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MATHEMATICAL MODELING OF THE DIGGING PROCESS OF BUCKET WHEEL EXCAVATORS

Abstract. This paper deals with the mathematical modeling of the digging process of Bucket Wheel Excavators (BWEs). A simulator, namely BWDIG, written in FORTRAN 77 to run on IBM PC/XT/AT or compatible micro-computers, has been developed to describe the complex digging and loading operation of the bucket wheel. The input parameters for the simulator are referred to the geotechnical and physical properties of the rock mass, the constructional characteristics and the operational parameters of the BWE, the method of excavation, the geometry of the excavation profile, and the characteristics of the excavated material. The results of the simulation include the effective and theoretical output of the BWE, the specific energy required for digging the rock mass, the power consumption of the bucket wheel motor(s) and the digging time. The performance of the simulator has been tested successfully with data obtained from full-scale real-time measurements on a BWE operating at an opencast lignite mine in Greece. BWDIG can be used as a predictive model for the quantitative assessment of BWE diggability and the design of job-tailored BWEs.

1. INTRODUCTION

The continuous mining system which consists of Bucket Wheel Excavators (BWEs), Conveyors and Stackers is today the most efficient system for the opencast mining of extended lignite (brown coal) deposits, although its applications are extending into harder formations. With the increased emphasis placed on integrating land reclamation with the basic mining operation, this continuous mining system offers, also, advantages for rapid land reclamation to minimize adverse environmental impacts and the relevant cost.

Modern BWEs, mainly of medium and large size, are highly customize to meet specific mine requirements, and their design is based on specifications provided by the user to the manufacturer (job-taylored machines). In order to specify the constructional characteristics and the operational parameters of a BWE, it is of vital importance to determine, as accurate as possible, the properties of the rock mass to be excavated affecting BWE diggability. Since a considerable period of time passes between the specification of a BWE and its installation at the minesite, the data concerning rock mass properties, at that time, are limited and are obtained from geotechnical logs of cored exploration drillholes or from tests on drillcores.

The ideal procedure to determine BWE diggability is to conduct a trial excavation with a BWE at the minesite where it is going to operate, but this is rather always not practical. An alternative approach is to relate BWE diggability to various geological and geotechnical parameters.

The determination of the ease of excavation of a rock mass has been based mainly on empirical and/or intuitive processes and a number of diggability criteria has been published (Panagiotou,1989 - Hadjigeorgiou et al.1988 - Wade et al,1987). All these criteria are qualitative and the rock mass is classified as "not diggable", "diggable", "easy diggable" or that "blasting/ripping is required prior to mechanical excavation". But quantitative rather than qualitative information is required for design purposes.

Modern excavating equipment operating in opencast mines has become more powerful and capable to excavate harder formations, and as a result a rock mass required blasting/ripping prior to mechanical excavation in the past, nowadays can be handled without any preparation. Therefore, it is now necessary to approach diggability in a quantitavive manner and to take into account in its assessment the geotechnical parameters of the rock mass, as well as the constructional characteristics and the operational parameters of the equipment.

This paper describes a mathematical model of the digging process of BWEs, which can be used as a predictive model for the assessment of BWE diggability.

2. BASIC BWE OPERATION

Modern BWEs are, mainly, constructed with crowd-less type bucket wheel booms and excavate according to the full block - terrace cut method (Figure 1).

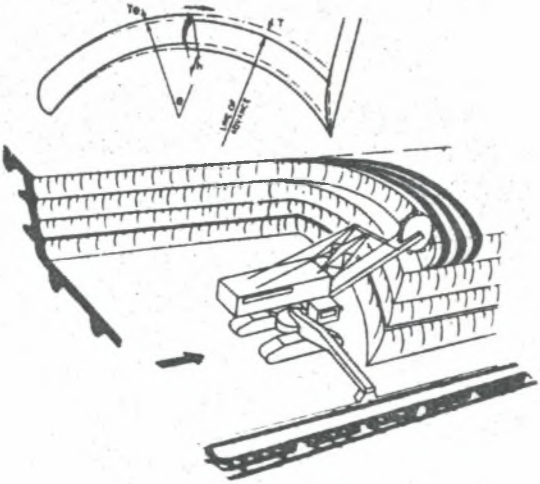

Fig. 1. BWE excavating according to the Full Block - Terace Cut Method

The BWE is positioned in front of the working face and the direction of digging is perpendicular to the direction of mining. The rock mass is excavated by slewing the bucket wheel, while rotating, back and forth through an arc with each pass at a selected cut depth, and digging alternately in both directions. Bucket wheel rotating or cutting speed is dictated by the rock mass characteristics and the slewing speed of the bucket wheel boom. The slice of the rock excavated is sickle shaped, tapering at the ends as the slewing angle increases from the direction of BWE advance. As a result, the slice depth decreases and BWE output is reduced, unless slewing speed is proportionally increased. Modern BWE are equipped with devices for programmed automatic adjustment of the slewing speed to maintain a constant output. The face slope is established by a series of bench type cuts made by the forward arc of the bucket wheel. The BWE is advanced bodily in the direction of digging after each slewing pass to provide the slice depth, and this is repeated until the desired terrace depth is achieved. Then, the BWE is repositioned, by moving backward bodily, for the start of the next terracing cut sequence.

A very close approximation of the slice depth at any angle of slew is given by the equation (Rodgers,1960):

$$T\theta = T\left(\cos\theta + \frac{\sin^2\theta}{2P}\right) \qquad (1)$$

where:

$$P = \frac{R}{T} \tag{2}$$

Tθ = slice depth at slewing angle θ, m
T = slice depth in the direction of advance, m
R = slewing radius, m
θ = slewing angle from the direction of advance

In order to maintain a constant output the slewing speed of the bucket wheel boom should be increased according to the equation :

$$V_{slew}(\theta) = \frac{V_{slew}}{\cos\theta} \tag{3}$$

where:

Vslew(θ) = slewing speed at slewing angle θ, m/min
Vslew = slewing speed at θ = 0°, m/min

3. ASSESSMENT OF BWE DIGGABILITY

Due to the complexity of the BWE digging operation, the fact that the geometry of the excavation profile is changing along the arc of the face and that, apart of digging the rock mass, the bucket wheel is loading the excavated material onto the bucket wheel boom conveyor belt, in assessing BWE diggability the following factors should be taken into consideration (Panagiotou,1989):

- the properties of the rock mass
- the BWE constructional characteristics
- the BWE operational parameters
- the geometry of the excavation profile
- the characteristics of the excavated material
- the method of excavation

When one is confronted with rock, he must visualize the rock as an assemblage of intact rock blocks separated by different types of natural or artificial discontinuities. In assessing BWE diggability both the properties of intact rock material and the properties of the discontinuities are incorporated. In general, the properties of the various sets of discontinuities are of greater importance than those of the intact rock. This has been recognized in practice and the aim of blasting difficult to mined rocks prior to excavation by BWEs, is to create artificial discontinuities into the rock mass (Golosinski,1984 - Musil,1987 - Hojdar,1987 - Kumaraswamy et al,1987).

The constructional characteristics of the BWE that affect its performance and the ability to excavate various rock formations, and determine the geometry of the excavation profile, include the bucket wheel diameter, the number, volume and shape of the buckets, the type and geometry of the cutting tools, the slewing radius of the bucket wheel boom, the existence of an automatic slewing device, and the rating of the bucket wheel motor(s). BWE operational parameters affecting its diggability are the cutting speed of the bucket wheel and the slewing speed of the bucket wheel boom.

4. THE BWDIG SIMULATOR

BWDIG (Bucket Wheel DIGger) is a simulation model - program, written in FORTRAN 77 to run on IBM PC/XT/AT or compatible microcomputers.

The model simulates the digging process of a BWE with a crowdless type boom and a vertical bucket wheel, according to excavation method described in paragraph 2. The flowchart of the program is given in Figure 2.

In order to incorporate both the geotechnical properties of intact rock and the properties of the discontinuities, the failure criterion described by Hoek & Brown has been used (Hoek et al,1980 - Hoek et al,1981). According to this criterion the shear and tensile strength of a rock mass is given by the equations [4] and [6] respectively:

$$\tau = A \sigma c \left(\frac{\sigma}{\sigma c} - T \right)^{B} \qquad (4)$$

$$T = \frac{1}{2} \left(m - \sqrt{m^2 + 4s} \right) \qquad (5)$$

$$\sigma t = \frac{1}{2} \sigma c \left(m - \sqrt{m^2 + 4s} \right) \qquad (6)$$

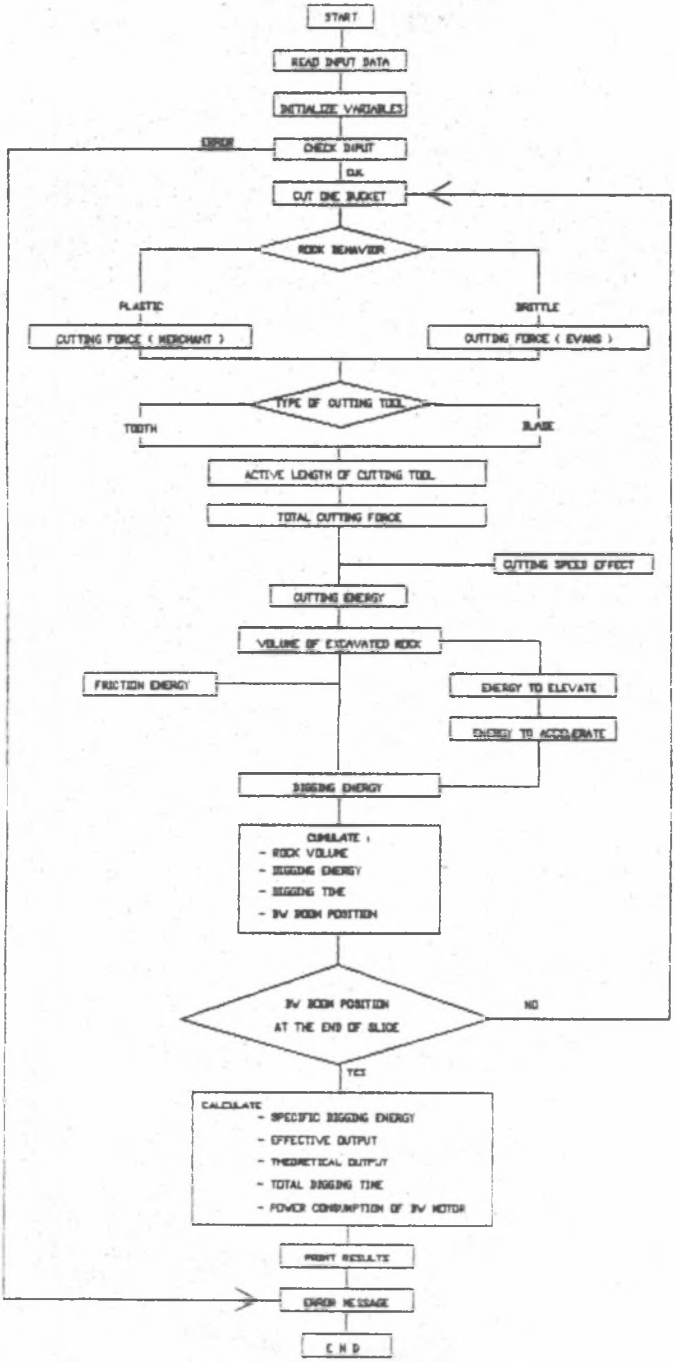

Fig. 2. Flowchart of BWEDIG simulator

where:

τ = shear strength of rock mass, kg/cm^2,
σc = uniaxial compressive strength of intact rock material, Kg/cm^2,
σ = normal stress, Kg/cm^2,
σt = tensile strength of rock mass, Kg/cm^2,
m,s = dimensionless constants which depend upon the properties of the rock and the degree of jointing or fracturing,
A,B = dimensionless constants defining the shape of the Mohr failure envelope.

The constants m, s, A, and B are determined from the results of laboratory triaxial tests, but when such data are not available or when it is required to estimate the strength of a large rock mass, these constants, for various rock types and rock mass quality, are provided in a table by Hoek et al,1981. In order to use this table the rock mass rating according to the CSIR Geomechanics Classification (Bieniawski,1977) should be estimated from borehole data and point load tests on drillcores. Using equation [4] the Mohr failure envelope is plotted and the frictional (φ) and cohesive (c) strength characteristics of the rock mass are derived.

Rock is characterized as brittle or plastic by using the "Coefficiency of Plasticity", which is estimated from Shore Scleroscope rebound hardness tests, and given by (McFeat-Smith,1977):

$$K = \frac{H2 - H1}{H1} 100 \qquad (7)$$

where:

K = coefficiency of plasticity, %
H2 = final hardness value after approximately 20 tests
H1 = average rock hardness value

Plastic rocks have high K values; low K values are obtained from brittle rocks.

Owning to the different mode of rock breakage under the action of the wedge-type cutting tools of the buckets, the cutting force of plastic rocks is predicted by using the Merchant's shear cutting theory (Merchant,1944 - Gottlieb et al,1981):

$$Fc = \frac{2\ c\ d\ \sin\ (\ \beta + \varphi'\ )}{[\cos\ \varphi\ +\ \cos\ (\ \beta + \varphi'\ )]\ [1 - \tan\ 1/2\ (\ \beta + \varphi' + \varphi\ )]} \tag{8}$$

and the cutting force of brittle rocks is predicted by using the Evans' tensile cutting theory (Evans et al, 1973):

$$Fc = \frac{2\ \sigma t\ d\ \sin\ (\ \beta/2 + \varphi'\ )}{1 - \sin\ (\ \beta/2 + \varphi'\ )} \tag{9}$$

where:

Fc = cutting force per unit length of tool edge, Kg/cm,
c = cohesion of rock, Kg/cm^2,
d = depth of cut, cm,
σt = tensile strength of rock, Kg/cm^2,
β = $\pi/2 - \varepsilon$,
ε = cutting tool rake angle,
φ = internal friction angle of rock,
φ' = friction angle between rock and cutting tool.

BWDIG is programmed to reflect the dynamic characteristics of the BWE digging process, and rate equations are used to generate the interaction between the unit operations encompassed by the system simulated. Standard deterministic simulation enables the BWE to performs according to its constructional and operational capabilities along the excavation profile. The interactive procedure used in the model is as follows (Panagiotou,1989):

Step 1 : Cut one bucket, cumulate excavated material, energy consumption for digging, and digging time.
Step 2 : Calculate width traversed by the bucket wheel boom to take one bucket of material.
Step 3 : Calculate the position of the bucket wheel boom.
Step 4 : (a) If the position of the bucket wheel boom is not at the end of the slice, go to Step 1.
(b) If the position of the bucket wheel boom is at the end of the slice, the simulation stops and the simulator calculates:

- the specific digging energy of the rock mass
- the effective output of the BWE
- the theoretical output of the BWE
- the total digging time
- the power consumption of the digging motor(s)

The digging energy required to excavate the rock mass during each bucket pass along the excavation profile is given by:

$$Ed = Ec + Efr + Ee + Ea \tag{10}$$

where:

Ed = digging energy, Kg.m

Ec = energy required to cut the rock, Kg.m

Efr = energy required to overcome friction between the metal surfaces and the rock, Kg.m

Ee = energy required to elevate excavated material being into the bucket along the discharge trajectory, Kg.m

Ea = energy required to accelerate excavated material being into the bucket, Kg.m

The specific digging energy of the rock mass is given by:

$$SE = 2.724\ 10^{-6}\ \frac{Et}{Vl} \tag{11}$$

where:

SE = specific digging energy, KWh/m^3 l

Et = total digging energy, Kg.m

Vl = total volume of excavated (loose) material, m^3 l

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 1.  BW DIAMETER,M                          >7.5
 2.  NO OF BUCKETS                          >10
 3.  CUTTING SPEED,M/SEC                    >2.43
 4.  SLEWING SPEED,THETA=0,M/MIN            >12
 5.  VARIABLE SLEWING SPEED,YES=1,NO=0      >0
 6.  SLEWING SPEED MAX,M/MIN                >40
 7.  BUCKET CAPACITY,CU.M                   >0.6
 8.  RADIUS OF SLEW,M                       >31.75
 9.  MECHANICAL EFFICIENCY                  >0.8
10.  ELECTRICAL EFFICIENCY                  >0.9
11.  HEIGHT OF BUCKET,M                     >0.63
12.  SLEW ANGLE,DEG                         >50
13.  HEIGHT OF BENCH,M                      >3
14.  DEPTH OF SLICE,THETA=0,M               >0.45
15.  TYPE OF ROCK,PL OR BR                  >'PL'
16.  COHESION,KG/SQ.CM                      >0.8
17.  INTERNAL FRICTION ANGLE,DEG            >30
18.  TENSILE STRENGTH,KG/SQ.CM              >1
19.  CUTTING TOOL RAKE ANGLE,DEG            >55
20.  RADIUS OF BUCKET LIP,M                 >0.3
21.  TEETH ON BUCKET,YES=1,NO=0             >0
22.  TEETH PER M                            >1
23.  LENGTH OF TOOTH EDGE,M                 >0
24.  UNIT WEIGHT OF ROCK,KG/CU.M            >2000
25.  SWELL FACTOR                           >1.45
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Fig. 3. Input data of a simulation run

The performance of BWDIG has been tested successfully with data obtained from full-scale real-time measurements on a BWE, type SchRs 600/3.3 x 21, operating at the Kardia Lignite Mine, Ptolemais, of the Public Power Corporation of Greece (Panagiotou,1989). The listing of the input data and the corresponded output of a simulation run for testing BWDIG is given in Figure 3 and Figure 4 respectively.

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***** SIMULATION REPORT *****

SPECIFIC DIGGING ENERGY,KWH/CU.M             >          .1447


EFFECTIVE OUTPUT,CU.M LOOSE/HOUR             >        1240.84


THEORETICAL OUTPUT,CU.M LOOSE/HOUR           >        2227.73


DIGGING TIME,MIN                             >           2.31


POWER CONSUMPTION OF DIGGING MOTOR,KW        >         249.33
 Program STOP
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Fig. 4. BWDIG output; input data as per Figure 3

5. CONCLUSIONS

BWDIG, the simulation model described in this paper, is able to predict BWE diggability quantitatively, estimating the specific digging energy required to excavate the rock mass, and the effective output of the BWE. These two parameters are easily combined with economical and operational factors of the mining operation. BWDIG is amenable to manipulation; the user may vary the input data, which are dealing with the constructional characteristics and the operational parameters of the BWE, the type and geometry of the cutting tools and the excavation profile, and combine them in a such a way, so as a BWE under design be able to excavate a certain rock mass, while it maintains a desired output rate. In this sense, BWDIG can be used as a tool for designing job-tailored BWEs.

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MATEMATYCZNE MODELOWANIE PROCESU KOPANIA WYKONYWANEGO PRZEZ WIELONACZYNIOWE KOPARKI KOŁOWE

Streszczenie

Niniejszy artykuł omawia matematyczne modelowanie procesu kopania realizowanego przez wielonaczyniowe koparki kołowe. Dla opisania kompleksowego sterowania kopaniem i załadunkiem tej kołowej koparki, opracowano symulator BWDIG w proceduralnym języku FORTRAN 77, pracujący na komputerze IBM PC/XT/AT lub kompatybilnych mikrokomputerach.

Wejściowe parametry dla symulatora odnoszą się do geotechnicznych i fizycznych własności górotworu, cech konstrukcyjnych i parametrów eksploatacyjnych tej wielonaczyniowej koparki, sposobu urabiania, geometrii profilu wykopu oraz cech wydobytego materiału. Wyniki symulacji obejmują rzeczywiste i teoretyczne wydajności tej koparki, energię właściwą potrzebną do kopania górotworu, zużycie mocy przez silnik(i) koparki oraz czas kopania. Z powodzeniem przebadano osiągi symulatora porównując je z danymi uzyskanymi podczas pomiarów w skali naturalnej i czasie rzeczywistym w okrywkowej kopalni lignitu w Grecji. Wielonaczyniowa koparka wyposażona w ten symulator może stanowić informacyjny model dla jakościowego i ilościowego określania zdolności kopania i konstrukcji tych koparek.

МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССА КОПАНИЯ, ПРОИЗВОДИМОГО МНОГОКОВШЕВЫМИ РОТОРНЫМИ ЭКСКАВАТОРАМИ

Резюме

В настоящей статье обсуждается математическое моделирование процесса копания, реализируемого многоковшевым роторным экскаватором. Для описания комплексного управления копания и загрузки этого роторного экскаватора, разработано симулятор BWDIG в процедуральном языке ФОРТРАН 77, для работы на компьюторе IBM PC/XT/AT или на компатебильных микрокомпьюторах. Входные параметры для симулятора относятся к геотехническим и физическим свойствам горных пород, окружающих горные выработки, к конструкционным свойствам и эксплутационным параметрам этого многоковшевого экскаватора, способу вырубки и свойствам добытого материала. Результаты симуляции охватывают действительные и теоретические производительности этого экскаватора, собственную энергию, необходимую для копания горной породы, расход мощности двигателями экскаватора и времени копания. С успехом испытано характеристики симулятора, сравнивая их с данными полученными во время измерений в натуральном масштабе и действительном времени в карьере лигнита в Греции. Многоковшевой экскаватор оснащен этим симулятором - он может служить информационной моделью для качественного и количественного определения способности копания и конструкции этих экскаваторов.