The Working Efficiency of a Bulldozer

By

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Introduction

To advance in the rationalization of construction works, the production rate of earth moving machinery must be grasped perfectly as it is the fundamental factor to lay construction planning. The values of the production rate, which are used in estimating the construction cost, are obtained from various intensive research in all fields. As the most reliable data which is applicable to all has not yet been acquired, each is applying one's own reference data in estimating. Among them, however, still left behind is the recent advancement of construction machinery. Now, it has come to the stage that many of these numerical values need correction.

For example, the increment in horse-power, the adaptation of torque converter, power-shift transmission, finger control system, etc., have not only led to better working efficiency and utility, but also to making daily repairs unnecessary and lessening accidents. Therefore, the production rate of all equipment has increased. But, in reality, due to the complexity in working conditions and accidental time losses, this improvement has been left unnoticed.

As a first step to solve all these problems, this research is conducted by reexamining the general formula of the production rate of construction machinery with all relating factors analysed. Secondly, taking the most fundamental machinery, the Bulldozer, all effecting factors leading to the production rate are theoretically and experimentally analysed. The result of this is designated to be one of the reference data for future use in estimation of constructon cost.

1. General Formula of production Rate

Though there are various considerations on the general expression of

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production rate of construction machinery, here the following expressions are taken into cosideration.

1–1 One-cycle production. (Volume of workdone per cycle)

If the actual volume of workdone per cycle of a machine is taken as q,

then, $$q = Cq_0 \qquad \cdots\cdots (1)$$

where, q_0 is the standard capacity,
or bowl capacity (bulldozer),
or bucket capacity (shovel),
C is the capacity factor,
or bucket efficiency (universal shovel).

The different values of C have been obtained through the conditions of equipment, working conditions and the property of soil.

There are also different considerations on the calculation of standard capacity q_0 and here it is considered in the following manner.

1–2 One-hour production. (Volume of workdone per hour)

Theoretically, the volume of workdone per hour can be calculated by basing it on the one-cycle production (1–1), but actually there are many time losses and thus it does not coincide with the theoretical value.

Now, suppose that the actual volume of work done per hour is Q,

then, $$Q = Knq \qquad \cdots\cdots (2)$$

where q: volume of workdone per cycle.
n: number of cycles per hour.
K: efficiency factor [the rate of actual workdone in an hour (60 min)]

The causes of the small efficiency factor are those of intermediate stops, minor accidents, etc. These causes should be reduced as far as possible.

1–3 One-term production

Let the average working rate for a long term be $\bar{Q}$, then

$$\bar{Q} = K_w Q \qquad \cdots\cdots (3)$$

Here, Q is the actual volume of workdone per hour as shown in Eq. (2).

K_w is the working time rate. This is the rate of total actual working hours at the site and the whole working hours for that term. This also depends much on weather, resting time, repairs, accidents, etc.

From equations (1), (2) and (3), we have

$$\bar{Q} = K_w K C n q_0 \qquad \cdots\cdots(4)$$

This is the general formula of production rate.

2. Production Rate of Bolldozers

Applying Eq. (4) for the production rate of the bulldozer, we have

$$\left.\begin{aligned}\bar{Q} &= K_w K C \frac{60}{\tau} q_0 \\ \tau &= \frac{l}{v_1} + \frac{l}{v_2} + c\end{aligned}\right\} \qquad \cdots\cdots(5)$$

where,
- τ : cycle time (min)
- l : dozing distance (m)
- v_1: forward dozing speed (m/min)
- v_2: backward speed (m/min)
- c : gear changing time (min)

All effecting factors of Eq. (5) are analysed as follows:

2-1. Standard bowl capacity q_0

There are various speculations about the determination of the standard bowl capacity of bulldozer. In order to analyse it, the formation of the collected soil in front of the bulldozer must be taken into consideration.

Generally, when dozing with board full of soil, it is likely that the soil has piled up higher than the board as shown in Fig. 1. The resting angle θ' is somehow bigger than the static resting angle θ. But when dozing motion is stopped, the upper part of the piled-up soil slides down and its inclination angle to the horizontal surface becomes close to the static resting angle θ as shown in Fig. 2.

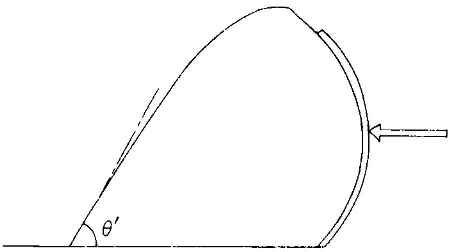

Fig. 1. Formation of soil on board during dozing.

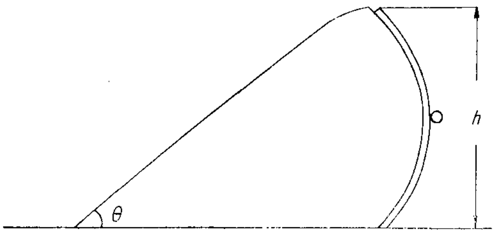

Fig. 2. Formation of soil on board when stopped.

Now, suppose that the soil collected is in the shape of the prism as shown in Fig. 2, then the standard bowl capacity q_0 can be expressed as follows:

$$q_0 = Bh^2 \cot \theta$$

when the width of the board is taken as $2B$, the height of board h, the curved part of board being neglected.

The inclination angle θ varies according to the kind of soil, anyhow the standard value of it is taken as, $\theta = 30°$.

The following equation is one which we are using in application.

$$q_0 = kBh^2$$
$$k = 1.25 \quad \text{or} \quad 1.61 \quad \text{or} \quad \sqrt{3}$$

The practical result of different dozers obtained through investigations conducted by the Construction Ministry is shown in Fig. 3.

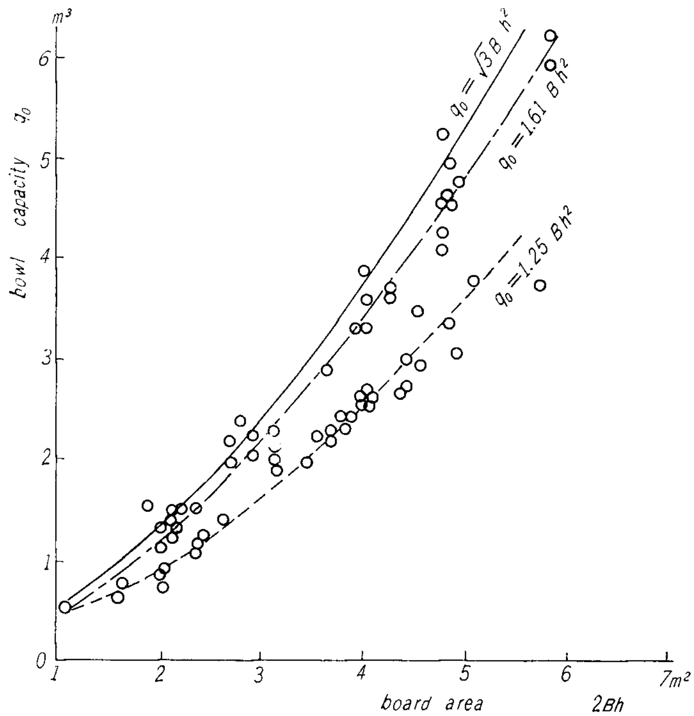

Fig. 3. Bowl capacity and board area (from report of the Construction Ministry)

From Drees' experimental research, the curvature of board and inclination angle have different effects. The results of which are as follows:

2-2. Types of Boards[1)]

The curvatures of the boards of bulldozers are of different degrees depends

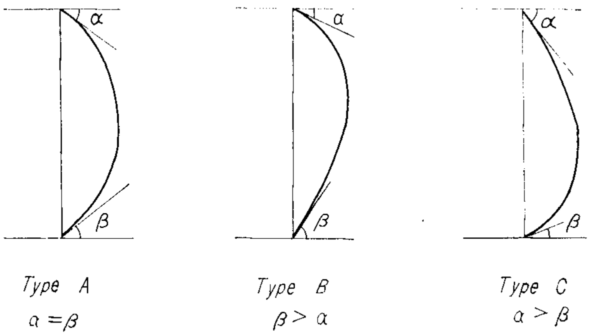

Fig. 4. Types of boards.

on the purpose of their operation. Practically, the most extensively used types of boards can be classified into the three categories as in the Fig. 4.

Effects of sand on the board. (Fig. 5, Fig. 7)

i) The dozing resistance is minimum when the vertical inclination of the board δ is $-15°$.

ii) The principal cutting resistance P is about the same for all 3 types of board.

iii) The total resistance R is 5 to 10% less than others for type A at $\delta=-15°$.

iv) The volume removed is maximum when types A and C at $\delta=-15°$ and type B at $\delta=0°$.

v) It is advantageous to have small depth of cut.

Effects of sand on the plane cutting edge. (Fig. 6)

i) It is ideal to have the angle of cutting edge β below 20°, but the cutting surface will be too long and becomes ineffective.

ii) When the ratio of thickness of soil on board t and the height of cutting edge h is 1:3 and the length of cutting edge l is 1:9, the resultant force R increases 60% to 90% at the cutting angle $\beta=20°$.

iii) It is advisable to have the cutting angle at 30°, because compared with the angle of 45° the principal cutting force P is 10% to 20% less.

iv) On increasing the cutting speed v twice, the required power increases 117%.

It is ideal to have the cutting angle as small as possible, but with too small angle it is found ineffective practically. Hence for sand, it is more advantageous to have a symmetrical board as those of type A and it is best at the vertical inclination of $-15°$.

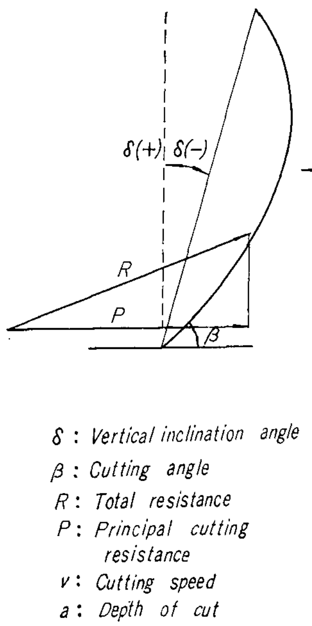

Fig. 5. Soil resistances on board.

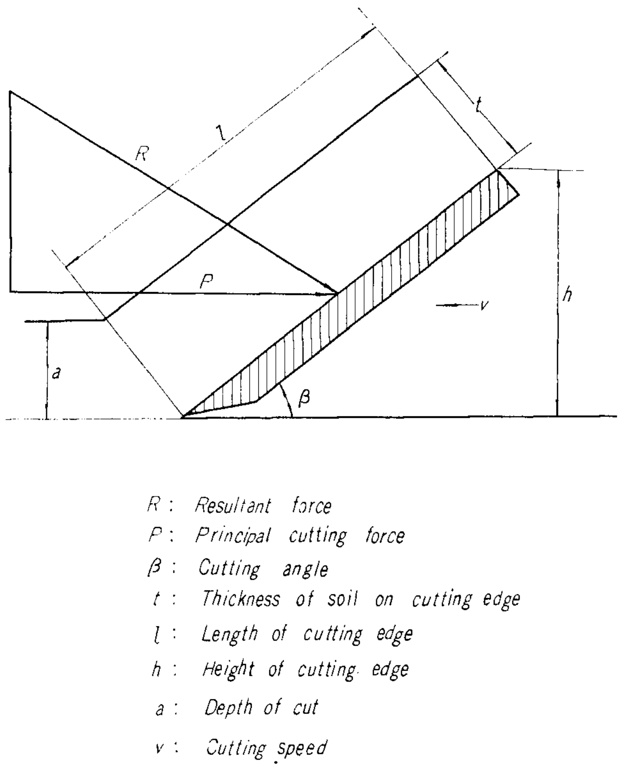

Fig. 6. Soil resistances on plane cutting edge.

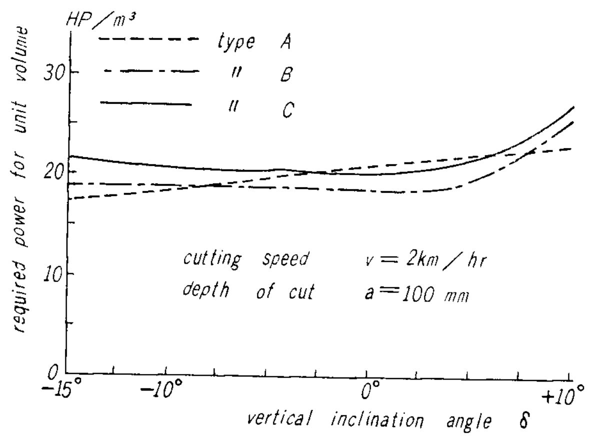

Fig. 7. Required power and vertical inclination angle of boards (sand).

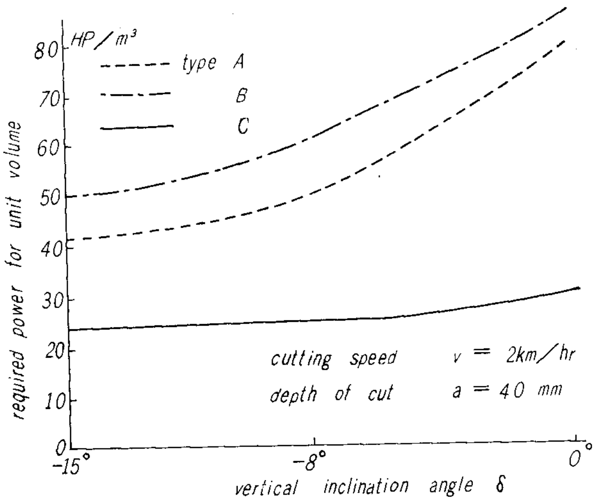

Fig. 8. Required power and vertical inclination angle of boards (silt).

Effects of silt on the board. (Fig. 5, Fig. 8)

i) When the vertical inclination $\delta=-15°$, the cutting resistance R is minimum.

ii) In this case board type C is very effective, the principal cutting resistance P is only half of that of the others.

iii) To allow the earth sliding smoothly along the surface of board, the cutting angle β should be kept as small as possible.

iv) The silt rolling motion is disturbed if the upper part of board is severely curved.

v) It is advantageous to have wide and low board.

Effects of silt on plane cutting edge. (Fig. 6)

i) The influence of the cutting angle for silt is more distinguished than that for sand; the cutting angle of 20° to 30° being most suitable.

ii) On doubling the cutting speed v, the required power increases 120%.

iii) On increasing the cutting angle from 30° to 45°, the required cutting power increases 30% to 35%.

For silt, the principal cutting resistance is small if the cutting angle is small. Therefore board type C is most suitable for this purpose. The smooth silt rolling motion is very important in affecting the volume removed.

In the above we have been dealing with cases of vertical inclination and cutting angle of the board, but the volume of soil removed will be different if the board is attached at an angle as those of angle-dozer or tilt-dozer.

As mentioned in 2-1, the dozing volume of soil differs in accordance with soil. This effect is included in the capacity factor of equation (1), where standard bowl capacity is taken as $\sqrt{3}Bh^2$.

2-3. Effects of dozing speed

The relation between dozing speed and dozing resistance varies according to the property of soil. Generally it is in a straight line as shown in Fig. 9.

$$P = P_0 + k_1 v_1 \qquad \cdots\cdots (6)$$

Here, P is the resistance with constant dozing volume at speed v_1, P_0 is that at $v_1=0$ and k_1 is the coefficient factor.

From the special characteristic of torque converter, the relation between

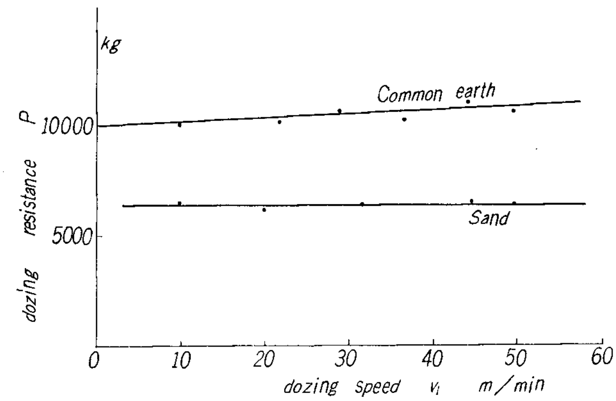

Fig. 9. Dozing resistance and dozing speed.

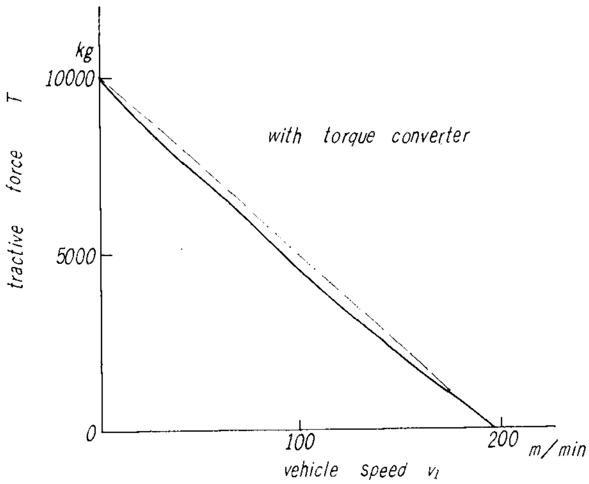

Fig. 10. Tractive force and vehicle speed.

tractive force T and the speed of a certain vehicle is shown in Fig. 10. For simplification it is taken as a straight line.

$$T = T_0 - k_2 v_1 \qquad \cdots\cdots(7)$$

The dozing resistance is directly proportional to the dozing volume

$$P_0 = k_3 q \qquad \cdots\cdots(8)$$

On firm bases where the tractive force is used to its maximum

$$P = T \qquad \cdots\cdots(9)$$

From equations (6), (7), (8), (9),

$$T_0 - k_2 v_1 = k_3 q + k_1 v_1,$$

$$\therefore\ q = \frac{T_0}{k_3} - \frac{k_1 + k_2}{k_3} v_1.$$

Putting

$$\frac{T_0}{k_3} = A, \quad \frac{k_1 + k_2}{k_3} = B,$$

then,

$$q = A - B v_1 \qquad \cdots\cdots(10)$$

The volume of work done per hour Q becomes

$$Q = 60q/\tau = 60q \Big/ \left(\frac{l}{v_1} + \frac{l}{v_2} + c\right)$$

where,
- τ: cycle time
- l: dozing distance
- v_1: dozing speed
- v_2: backing speed
- c: gear-changing time

Putting

$$\frac{l}{v_2} + c = D$$

then,

$$Q = 60 \frac{A v_1 - B v_1^2}{l + D v_1} \qquad \cdots\cdots(11)$$

To find the maximum value of Q, differentiating Eq. (11) by v_1 and putting it equal to 0.

Then,

$$BD v_1^2 + 2Bl v_1 - Al = 0,$$

i.e.

$$v_1^2 + 2\frac{l}{D} v_1 - \frac{Al}{BD} = 0,$$

$$\therefore\ v_1 = -\frac{l}{D} \pm \sqrt{\left(\frac{l}{D}\right)^2 + \frac{Al}{BD}}$$

$v_1 > 0$:

$$\therefore\ v_1 = \sqrt{\left(\frac{l}{D}\right)^2 + \frac{Al}{BD}} - \frac{l}{D} \qquad \cdots\cdots(12)$$

at this speed, Q becomes maximum.

Introducing all factors back to their original form, we have

$$v_1 = \frac{lv_2}{l+cv_2}\left\{\sqrt{1+\frac{T_0\left(\frac{1}{v_2}+\frac{c}{l}\right)}{k_1+k_2}}-1\right\} \quad \cdots\cdots(13)$$

The most appropriate working speed v_1 is the function of backing speed v_2. It can be shown as in Fig. 11,

where, $c = 0.2$ min., $T_0 = 10{,}000$ kg,

$k_1 = 20$ kg/m/min, $k_2 = 40$ kg/m/min.

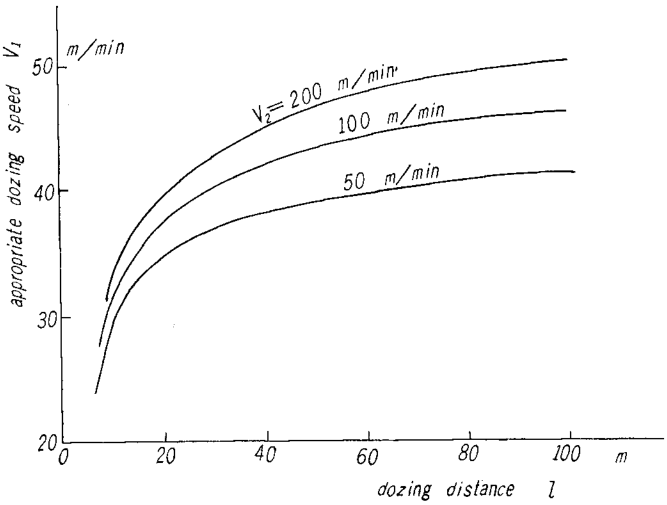

Fig. 11. Appropriate dozing speed.

The bigger the value of v_2, the bigger the value can be taken for v_1.

In case of sandy soil where the dozing resistance is constant and has no relation with speed, we have

$$q = \frac{T_0}{k_3} - \frac{k_2}{k_3}v_1,$$

$$\therefore\ q = A - B'v_1 \quad \cdots\cdots(10)'$$

where, $B' = \frac{k_2}{k_3}$.

Hence, in Eq. (12), putting $B = B'$

then, Eq. (13) can be written as

$$v_1 = \frac{lv_2}{l+cv_2}\left\{\sqrt{1+\frac{T_0\left(\frac{1}{v_2}+\frac{c}{l}\right)}{k_2}}-1\right\} \quad \cdots\cdots(13)'$$

2-4. Effects of slopes on dozing earth volume

It is clear that down-hill dozing is specially of great advantages. Up to now, this relationship has shown with all kinds of data. Here, the following analysis is conducted.

Concerning the dozing volume per cycle

In both level-dozing and slope-dozing operation, the angle between the horizontal ground and the slope of soil gathered in front of the board is taken as constant (θ in Fig. 2)

Here, let

q_0 be dozing-volume at level-dozing,

q_ε be dozing-volume at slope-dozing of slope angle ε,

h be height of the board.

Now taking the vertical height h for both cases,

then,

$$q_0 = Bh^2 \cot \theta \qquad \cdots\cdots(14)$$

$$q_\varepsilon = Bh^2 \cot (\theta - \varepsilon) \qquad \cdots\cdots(15)$$

Concerning the dozing resistance

As mentioned previously, the dozing resistance is directly proportional to the dozing volume.

Let k_3 be the coefficient of this proportionality.

The dozing resistance P_0 at level-dozing can be expressed as:

$$P_0 = k_3 q_0 = k_3 B h^2 \cot \theta \qquad \cdots\cdots(16)$$

The down-hill-dozing resistance P_ε at slope angle ε can be expressed as:

$$\begin{aligned} P_\varepsilon &= k_3 q_\varepsilon - \gamma q_\varepsilon \sin \varepsilon \\ &= (k_3 - \gamma \sin \varepsilon) k_3 B h^2 \cot (\theta - \varepsilon) \end{aligned} \qquad \cdots\cdots(17)$$

where, γ is the weight of unit volume of soil.

Concerning the force generated by dozer

Let the horizontal force be P_0, then the force at the slope P_ε will be

$$P_\varepsilon = P_0 + W \sin \varepsilon \qquad \cdots\cdots(18)$$

where W is the weight of the dozer.

If the ground surface is firm and slipping does not occur, all of the produced force will be utilized effectively for dozing.

Then equation (17) = equation (18)

$$P_0 + W \sin \varepsilon = (k_3 - \gamma \sin \varepsilon) q_\varepsilon ,$$

$$\therefore\ q_\varepsilon = \frac{P_0 + W \sin \varepsilon}{k_3 - \gamma \sin \varepsilon} \qquad \cdots\cdots(19)$$

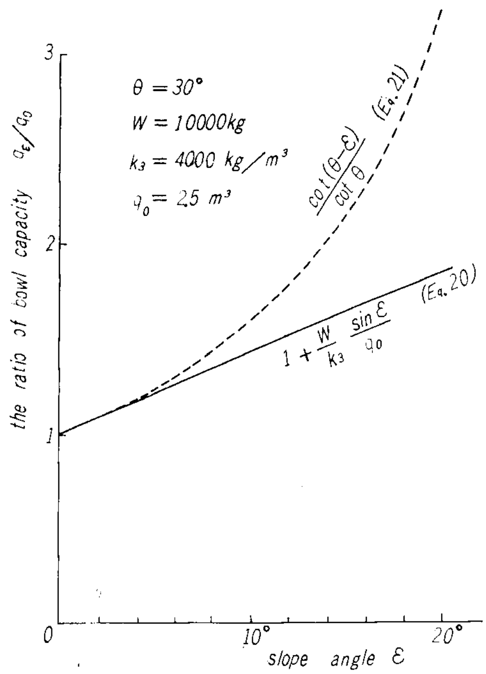

Fig. 12. Bowl capacity and slope angle.

This is as shown in Fig. 12. Since γ is small compared with k_3, then,

$$q_\varepsilon \fallingdotseq (P_0 + W \sin \varepsilon)/k_3$$

the relation becomes a straight line,

i.e. $$q_\varepsilon \fallingdotseq q_0 + \frac{W}{k_3} \sin \varepsilon \quad \cdots\cdots(20)$$

From Eq. (14) and (15)

$$q_\varepsilon = \frac{\cot(\theta - \varepsilon)}{\cot \theta} q_0 \quad \cdots\cdots(21)$$

It can be rewritten as

$$q_\varepsilon = \left\{1 + \frac{\sin \theta}{\sin(\theta - \varepsilon)} \frac{1}{\cos \theta}\right\} q_0 \quad \cdots(22)$$

When plotting Eq. (22) into the above Fig. 12, it becomes a broken line,

where $q_0 = 2.5\,\text{m}^3$, $W = 10{,}000\,\text{kg}$, $k_3 = 4{,}000\,\text{kg/m}^3$, $\theta = 30°$.

But actually, if the inclination angle is too big, it causes difficulty in backward motion. On the whole it is not effective.

The value inside the bracket of Eq. (22) is the value of C of Eq. (5).

The factors K_w and K of Eq. (5) need many reference data based on long working terms, it is left unsolved here as the required data are not available at present.

3. Efficiency Survey

It is the investigation that is conducted on a short time basis when the operation is getting on in a smooth favorable condition. The survey mainly consists of gathering the number of cycles performed in an hour and the corresponding volume of workdone. It is no doubt the working conditions are noted down simultaneously for reference.

i) Date and time.
ii) Weather and temperature.
iii) Average slope.
iv) Average distance.
v) Speed. (Forward and backward)
vi) Number of cycles per hour,

vii) Cycle-time.
viii) Volume of workdone per hour.
ix) Volume of workdone per cycle.
x) Conditions of soil:
  a) Water-content.
  b) Penetrating factor.
  c) Easy or difficult operation.
  a), b) investigations are conducted during the survey or after the survey.

The following studies are based on the data extracted from the Report of the Construction Ministry.

3-1. Effects of Slope on Efficiency

Down-hill dozing is of great advantages due to the additional forces of the bulldozer's own weight. On steep slopes where backward motion is difficult, it should be done with the help of another bulldozer or by the utilization of the winch at the back.

Fig. 13 is drawn with the degrees of the slopes against the volume of soil removed per hour. Briefly the bulldozers are classified into 3 categories accorcing to their weights. Since the data are taken from various working sites under different working conditions, the variation is likely to be big.

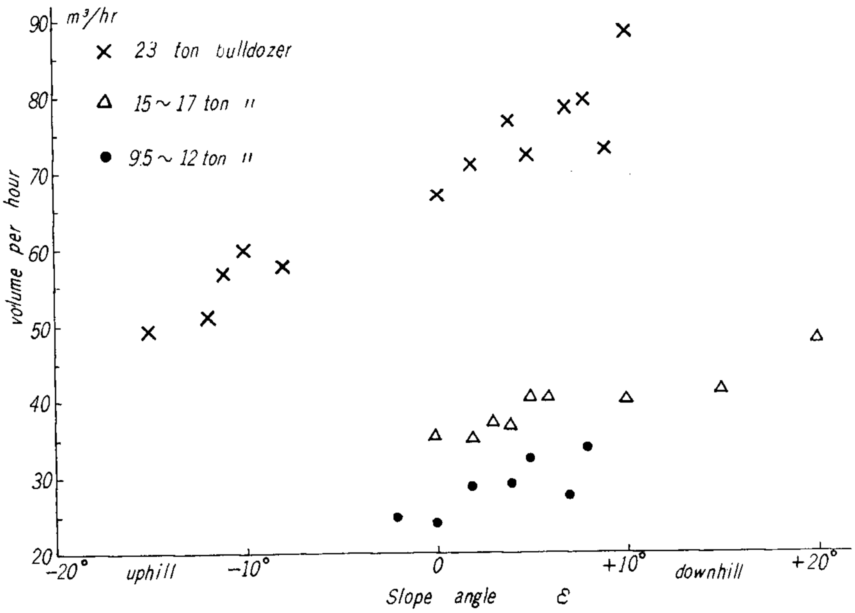

Fig. 13. Removed earth volume and slope angle.

However, it is found on down-hill dozing that the volume of soil removed increases and vice versa with up-hill dozing. Anyhow, it should be noticed that down-hill dozing should be practized up to the maximum of 20° inclination. Beyond this a reverse result is likely to occur.

Concerning the down-hill dozing test (Fig. 14)

This is the investigation undertaken at the Mukoyama working site in Takarazuka. Places of slopes 0°, 7.5°, 11°, and 14° were chosen and the same bulldozer Caterpillar D9 (19A) did all the works. All dozing in different slopes are done with the same slot method. The volumes at different slopes are measured, the result of which is as shown in the figure. The volume of soil increases rapidly as the degrees of slope increases. This is partly helped by the high-piling-up of soil at the sides of the steeper slopes, thus preventing the side-spliting of soil to a great extent.

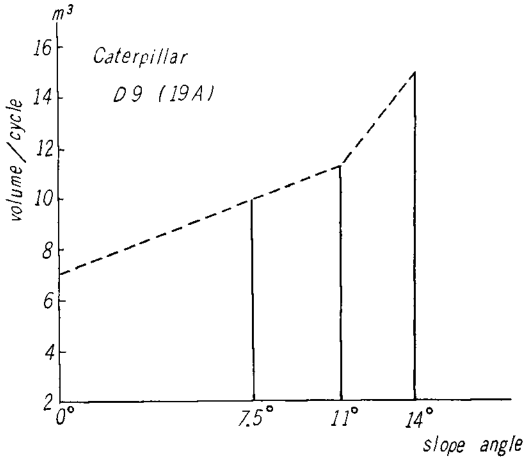

Fig. 14. Down-hill dozing test at Mukoyama.

3-2. Effects of speed on dozing volume

The bulldozer is attached with a main transmission which enables the changing of its speeds to meet the requirement. The number of gears varies according to the types and capacities. Even though it may have many gears, usually for soil dozing the first and second of the forward and backward motions are most extensively used. They are slow, but powerful and steady.

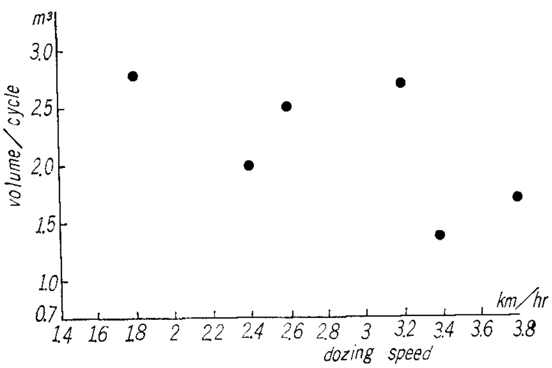

Fig. 15. Dozing speed and volume.

In Fig. 15, which is drawn with the speeds against the volume of soil removed per cycle, the speed of 1.8 km/h to 3.4 km/h is usually the lst. gear of the large-size bulldozers. The smaller ones have their lst. gear of about 2.6 km/h and 2nd gear of about 3.4 km/h respectively. In the figure one cannot foretell exactly that the faster the speed, the lesser the volume removed. Because they have different values and all the data are taken from various places under all kinds of working conditions. Therefore one can only say that the effects of speed on efficiency depends much on the bulldozer's power, the conditions of the site and the operator's skill in using it.

3-3. Effects of water-content on dozing volume

The water-content varies greatly as to the places and kinds of soil. It has comparably large effects on the efficiency of bulldozer.

Fig. 16. is drawn with the percentage of water-content of all kinds of soil shown against the volume of soil removed. The effects seem to be little at high water-content, because this depends much on the other properties of soil.

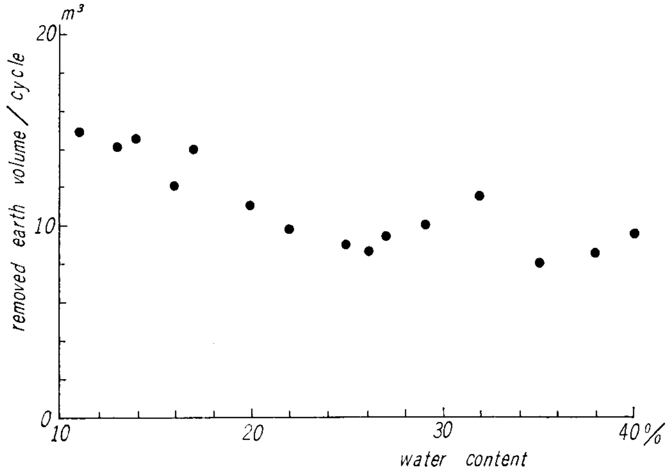

Fig. 16. Removed earth volume and water content of soil.

Conclusion

As mentioned above, the factors which affect the efficiency of the bulldozer, one of the most widely used pieces of construction machinery, have been analysed. The conclusion can be summarized as follows:

(1) The standard bowl capacity of the dozing board in its simpliest form is

$$q_0 = \sqrt{3}\,Bh^2$$

where, $2B$ is the width of the board and h its height.

The differences due to different soil properties, machinery conditions and working conditions are adjusted through the capacity factor.

(2) To increase the capacity factor for ordinary soil, the board of type C of Fig. 4 should be used. The vertical inclination angle should be adjusted at about $-15°$. A cutting angle of 30° is suitable.

(3) In the result obtained from the theoretical analysis of the dozing speed influence on the production rate, when the dozing distance and the backing speed are given, the most suitable dozing speed to get the maximum volume of workdone can be obtained as in Fig. 11.

According to the figure, the suitable dozing speed for short distance dozing is 30–40 m/min (1.8–2.4 km/hr) and long distance dozing is 40–50 m/min (2.4–3.0 km/hr).

(4) For down-hill dozing it is very useful to increase the efficiency. In theoretical analysis, practical experiments and investigation results, if the slope is over 10°, the volume of workdone is increased rapidly. But, when over 20° the resistance which occurs in backing is big and thus is disadvantageous.

Though this has been well known, generally, due to the fact that the influence of the topography is great the most suitable slope cannot be obtained.

As far as possible down-hill dozing should be done at 10–15°.

(5) The influence of water content on production rate is considerably large, but when the water content is above 25%, the effect is small. This is due to the facts that the plasticity index of cohesive soil is comparatively large.

Finally the author would like to thank the Kinki Construction Ministry's Office and the Bulldozer Koji Company for their kind cooperation, which was of great help to this research, and Mr. Htun Myint, student from Burma, for his earnest collaboration.

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