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PJBS

ISSN 1028-8880

Pakistan Journal of Biological Sciences

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Pakistan Journal of Biological Sciences 11 (11): 1422-1428, 2008
ISSN 1028-8880

Physical Soil Properties and Slope Treatments Effects on Hydraulic Excavator Productivity for Forest Road Construction

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Abstract: Effects of moisture, porosity and soil bulk density properties, grubbing time and terrain side slopes on pc 220 komatsu hydraulic excavator productivity were investigated in Miana forests road construction project which located in the northern forest of Iran. Soil moisture and porosity determined by samples were taken from undisturbed soil. The elements of daily works were measured with a digital stop watch and video camera in 14 observations (days). The road length and cross section profiles after each 20 m were selected to estimate earthworks volume. Results showed that the mean production rates for the pc 220 komatsu excavators were 60.13 $m^3 h^{-1}$ and earthwork 14.76 $m h^{-1}$ when the mean depth of excavation or cutting was 4.27 $m^3 m^{-1}$, respectively. There was no significant effects ($p = 0.5288$) from the slope classes' treatments on productivity, whereas grubbing time, soil moisture, bulk density and porosity had significantly affected on excavator earthworks volume ($p<0.0001$). Clear difference was showed between the earthwork length by slope classes ($p = 0.0060$). Grubbing time ($p = 0.2180$), soil moisture ($p = 0.1622$), bulk density ($p = 0.2490$) and porosity ($p = 0.2159$) had no significant effect on the excavator earthworks length.

Key words: Forest road, physical soil properties, grubbing time, slope, hydraulic excavator

INTRODUCTION

Forest roads are a necessary part of forest management. Road networks provide access to the forest for harvests, fire protection and administration and non-timber uses such as grazing, mining and wildlife habitat (Forman, 2000; Lugo and Gucinski, 2000; Demir and Hasdemir, 2005). The method and equipment used in road construction is an economical and technical important factor in road building, locating and designing (Reed *et al*., 1996). Forest roads should be planned in agreement with the land structure involved and during the planning of roads, the descents and ascents should be provided as to allow a minimum amount of excavation. Furthermore, dozers should in no case be used during the construction of roads, instead of them, excavators should be used (Demir, 2007; Pinard *et al*., 2000).

Hydraulic excavators in forest roads construction has been the major step towards environmentally sound road construction practices (Bulmer, 2000; Tunay, 2006). In some of the important tree stands, marshy, hilly and stoniness terrain of the northern forests of Iran, using excavators not only replaced bulldozers in forest road construction but also improved the quality of roads while reducing environmental impacts of these complex engineering structures (Hosseini and Jalilvand, 2007; Lotfalian *et al*., 2007). The features and advantages of the hydraulic excavator in forest road construction are ability to build the drainage structures, excavation, digging, loading, dredging, stump grubbing, pipe laying, soil and stone materials side cast and breaking the stones and rock by hydraulic hammer (Balci and Bilgin, 2007; FAO, 1998; Towarek, 2003; Filipsson and Eriksson, 1989).

Each machine formed an operating unit and the total time spent on the site per day was referred to as work place time. Work place time was segregated into effective machine working time, necessary and unnecessary delay times and lunch time (Björheden, 1991). Effective machine working time and necessary delay time formed product working time (Abeli, 1993; Edwards *et al*., 2002).

Productivity is defined as the rate of product output per time unit (meter or cubic meter of excavated road) for a given production system, the production rates of a studied system can easily be estimated if time studies combined with measurements of the output of production and it has been completed per effective machine in a working time. Terrain and climate conditions, stoniness, engine power, soil moisture, soil bulk density and porosity, soil depth, number of stumps, using type of excavator, bucket volume and the operators' experience affected on productivity (Coetzee *et al*., 2007; Johansson, 1995).

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The effect of soil moisture and boulder frequency on excavator productivity in forest road subgrade preparation with a width of four meters was studied in central Sweden. Results showed that in soil moisture class mesic and less than one boulder per 100 m^2 the estimated productivity rate for Hitachi 121 LC excavator with 121 kW engine power was 11.3 m h^{-1}. When soil moisture class changed from mesic to moist, the productivity rate decreased 1.5 m h^{-1}. When boulder frequency was between 1 and 4 or greater than four boulders per 100 m^2, the productivity rate was estimated to decrease by 1.6 and 4.2 m h^{-1}. The average length of subgrade was prepared 12.7 m h^{-1} (Filipsson and Eriksson, 1989).

Productivity of Kobelco IV SK210, Komatsu PC300LC and Caterpillar 320L excavators in different side slopes of Sweden forests was estimated. Results showed that the excavator productivity reduced by increase side slope, as well as Kobelco Excavator in side slope 50-55 percent could built 5.69 m h^{-1} roads, but in slope classes 40-45 (Komatsu) and 75-80% (Caterpillar) the production rate was 5.24 and 2.42 m h^{-1}, respectively (IUFRO, 1995). Hydraulic excavator's production rates for constructing 6 to 7 m wide forest roads in 0-40, 40-60 and more than 60% side slopes, were 12-16, 10-13 and 8-10 m h^{-1}, respectively (Schiess *et al*., 1986).

The purpose of this study was to determine the effects of soil moisture, soil porosity, soil bulk density, stump diameter in grubbing operations and terrain side slopes on hourly productivity of hydraulic excavator Komatsu pc 220. This machine used in constructing the secondary forest access roads in Miana forests of Mazandaran province that is located in the northern forest of Iran closed to the Caspian sea. The results of this research will be useful to control forest road construction project and managing excavator machines.

MATERIALS AND METHODS

Study area: This study was conducted in late August 2007. Measurements were carried out in Miana forest which is located in deciduous northern forest of Iran between 52° 56' 30" to 52° 59' 25" East longitudes and 36° 12' 25" to 36° 16' 35" North latitude (Fig. 1). Annual mean temperature ranges from +12 to +14 °C. Annual mean precipitation is between 900 and 1000 mm. The forest altitude ranges from 320 to 1060 m above sea level. The terrain side slopes are 0 to more than 80%. Soil textures range from loam to loamy silt and loamy clay. The study compartments has four kinds of soil consist of non development randzin, washed brown soil with calsic

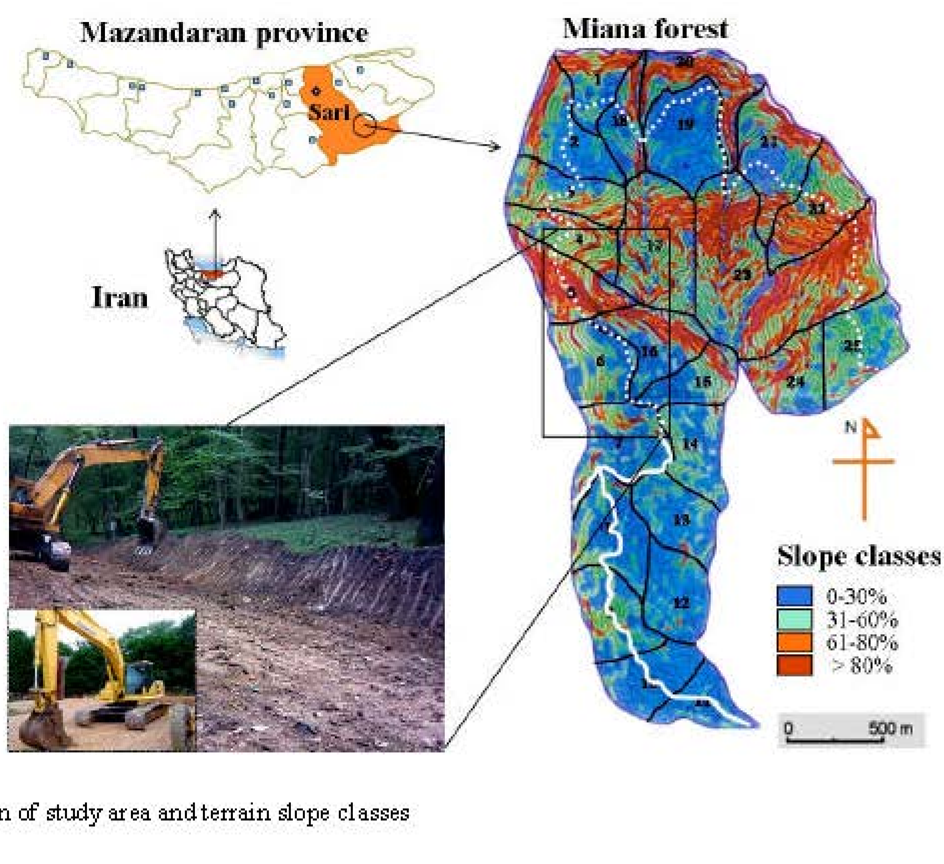

Fig. 1: Location of study area and terrain slope classes

Table 1: General data of hydraulic excavator komatsu pc 220

Engine power (kW)	Machine age (year)	Weight (ton)	Bucket capacity (m^3)	Operator experience (year)
134	25	24	1	10

horizon, calcareous brown soil and brown with alkaline soil pH. The bed rock is limestone, calcareous sandstone, marl lime and calcareous conglomerate. The total Miana forest area is 1831 ha. For this area 10800 m road was predicted in year 1996.

Variables measurements: The variables were measured on about 2 kilometers of predicted forest roads that placed in compartments 4, 5, 6, 15 and 16 of Miana forest. Later these segments of roads were constructed by excavator komatsu pc 220 (Table 1). The roadway width was 6 meters. All trees within the right of way were felled and skidded before excavating operation started.

To determine the mineral soil bulk density (g cm^{-3}), porosity and moisture content (%) in each of work days, sets of undisturbed soil samples having a defined volume (448.5 cm^3 cylinder) were taken from 0-20 cm depths at randomly selected locations of cut slopes center points of skid-trail (along the predicted roads). Soil samples were oven-dried at 105°C for at least 24 h and weighed. Soil Bulk Density (BD), soil porosity (P) and moisture content (W) were calculated using Eq. 1, 2 and 3 shown below: The particle density (PD) for most of the soil was about 2.6 g m^{-3} (Mahmoodi and Hakimian, 2001; Zarrinkafsh, 1993; Dumroese *et al*., 1999; Froelich *et al*., 1985; Saleem Akhtar *et al*., 2001):

$$BD = \frac{m_{soil}}{V_{cylinder}} \tag{1}$$

$$P(\%) = 100 - (\frac{BD}{PD} \times 100) \tag{2}$$

$$W(\%) = \frac{Ww}{Ws} \times 100 \tag{3}$$

where, M_{soil} and $V_{cylinder}$ are dry weight of soil (g) and cylinder volume (cm^3), respectively. Also, W_w and W_s are the weight of soil moisture and weight of dried soil particles, respectively.

The elements of the machine daily work were measured with a digital stop watch and video camera in 14 observations (days). The continuous time method applied for this study. Then, the productive time per day calculated from time and work study data. To determine the productivity of excavator in two terrain slope classes 30-50 and 50-70%, daily amount of earth work volume cut or filled per area was estimated. Therefore road length and cross section profiles after every 20 m on tangent sections were taken by meter and clinometers, before and after the days operation. Cross section road profiles were later plotted and their cross end section areas were also determined. To estimate the volume of cutting or filling soil per road section, the average end area method was used (Eq. 4):

$$V_{i,i+1} = 0.5(A_i + A_{i+1})L_{i,i+1} \tag{4}$$

where, $V_{i,\,i+1}$ volume cutting or filling soil between i^{th} road station and the next station (i+1), m^3; A_i and A_{i+1} are cross sectional end area of i^{th} road station and the next station (i+1), m^2; $L_{i,\,i+1}$ is the distance between road station i and the next station (i+1), m.

When calculating the fill volume, a swell coefficient of 0.8 was used (Abeli *et al*., 2000).

Statistical analyses: Analysis of variance and regression analysis were conducted using GLM and REG procedures in SAS statistical programming software, respectively. Linear regression model was used to determine the dependence between different factors and excavator productivity. Means were compared using tukey's multiple group mean comparison test. Level of significance used in all results was $p<0.01$.

RESULTS AND DISCUSSION

Time study and earthwork data: The percentage of productive working time to work place time for pc 220 komatsu excavator was 86.5% it implied that machine utilization was high. In the structure of daily delay times, 22.22% refers to personal reasons which operator consumed to talk to his friends by mobile phone. Also, 77.78% of total delay time refers to operational delay which occurs during skidding and extracting of timber by HSM skidder along the excavator earth working operations area. The mean production rates for the pc 220 komatsu excavator were 60.13 m^3 h^{-1} and 14.76 m h^{-1} when the mean depth of excavation or cutting was 4.27 m^3 m^{-1} (Table 2). In this study, estimated mean production rate for komatsu excavator (14.76 m h^{-1}) are much higher than those reported by IUFRO (1995). Productivity of Komatsu pc 300LC excavators in slope classes 40-45 (Komatsu) was 5.24 m h^{-1} (IUFRO, 1995). Operators' long working experience, low frequency of stumps and boulders, low depth of excavation (m^3 m^{-1}) and high productive working time contributed to product rate of komatsu pc 220 hydraulic excavators being higher than the Komatsu pc 300 LC excavators. Production rates for constructing 6 to 7 m wide forest roads in 0-40, 40-60 and more than 60% side slopes, were 12-16, 10-13 and 8-10 m h^{-1}, respectively (Schiess *et al*., 1986). In Sweden, where excavator machines were used for subgrading a forest road, the average length of subgrade prepared was 12.7 m h^{-1} (Filipsson and Eriksson, 1989). Similar results were also observed in this research (14.76 m h^{-1} in slope class 30-70%). However, the production rates found in this study appear to be within the acceptable range.

Analysis of variance: The results of analysis of variance revealed high significant differences between excavator earthworks volume in different grubbing times ($p < 0.0001$). Whereas, grubbing time ($p = 0.2180$), soil moisture ($p = 0.1622$), bulk density ($p = 0.2490$) and porosity ($p = 0.2159$) had no significant effect on excavator earthworks length.

Mean earthworks volume (m^3 h^{-1}) in soil moisture class 24 - 28 %, was significantly less (-15.61 m^3 h^{-1}) than soil moisture class 20-24% ($p<0.0001$). Mean earthworks volume was significantly lower at the compacted area ($p<0.0001$). If the soil bulk density class changes from 1.10-1.20% which was more than that of 1.40% in the productivity rate (m^3 h^{-1}) and it was estimated to decrease by 21.84 m^3 h^{-1}. Soil compaction decreases soil macro pores. In the current study, soil porosity could have positive significant effects on excavator earthworks volume ($p<0.0001$).

There were no significant effects ($p = 0.5288$) from the slope classes' treatments on earthwork volume. But a clear difference ($p = 0.0060$) was showed between the earthwork length in different slope classes (Table 3).

Regression analysis: Regression analysis showed that the grubbing time depends on the number of stumps, tree species, stump diameter, soil moisture, soil compaction, rooting system, rooting depth and grubbing machine power (Yildiz *et al*., 2007). In this study there was a linear relationship between the earthwork volume (m^3 m^{-1}) of Komatsu excavator and grubbing time ($R^2 = 0.59$, $p = 0.0013$). Excavator earthworks volume decreased with increasing grubbing time. This negative correlation ($R^2 = 0.32$, $p = 0.0354$) was observed for excavator earthworking length (Table 4). Also, the results showed that *Diospyrus lotus* L. stump diameter had a significant effect on grubbing time ($R^2 = 0.79$, $p<0.0001$). Grubbing time increased with increasing the *Diospyrus lotus* L. stump diameter (Table 5). This species were most frequent within the Miana forest road excavation area. Mean diameters at breast height (dbh) of these trees were 45 cm.

Table 2: Summary of time study and earthworks volume statistical data for all observations

Variables		Work elements	
No. of observations (days)	14.00	Lunch time (h day^{-1})	0.78
Work place time (h day^{-1})	6.46	Operational delay time (h day^{-1})	0.07
Productive time (h day^{-1})	5.59	Earth works volume (m^3 day^{-1})	336.13
Personal delay time (h day^{-1})	0.02	Depth of cut (m^3 m^{-1})	4.27
Earth works length (m day^{-1})	82.28	Production rate (m h^{-1})	14.76
Production rate (m^3 h^{-1})	60.13		

Table 3: Effects of soil, terrain slopes and grubbing time on excavator productivity (Komatsu PC 220)

			Productivity Mean±SE	
Variables	Classes	No	Earthworks volume (m^3 h^{-1})	Earthworks length (m h^{-1})
Slope (%)	30-50	8	61.57±3.45^a	17.00±1.21^a
	50-70	6	58.21±3.82^a	11.77±0.80^b
	1.10-1.20	3	72.11±1.21^a	16.97±1.18
Soil bulk density (g cm^{-3})	1.20-1.30	3	66.90±2.91^a	15.70±2.65^a
	1.30-1.40	3	57.82±0.51^b	16.27±2.07^a
	>1.40	5	50.27±0.78^b	11.96±1.66^a
	20-24	7	67.94±2.20^a	16.23±1.12^a
Soil moisture (%)	24-28	7	52.33±1.44^b	13.29±1.62^a
	30-40	1	48.37±0.00^{ac}	10.23±0.00^a
	40-45	4	50.74±0.80^c	12.39±2.07^a
Soil porosity (%)	45-50	5	60.81±2.28^a	16.82±1.53^a
	>50	4	71.60±0.99^b	15.68±1.53^a
	0-0.08	6	69.50±1.83^a	16.33±1.33^a
Grubbing time (h)	0.08-0.16	4	56.62±1.25^b	15.20±1.82^a
	>0.16	4	49.58±0.47^b	11.95±2.14^a

Means and standard errors within the table followed by the same script are not significantly different as determined by tukeys test at 1% level

Table 4: Regression equations of excavator productivity (y) and grubbing time (x)

Variable	Regression equation	R^2	SD	F-value	Pr>F
Productivity (m^3 h^{-1})	$y = -31.997x + 65.33$	0.59	6.23	17.40	0.0013
Productivity (m h^{-1})	$y = -9.7175x + 16.338$	0.32	3.32	5.62	0.0354

Table 5: Regression equation of *Diospyrus lotus* L. grubbing time (y) related to diameter of stumps (x)

Variable	Regression equation	R^2	SD	F-value	Pr>F
Grubbing time (h)	y = 0.0035x - 0.0953	0.79	0.03	54.21	0.0001

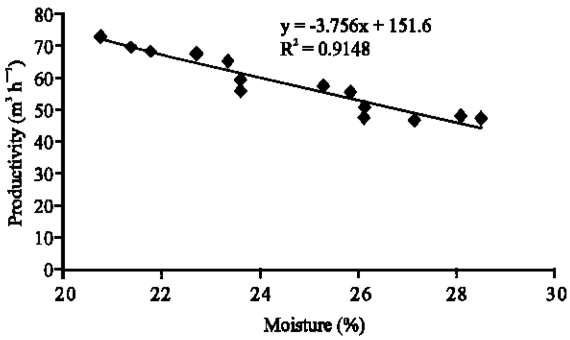

Fig. 2: Soil moisture and earthworks volume

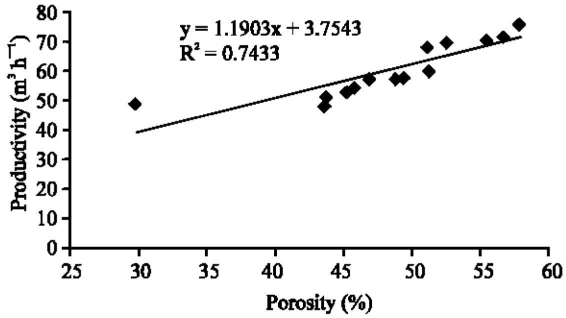

Fig. 5: Soil porosity and earthworks volume

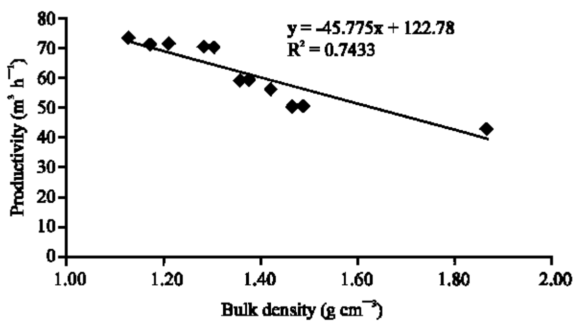

Fig. 3: Soil bulk density and earthworks volume

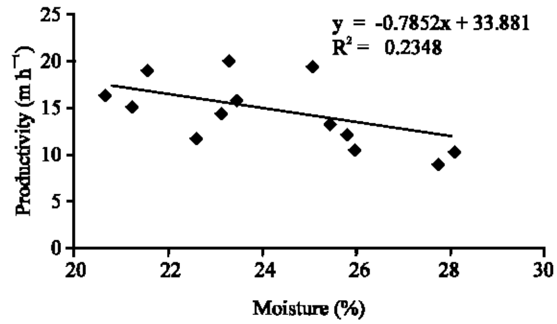

Fig. 6: Soil moisture and earthworks length

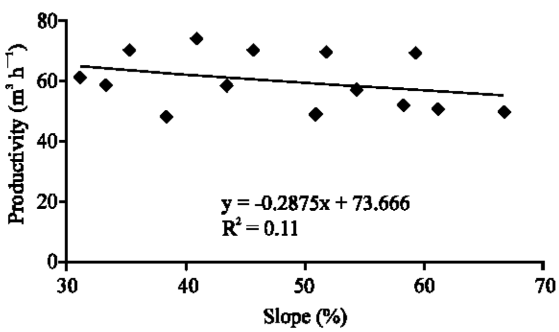

Fig. 4: Terrain slope and earthworks volume

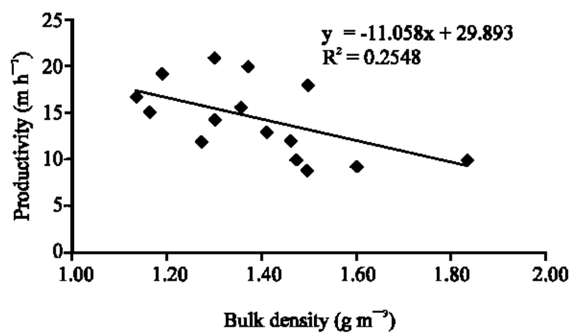

Fig. 7: Soil moisture and earthworks length

Results indicated that soil moisture ($p<0.0001$) and soil bulk density ($p<0.0001$) had a negative effect on excavator earthworks volume (Fig. 2, 3). It is in agreement with the results gotten by Filipsson and Eriksson (1989). They reported that excavator productivity decreased with increasing soil moisture and frequency of boulders. There was no linear relationship ($p = 0.2467$) between the amount of earth works volume and the terrain slope classes (Fig. 4). While the soil porosity showed a positive effect ($p<0.0001$) on $m^3\ m^{-1}$ productivity (Fig. 5). The increase in excavator productivity during earthworking operations occurred more rapidly with increase the soil porosity. No significant linear relationships were observed between the soil moisture ($p = 0.0791$, Fig. 6) and bulk density ($p = 0.0657$, Fig. 7) and excavator Earthworks length. But a relative reduction was observed in Earthworks length with increasing soil moisture and compaction, although these correlations weren't

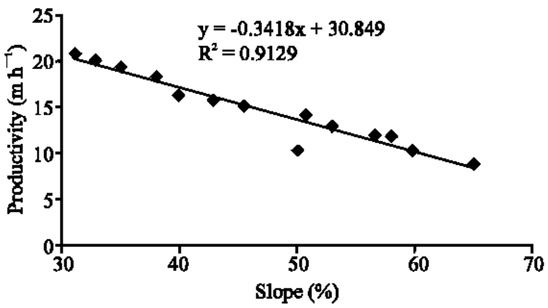

Fig. 8: Terrain slope and earthworks length

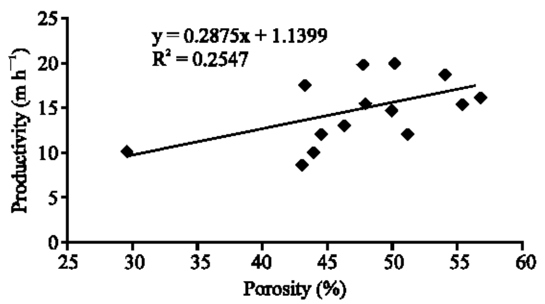

Fig. 9: Soil porosity and earthworks length

significant. Correlation between the amount of excavator earthworks length and the side slope classes ($p<0.0001$) during the excavating operation was significant (Fig. 8). There wasn't significant linear relationship ($p = 0.0657$, Fig. 9) between the soil porosity and hourly excavator earthworks length.

Through regression analysis, the equations for predicting hourly earthworks volume (Eq. 5) and hourly earthworks length (Equation 6(from slope classes (x_1), grubbing time (x_2) and soil moisture (x) were found.

$$Y\ (m^3h^{-1}) = 151.60218^{***} - 3.75598^{***}(x) \quad (5)$$

$$Y\ (m\,h^{-1}) = 29.99946^{***} - 0.31183^{***}(x_1) - 3.43918^{*}(x_2) \quad (6)$$

Excavator machines has multimodal applications in forestry operations which includes road excavating, loading, wood harvesting, timber extracting (Bergroth *et al*., 2006; Wang and Haarlaa, 2002), grubbing (Saarinen, 2006), culvert installations, blasting of rocks and big boulders. Thus, from operational point of view the larger excavators with different attachments such as blades, hydraulic hammer, brush cutter, harvester head, bucket, grapple and winch could be recommended for improving excavator productivity in forest road construction project (Budny *et al*., 2003). Furthermore, it is necessary qualified workers, to work with best machines such as hydraulic excavators and using methods to construct forest road and forest harvesting for minimizing environmental damages (Acar, 2005).

CONCLUSION

Results of this study showed that the mean production rates for the pc 220 komatsu excavators were 60.13 $m^3\,h^{-1}$ and earthwork 14.76 $m\,h^{-1}$ when the mean depth of excavation or cutting was 4.27 $m^3\ m^{-1}$, respectively. There was no significant effects from the slope classes' treatments on productivity ($m^3\ h^{-1}$), whereas grubbing time, soil moisture, bulk density and porosity had significantly affected on excavator earthworks volume. Clear difference was showed between the earthwork lengths by slope classes. Grubbing time, soil moisture, bulk density and porosity had no significant effect on the excavator earthworks length.

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