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A Study on Tractive Resistance Prediction of Logging machine

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집재기계의 견인저항예측에 관한 연구

吳宰憲[1] · 車斗松[2]

요 약

본 연구는 지면끌기집재에 사용되는 기계에 의해 견인되는 견인목의 견인저항을 예측하기 위해 견인목의 중량, 견인저항계수, 지면의 경사 등의 함수로 표현된 수학적 모델들을 개발하였다. 또한 만능재료시험기와 토양조를 이용한 실험실조건에서 4개 수종(잣나무, 일본잎갈나무, 신갈나무, 굴참나무)의 견인저항계수를 산출하였다. 산출한 견인저항계수와 가상 조건을 이용하여 개발된 3가지의 수학적 견인저항 모델에 적용하였다. 그 결과 견인목 중량에 대한 견인저항력의 비(T/Wt)는 지면의 경사가 증가할수록 선형적으로 증가하였으며, 반지면끌기집재가 지면끌기집재보다 견인저항력이 더 작게 나타났다. 본 연구의 결과는 집재작업기계의 선정과 집재윈치의 동력요구량 산정에 기본적인 자료로 활용할 수 있을 것이다.

ABSTRACT

This study was conducted to predict the tractive resistance for tree length logs being skidded by ground based logging machine. The mathematical models for predicting the tractive resistance of tree length log have been developed. The tractive resistance is expressed as a function of log weight, skidding coefficient, and ground gradient. The skidding coefficients for four species of Korean pine, Japanese larch, mongolian oak, and cork oak were determined under laboratory condition using universal testing machine and small soil bin. Three different tractive resistance models were applied to four species and compared with each other. The ratios(T/Wt) of skidding-line tensions to the skidding log weight increased linearly with increment in ground gradient. Semi-ground skidding generally required smaller tensions than ground skidding under given condition. Results of this study can be utilized as basic information for logging machine selection and power requirement of skidding winch.

Key words ; Tractive resistance, ground skidding, forest machine, logging machine, forest mechanization

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INTRODUCTION

Through the reforestation programs and tending operations during the last 30 years, most of forests in Korea are now of size to allow thinning or harvesting in certain area.

Consequently, to use the small available wood and to increase the expectation for intermediate yields, logging machine development and well-planned logging systems are required. But, logging operations in Korea have been so limited that few researches have been reported in harvesting. Although 68% of the total territory is forested, Korea has minimal experience in commercial logging operations since most of the forest is immature.

Recently, forest mechanization has increased considerably for decades due to the increased demand for forest products and to the reduced availability of labor. So, large and high performance equipment from other industrial operations and imported forestry machine has been adapted to forest operations, and many different harvesting systems and equipments are available for forest operations.

The timber harvesting methods depend on terrain conditions. Costs depend on whether machines can enter the forest or whether timber has to be transported by cable to the machines positioned on the forest road. Terrain in Korea is typically steep, with many valleys. Often, mountainous regions are not conducive to ground based harvesting systems. Also, ground based harvesting systems may cause more soil disturbance than cable or aerial systems especially on steep slope or rough ground. In ground skidding, skidders and tractors can be operated successfully on less than 25% and 35% slopes, respectively(Studier and Binkley, 1974). In general, because ground based harvesting systems are less expensive in purchase and operation, extracting trees from the forest by sliding or skidding with one end dragging on the ground are a time honored practice and used worldwide(Hassan and Gustafson, 1983). Also, Transport of timber in forest operations is a dominating part of the total work input. For all the importance of skidding in the harvest of the forest, surprisingly little is known regarding the mechanics of skidding, especially when compared with what is known about tractors and their implements and loadings in the agricultural machinery field.

In advanced nations of forestry, numerous studies of skidding are available and considerable research work has been done on skidding force for five recent decades. In skidding operation, the coefficient of tractive resistance is the most important factor for deciding the maximum payload and the maximum gradient of a skid road. In relation to this, Kamiizaka and Shishiuchi(1962) and Shishiuchi(1980) measured experimentally coefficients of tractive resistance for full-tree skidding and tree-length log skidding. Perumpral et al.(1977) developed a mathematical model for predicting the forces required to skid tree-length logs on level ground. Also, Sakai(1989) measured the tractive resistance of full-tree skidding and tree-length log skidding and their differences were compared.

In Korea, the studies of harvesting system for ground based machine and ground vehicle mechanics for forest operation were reported(Chung, 1995; Cho, 1997; Song, 1999), but they were about skidding model of tree-length log using arches, time study of harvesting system, and development of harvesting machine. Concrete analysis of skidding mechanics according to operation methods and measurement of skidding coefficient is very few in Korea. Although the actual tractive resistance may vary over a wide range because of such variable factors as angle of choker line to the horizontal, ground surface condition, and tree species, we measured skidding coefficient of tree length logs according to the tree species at controlled conditions.

The relationship between the trees and the machine carrying the load is of great importance in maximizing productivity, optimizing energy efficiency, and minimizing machine operating costs(Hassan and Sirois, 1983). Also the coefficient of skidding resistance is the most important factor for deciding the maximum payload and the maximum gradient of a skid road. Therefore, selecting and developing the skidding machine is required in consideration of the terrain characteristics and operation condition of the forest. To solve these problems, understanding engineering characteristics in skidding operation is also required. The objectives of this study were to measure the coefficient of skidding to apply skidding model under controlled condition and to derive the skidding model to predict tree length skidding forces according to the skidding methods.

THEORETICAL FORMULA FOR SKIDDING FORCE ANALYSIS

We derived a mathematical model to determine tractive resistance(T) as a function of log weight(W), ground slope (θ) and coefficient of skidding between soil and log(μs).

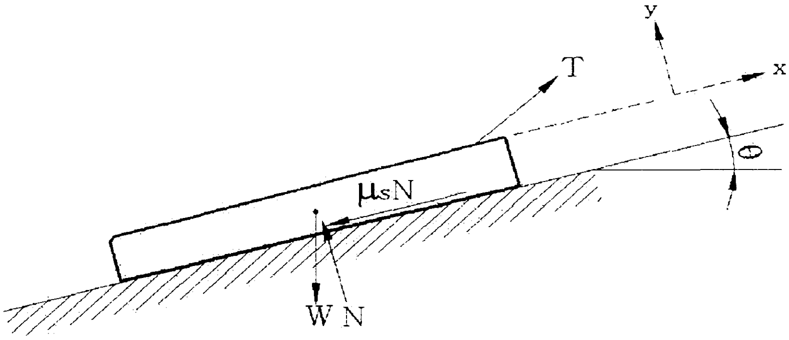


Figure 1. Free body diagram of the skidded log which is contacted with ground.

1. Ground skidding

For derivation of the theoretical formula, we chose reference axes along the ground surface and assumed that logs were in equilibrium. Therefore, the sum of forces about x- and y-directions must be zero,

$$\sum F_x = 0 \quad T\cos\beta - \mu_s N - W\sin\theta = 0 \cdots\cdots (1)$$

$$\sum F_y = 0 T\sin\beta + N - W\cos\theta = 0 \cdots\cdots\cdots\cdots (2)$$

Solving equation (1) and (2) for the β and T gives

$$\beta = \tan^{-1}\frac{W\cos\theta - N}{\mu_s N + W\sin\theta} \cdots\cdots\cdots\cdots (3)$$

$$T = \frac{W\ (\mu_s \cos\theta + \sin\theta)}{\cos\beta + \mu_s \sin\beta} \cdots\cdots\cdots (4)$$

2. Semi-ground skidding without deflection

The sum of forces about x - and y-directions and the moments around the point of chocker attachment must be zero,

$$\sum F_x = 0 \ T\cos\beta - N\sin\theta - \mu_s N\cos\theta = 0 \cdots (5)$$

$$\sum F_y = 0 \ T\sin\beta + N\cos\theta - \mu_s N\sin\theta - W = 0 \cdots (6)$$

$$\sum M_A = 0$$

$$(CG - L_b)\,W\cos(\alpha + \theta) - (L - L_b)\,N\cos\alpha - (L - L_b)\,\mu_s N\sin\alpha = 0$$

(7)

From these, N , β, and T may be calculated,

$$N = \frac{(CG - L_b)\,W\cos(\theta + \alpha)}{(L - L_b)(\cos\alpha + \mu_s \sin\alpha)} \cdots\cdots\cdots (8)$$

$$\beta = \tan^{-1}\left(\frac{W - N\cos\theta + \mu_s N\sin\theta}{\mu_s N\cos\theta + N\sin\theta}\right) \cdots\cdots\cdots (9)$$

$$T = \sqrt{(\mu N\cos\theta + N\sin\theta)^2 + (W - N\cos\theta + N\sin\theta)^2} \cdots (10)$$

CG may be estimated from the following formula, which assumes the log is a conical frustum of uniform density,

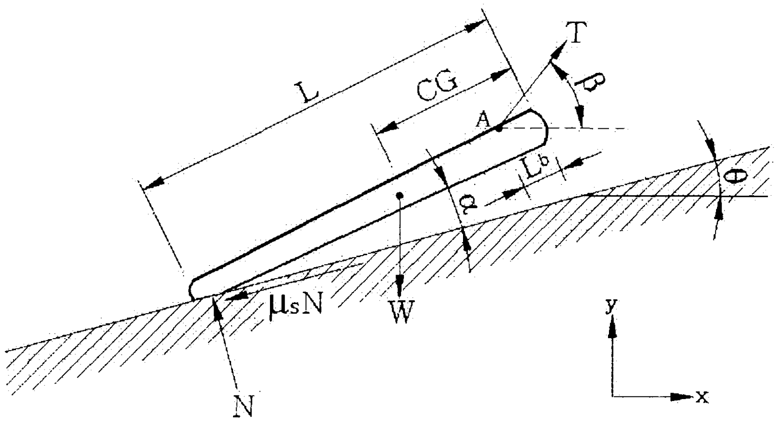


Figure 2. Free body diagram of a skidded log that one end is lifted without deflection.

$$CG=\left(\frac{L}{4}\right)\cdot\left(\frac{r_b^2+3r_t^2+2r_b r_t}{r_b^2+r_t^2+r_b r_t}\right)\cdots\cdots(11)$$

where, r_b is the butt end radius of log, and r_t is the top end radius of log.

3. Semi-ground skidding with deflection

For derivation of the theoretical formula it was assumed that the logs were in equilibrium. Therefore, the sum of moments about point A must be zero.

$$(W-N\cos\theta)\left[(L-L_b-L_c)\cos(\alpha+\theta)+\frac{L_c}{2}\cos\theta\right]-\mu_s N\cos\theta\left[(L-L_b-L_c)\sin(\alpha+\theta)+\frac{L_c}{2}\sin\theta\right]-W\left[(L-L_c-CG)\cos(\alpha+\theta)+\frac{L_c}{2}\cos\theta\right]=0 \cdots\cdots(12)$$

From equation(1) the relationship for N was derived as

$$N=\frac{W\cos(\alpha+\theta)(CG-L_b)}{\cos\theta\left[x\cos(\alpha+\theta)+\frac{L_c}{2}\cos\theta+\mu_s\left(x\sin(\alpha+\theta)+\frac{L_c}{2}\sin\theta\right)\right]}\cdots\cdots(13)$$

where, $x=L-L_b-L_c$.

The expressions for wire rope tension and their angle with horizontal level can be written as

$$T=\sqrt{(W-N\cos\theta)^2+(\mu_s N\cos\theta)^2} \text{ and } \beta=\left(\tan^{-1}\frac{\mu_s N\cos\theta}{W-N\cos\theta}\right)+90^\circ \cdots\cdots(14)$$

The center of gravity of the log(CG) is calculated from Perkins(1982),

$$CG=(0.23430+0.36891R-0.10353R^2)L \cdots\cdots (15)$$

where,

R = the ratio of top diameter to butt diameter, and

L = length of the log, m.

MATERIALS AND METHODS

1. Log and soil specimen

The four tree species, grown in the Experiment Forests of Kangwon National University, were selected for this study. Total twelve different specimens of 45-62

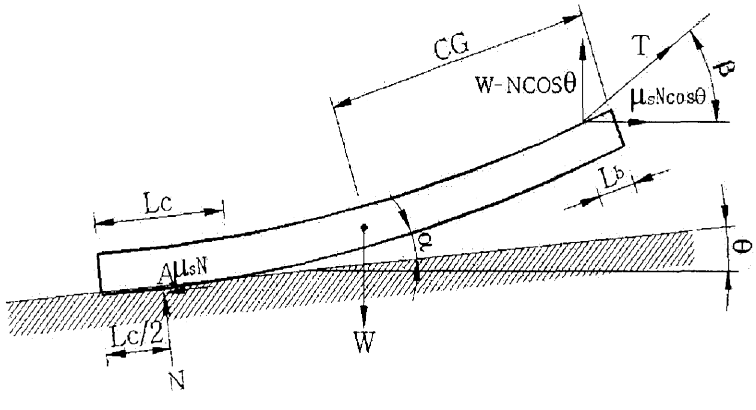


Figure 3. Free body diagram of the skidded log which one end is lifted with deflection.

Table 1. Summary of weight distribution and dimensions of log

Tree Species	Log no.	Length(m)	Average diameter(m)	Weight(N)
Korean pine (*Pinus koraiensis*)	1	0.53	0.19	29.07
	2	0.58	0.20	34.61
	3	0.59	0.20	34.06
Japanese larch (*Larix leptolepis*)	1	0.62	0.18	24.03
	2	0.59	0.16	18.72
	3	0.54	0.19	21.39
Mongolian oak (*Quercus mongolica*)	1	0.45	0.15	24.52
	2	0.56	0.15	27.81
	3	0.54	0.17	35.22
Cork oak (*Quercus variabilis*)	1	0.48	0.20	33.34
	2	0.52	0.18	33.40
	3	0.56	0.15	45.69

cm length were used for the measurement of the skidding coefficient. Physical parameters of each log specimen such as weight, length, and average diameter were measured and their results were summarized in Table 1. Soils used in this study were sampled from the forest floor in the Experiment Forests of Kangwon National University. According to grain size analysis of soil(KS F 2302), the soil was classified as sand. Prior to the test, the soil was placed in layers in the soil bin and compacted with a wooden tamper to obtain a density close to the field density of 1,273.4 kg/㎥. To determine the influence of soil surface condition on the skidding coefficient, tests were also conducted at condition of soil covered with logging residue. Thus logging residues like wood splinter, branch, needlecast and leaf litter were also collected from the sampled places for soil.

2. Experimental facility and procedure

Experimental facility used in this study is shown in Figure 4. This facility included small soil bin, loading mechanism, load-cell, and data acquisition system. The soil bin used for preparing the test section was 60×120×10 cm made of 1.2 cm ply wood. An universal testing machine(Model STM20, United Co.) with an approximate capacity of 10,000 kg was used to apply a horizontal pull to the log specimen.

This pull accomplished by translating the vertical motion of the crosshead of the machine into horizontal motion by using pulley and a wire cord combination. A tensile load-cell with a capacity of approximately 50kg and a recording system manufactured by United Company were used for sensing and recording the pull applied to the log specimen. The

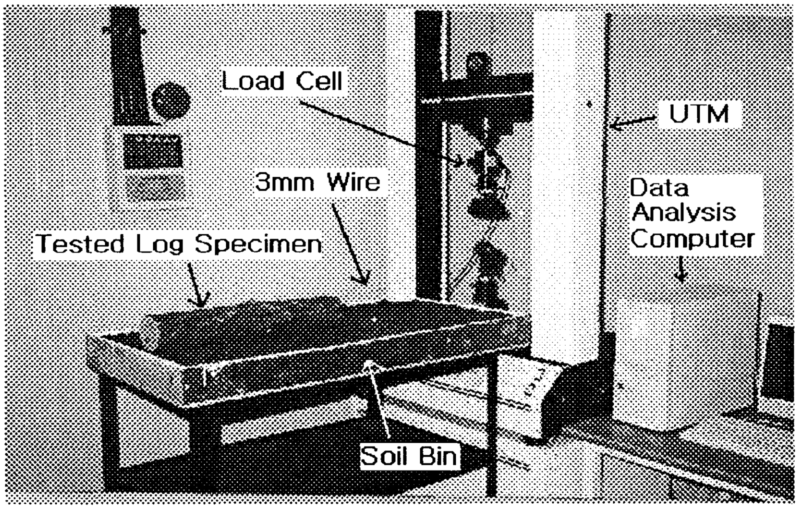


Figure 4. Experimental facility used for the determination of skidding coefficient.

load-cell was mounted directly on the crosshead. The steel wire from the specimen was attached to the load-cell through the pulley.

The test section was prepared, using a representative soil sample collected from the forest floor. Tests were conducted by activating the crosshead of the universal testing machine and recording the horizontal pull on the log specimen until the specimen began moving. For each normal load on the specimen the tests were repeated three times and the average pull was used for computing the coefficient of skidding. The normal loads were varied by placing dead weights on the specimen. For each specimen, tests were conducted at three different normal loads. Three different specimens approximately 23cm length were considered during the study. To determine the influence of ground condition on the skidding coefficient, tests were also conducted at two different ground conditions.

RESULTS AND DISCUSSION

1. Skidding coefficient

Results of laboratory tests on Korean pine, Japanese larch, mongolian oak, and cork oak specimens under two types of ground conditions are shown in Table 3. An analysis of variance for a incomplete block design was conducted with laboratory data. The three factors were tree species, ground conditions and normal loads. Results of the analysis of variance showed that, at the 1 percent significance level, the skidding coefficient is dependent upon all the factors(Table 2).

The observation that the coefficient is dependent upon the normal load indicates that friction alone does not account for the total resistance at the specimen-soil interface. One other factor which may have influenced the resistance to sliding was the adhesion between the specimen and the soil. As the normal load increases, the contact area can increase, causing an increase in the adhesional resistance.

Table 2. Analysis of variance for skidding coefficients test

Source	DF	SS	MS	F
Model	9	0.3039	0.0338	23.75**
Species	3	0.1869	0.0623	43.84**
Ground Condition	1	0.0168	0.0168	11.82**
Normal Load	5	0.0292	0.0058	4.11**
Error	62	0.0881	0.0014	

** : Significance at $\alpha = 0.01$.

The influence of adhesional force may be increased when the silt and clay content or moisture content of soil is high. But in this study moisture content of soil was not considered. Because soil used for test was classified as sand, adhesion effect of soil was lower than other soil types like silt and clay.

Other interesting observations were made from the laboratory data. Test results showed that the average skidding coefficient of Japanese larch is greater than those for other tree species under ground condition with logging residue. The influencing factor here may be the friction resistance force on the interface. Because the surface of Japanese larch is rough and gnarly, the friction resistance force between the log specimen and the ground which covered with logging residue would be higher compared with other tree species. In case of ground condition without logging residue, skidding coefficient of Japanese larch was higher than those for other tree species as well.

We know also that adhesion effect of sand soil was low through Duncan′s multiple range test($\alpha = 0.05$) for effects of normal load difference at each species(Table 3).

As expected, skidding coefficient values obtained for tested all tree species were different. In soil ground condition, skidding coefficient values without normal load were approximately the same by species. Also, the skidding coefficient was found to vary with changing ground condition.

2. Tractive resistance

In this study, we used some basic assumptions about the log being skidded. First, skidding is restricted to tree-length log. Derived theoretical formulas permit multiple logs, but these logs must be of identical dimensions. Also, the volume and weight of these identical logs is determined in a general fashion by assuming its shape to be a frustum of cone. Volume is calculated from butt diameter, top diameter, and log length. Weight is calculated from a formula adapted from Koch(1972)

$$W = \left(1 + \frac{MC}{100}\right) \cdot G \cdot 1000 \cdot V \quad \cdots\cdots\cdots\cdots\cdots (16)$$

Table 3. Results of laboratory tests to determine the skidding coefficient

Tree Species	Ground condition	Normal load (N)	Skidding coefficient (μs)	Duncan's grouping
Korean pine (*Pinus koraiensis*)	Covered with soil	29.07	0.88	a
		34.61	0.89	a
		34.06	0.81	b
	Covered with logging residue	29.07	0.91	a
		34.61	0.90	a
		34.06	0.90	a
Japanese larch (*Larix leptolepis*)	Covered with soil	24.03	0.87	a
		18.72	0.89	a
		21.39	0.94	a
	Covered with logging residue	24.03	0.99	a
		18.72	0.96	b
		21.39	1.07	a
Mongolian oak (*Quercus mongolica*)	Covered with soil	24.52	0.80	a
		27.81	0.79	a
		35.22	0.79	a
	Covered with logging residue	24.52	0.81	a
		27.81	0.72	b
		35.22	0.78	a
Cork oak (*Quercus variabilis*)	Covered with soil	33.34	0.88	a
		33.40	0.82	a
		45.69	0.86	a
	Covered with logging residue	33.34	0.91	a
		33.40	0.84	b
		45.69	0.80	c

* Skidding coefficients with the same letter are not significantly different($\alpha = 0.05$).

where,

W = Weight of a log, kg

MC = Moisture content(dry basis) of the log, %

G = specific gravity of the log

V = volume of the log, m^3 , and

1000 = weight of a cubic meter of water, kg

The values of the parameters to compare the difference of the skidding resistance by skidding methods are shown in Table 4.

The resulting ratios(T/Wt) of skidding-line tensions to the skidding log weight versus ground slopes by species of skidding log are plotted in Fig. 5.

From these graphs, as expected, it can be seen that the semi-ground skidding without deflection and the semi-ground skidding with deflection generally required smaller tensions than the ground skidding for a given conditions. This was because greater portions of weights of the log became supported by the cable instead of the ground.

As the slope decreased from the level ground, the skidding-line tensions for semi-ground skidding without deflection

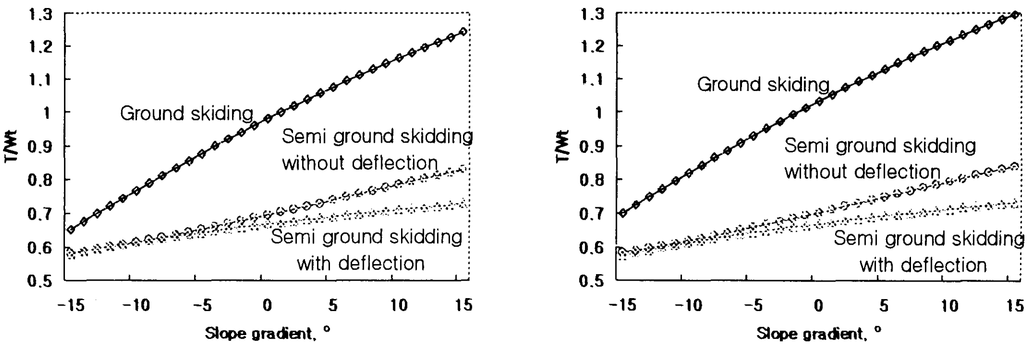
Table 4. Values of parameters used for simulation

Parameter	Skidding type		
	Ground skidding	Semi-ground skidding without deflection	Semi-ground skidding with deflection
L(total length of log) (m)	9.80	9.80	9.80
r_b(butt end radius of log) (cm)	-	8.75	-
r_t(top end radius of log) (cm)	-	5.20	-
L_b(choking distance from butt) (m)	-	0.50	0.50
L_c(portion of log dragging on the ground) (m)	-	-	0.30
α(angle of inclined logs to horizontal line) (°)	5.60	5.60	5.60

and the semi-ground skidding with deflection decreased, and finally approached constant. Also, as the slope increased from level ground, the skidding-line tensions for the semi-ground skidding without deflection and the semi-ground skidding with deflection are slightly different. Because these two models of semi-ground skidding are not different in down skidding, it can adopt without both skidding models in semi-ground skidding resistance calculation.

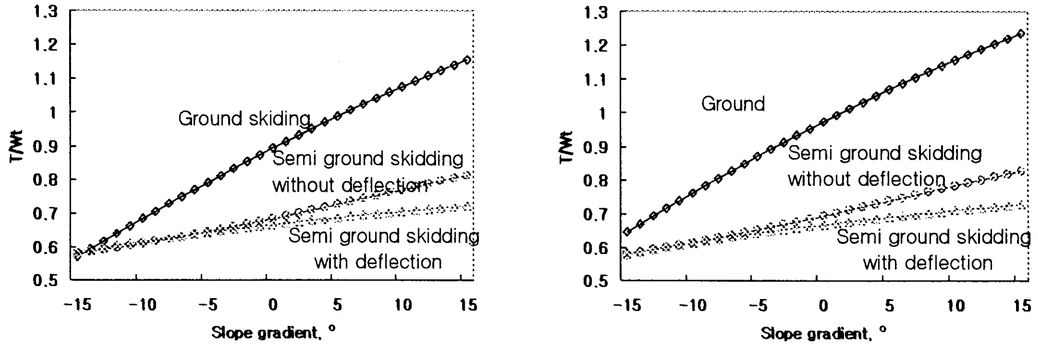
CONCLUSIONS

Mathematical skidding models as a function of log geometry, log weight, skidding coefficient, and ground gradient were developed to predict the tractive resistance for logs being skidded by ground based logging machine. In order to predict the tractive resistance, we find the skidding coefficient by experimental method. Skidding coefficient between log specimen and soil is dependent on normal load, soil surface condition, and tree species. As a result of model application, the ratios(T/Wt) of skidding-line tensions to the skidding log weight increased linearly with increases in ground gradient. Semi-ground skidding generally required smaller tensions than the ground



(a) Korean pine

(b) Japanese larch



(c) Mongolian oak (d) Cork oak

Figure 5. Relationship between the ratios(T/Wt) of skidding-line tensions to the skidding log weight and slope gradient by tree species.

skidding for a given conditions. Future research on skidding forces should include both field test and certain laboratory test.

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