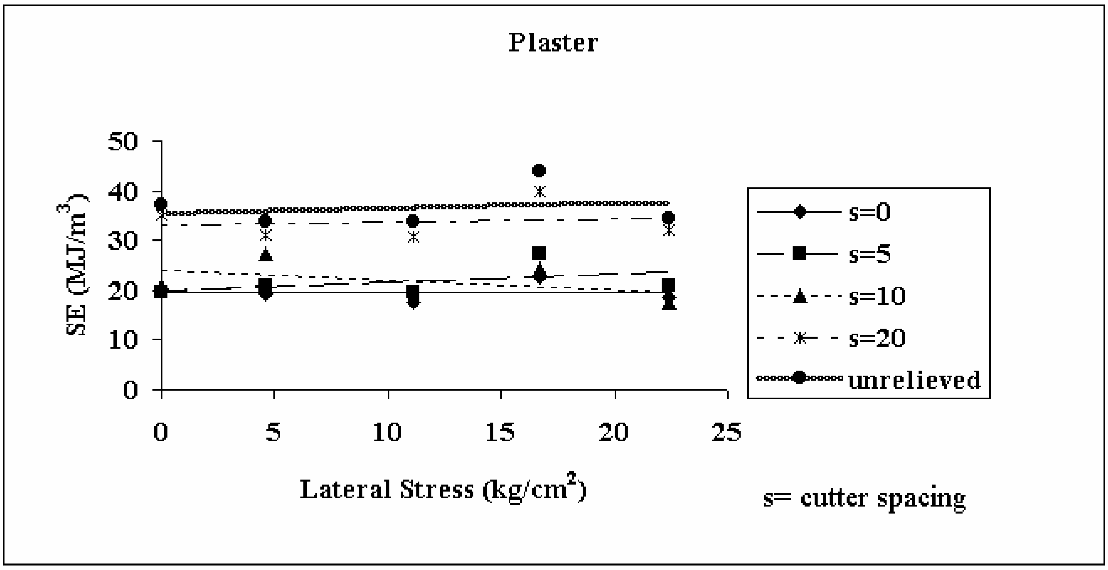

Figure 17 The effect of lateral stress on specific energy for plaster for relieved and unrelieved cutting.

4. CONCLUSIONS

A detailed research study was carried out using a numerical modelling software and small-scale rock cutting rig to investigate the effect of lateral stresses on the cutting efficiency of chisel type cutters. Numerical modelling showed that for unrelieved cutting lateral stresses dramatically decrease tensile stresses around the cutting groove up to a certain level of lateral stresses, in this case, a lateral stress of 1/5 or 1/4 of sample compressive strength in magnitude, causing an increase of around 60 percent in cutter force. However, for relieved cutting the effect of lateral stresses are less apparent, causing an increase in cutter force around 20 or 30 percent more than unstressed conditions. Experimental cutting tests justify the findings of numerical modelling used in this study. These results emphasise that specific energy values found in full-scale relieved cutting tests should be multiplied at least with a factor of 1.3 in performance prediction models, if tunnels under stresses are considered.

ACKNOWLEDGEMENT

The research study described in this paper is a part of NATO-TU Excavation Project sponsored by NATO Science for Stability Programme. The generous help and advise of Prof. Dr. Levent Ozdemir from Colorado School of Mines is acknowledged. The software used in this study is developed in Cornell and Kansas State University, by fracture mechanic group, thanks are due to all research people contributing to the development of this software.

REFERENCES

1. McFeat-Smith, I., and Fowell, R.J. Correlation of rock properties and the cutting performance of tunnelling machines. *Proceedings of a Conference on Rock Engineering.* The University of Newcastle Upon Tyne,1977, pp. 581-602.

2. McFeat-Smith, I., and Fowell, R.J. The Selection and application of roadheaders for rock tunnelling. *Rapid Excavation and Tunnelling Conference.* Atlanta, 1979, pp. 261-280.

3. Rostami, J., Ozdemir, L., and Neil, N.M. Performance prediction. A key issue in mechanical hard rock mining. *Mining Engineering.* November, 1994, pp. 1263-1267.

4. Bilgin, N., Seyrek, T., and Sahriar, K. Roadheader performance in İstanbul Golden Horn clean up contributes valuable data. *Tunnels and Tunnelling.* Vol. 20, No. 6. 1988, pp 41-44.

5. Bilgin, N., Seyrek, T., Erdinç. E., and Sahriar, K. Roadheader glean valuable tips for Istanbul Metro. *Tunnels and Tunnelling.* Vol 22, No. 10. 1990, pp 29-32.

6. Bilgin, N., Yazıcı, S., and Eskikaya, Ş. A model to predict the performance of roadheaders and impact hammers in tunnel drivages. *Proceedings, Eurock 96*. Torino, Balkema, 1996. pp.715-720.

7. Bilgin, N., Kuzu. C., and Eskikaya. Ş. Cutting performance of jack hammers and roadheaders in Istanbul Metro drivages. *Proceedings, World Tunnel Congress, Wienna.* Balkema, 1997. pp. 455-460

8. Eskikaya, Ş., Bilgin, N., Dinçer, T., and Özdemir, L. A model to predict the cutting performance of rapid excavation systems. *Proceedings of the Seventh International Symposium on Mine Planning and Equipment Selection, Calgary*. Balkema, 1998, pp.575-579.

9. Pomeroy, C.D. The effect of lateral pressure on the cutting of coal by wedge –shaped tools. *Proceedings of a Conference on Mechanical Properties of Non- Metallic Brittle Materials.* Conference organised by National Coal Board. Published by Butterworths Scientific Publications, London. 1958. pp 469-478.

10. Roxborough, F.F., Phillips, H.R. Applied rock and coal cutting mechanics. *Workshop Course. 156/81*. Australian Mineral Foundation. Adelaide, May, 1981. pp.1.1-20.6.

11. Swenson, D., and James, M. Franc2D/L, Version 1.3 User's Guide, *Kansas State University,* 1997. p. 87

12. Swenson, D., James. M., and Hardeman, B. Casca , Version 1.4 User's Guide. *Kansas University,* 1997. p. 26.