The Relationship between Man-hours and Machine-hours in Field Construction Work in Overseas Projects *

(The Productivity and Costs of Multinational Workers
and Multi-kind Machines)

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All construction work is executed by manpower and machine power. Manpower is measured by man-hours (mh), embracing various productivity rates. Machine power is measured by horsepower-hours (hp-hr) of an engine or a motor mounted on a machine. One hp is assumed to be approximately equal to the power of eight men. If the operating efficiency of an engine or a motor is assumed to be 50% or 25%, one hp will correspond to the power of four or two men. Horsepower-hour can be converted to mh; thus the unit rate of hp-hr and the mh per unit work volume is established. The unit costs of a hp-hr and a mh will be estimated by the all-in cost. The combined productivity and total cost of men and machines are defined by equations comprising the productivity of each nationality and each group of machines, the working hour ratio and the hourly unit cost ratio of men and machines.

Key Words : Construction man-hours, machine-hours, combined productivity, all-in costs, construction cost index.

1. Introduction

Construction work in Japan is usually done by subcontractors. The cost and schedule rely on the recruiting capacity of the subcontractor and the unit costs of the work volume under the lump-sum cost contract.

Overseas construction work, on the other hand, is more often executed by direct-hire workers, local and expatriate, than by subcontractors and a primary contractor also utilizes its own construction machines. It is impossible for a primary contractor to determine the total cost of a project and establish a manpower schedule, unless the productivity of locals and expatriates, including Japanese, in the country where the construction will be done is known. It is very important to clarify the relationship between man-power and machine power because the number of construction machines has a significant influence on the man-power required. This article discusses the relationship between man-hours and machine-hours, i.e., the productivity and cost of men and machines in field construction work overseas.

2. Machine Power and its Productivity

Productivity of multinational manpower

forces has already been discussed in a previously published article (Vol 28, No 236, 1985 of JSME Bulletin (1)).

The capacity of the engine or engines of a machine is measured in horse power (hp). A machine working volume is shown in hp-hr, which is the product of multiplying the total hp by the working hours of a machine. For example, a mobile crane with a 127-ton capacity has two engines, one for travelling and the other for lifting. The total hp is 540 hp. When the crane works 10,000 hours, its work volume is 5,400,000 hp-hr. Another example is a D-6 bulldozer which has a single 142 hp engine. When it works 10,000 hours, its work volume is 1,420,000 hp-hr. Transformer type welding machines don't have engines or motors, so their capacities are indicated in KVAs which can be converted to hp. The work volume is then calculated in hp-hr.

The productivity of machine power is determined by converting hp to man power, i.e., hp-hr to mh. One hp is defined as 0.7457 kw by the JAPANESE INDUSTRIAL STANDARD (JISZ8434-1971) and corresponds to the physical power of eight men. If the efficiency of machine is 50% or 25%, the productivity of a machine is estimated at 4 or 2 manpower, respectively.

Therefore, hp-hr can be easily converted to mh, and the work volume done by machines and men is computable using simple mathematics. For instance, moving 100 cubic meters of soil by 100 meters can be estimated by the hp-hr of a bulldozer and the mh required without the aid of machines. The hp-hr and mh depend on the condition of the soil but an average conversion rate of mh to hp-hr can be determined for those individual machines.

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3. Definition of Cost

Cost is defined here as all-in cost. All-in cost comprises all costs which are necessary to drive a machine and let workers work. It does not include fees and profits.

All-in manpower costs include, salaries, and bonuses paid in Japan, air fare, surface transportation fees, camp costs, food, insurance costs, overseas allowances, recreation costs, small tools expenses, overtime charges etc. For locals and expatriates, the same items apply.

All-in machine costs include compensation costs, operating costs including driver's costs, ocean freight, fuel and lubricating oil costs, maintenance costs, insurance costs etc. All-in cost is computed monthly and is divided by 250 hrs or 200 hrs and the hp, to determine manpower and machine power respectively.

The cost of employing Japanese in the country where construction is being done is estimated at one million yen or 1.2 million yen per month, ie, the mh cost is 4,000 yen or 4,800 yen. The cost of local employees varies from 250 yen/mh to 1,500 yen/mh and the hp-hr cost is 55 yen for a crane and 32 yen for a bulldozer. Of course, hp-hr costs are subject to the conditions of the country, machine and project.

4. Nomenclature

α : Work Volume Ratio

Work volume should be calculated in mh by the primary or main contractor, (Japanese in this paper) and converted from national productivity and machine productivity rates, as follows.

$$\sum_{i=1}^n \alpha_i = \alpha_1 + \alpha_2 + \dots + \alpha_n = 1 \quad (1)$$

This determines the ratio of the construction work done by each nationality or group of machines.

β : Mean Productivity

Manpower productivity equals labor productivity. Machine power productivity is determined by converting hp to mh. If the productivity of native workers in a country is the same as that of Japanese ones in Japan, it is set at 1.00. Working hours are indicated by the following indices;

$$\alpha_1/\beta_1, \alpha_2/\beta_2, \dots, \alpha_n/\beta_n$$

Therefore, the combined productivity (π) can be determined using the following equation:

$$\pi = \frac{1}{\sum_{i=1}^n \alpha_i/\beta_i} = \frac{1}{\alpha_1/\beta_1 + \alpha_2/\beta_2 + \dots + \alpha_n/\beta_n} \quad (2)$$

δ : Performance Factor

Performance factor is the inverse of productivity of Japanese workers at the job site and is only used where a single nationality is employed and a single group of machines is used.

$$\delta = \frac{1}{\beta_1} \quad (3)$$

γ : Hourly Unit Cost Ratio

The hourly unit cost ratio is obtained by dividing the unit mh cost of Japanese by the unit mh cost of another nationality or the unit hp-hr cost of a group of machines. Japanese unit cost vs the unit cost of local employees varies from 3 to 20. The unit cost of Japanese employees vs. the unit cost of machines varies from 40 to 200.

ξ : Working Hour Ratio

Working hour ratio is the ratio of the mh of other nationalities or the hp-hr of a group of machines to the mh of the primary nationality, ie, Japanese. In forms of manpower, this is nearly the same as the ratio of the number of workers a day.

π : Combined Productivity

The productivity of manpower combined with machine power is shown in Eq. (2).

λ : Construction Cost Index

This is the ratio of actual costs and the cost of construction done by Japanese workers without the aid of other nationalities and machines.

5. General Equation

α , β , δ , γ , ξ , π , and λ are called construction cost characteristic factors. When these factors indicate the sum of the manpower or machine power, the suffix m or a is applied to the factors. For instance, the work volume ratios of manpower and machine power are shown as α_m and α_a respectively.

$$\pi_m = \frac{\alpha_m}{\alpha_1/\beta_1 + \alpha_2/\beta_2 + \dots + \alpha_i/\beta_i} \quad (5)$$

$$\pi_a = \frac{\alpha_a}{\alpha_{i+1}/\beta_{i+1} + \dots + \alpha_n/\beta_n} \quad (6)$$

$$\pi = \frac{1}{\frac{\alpha_m}{\pi_m} + \frac{\alpha_a}{\pi_a}} \quad (7)$$

The working hour ratio (ξ) is shown as follows:

$$\xi_1 = \frac{\alpha_1/\beta_1}{\alpha_1/\beta_1} = 1, \xi_2 = \frac{\alpha_2/\beta_2}{\alpha_1/\beta_1}, \dots, \xi_n = \frac{\alpha_n/\beta_n}{\alpha_1/\beta_1}$$

The working hour ratios of manpower and machine power are defined as ξ_m and ξ_a , respectively and calculated as follows:

$$\xi_m = \xi_1 + \xi_2 + \dots + \xi_i \quad (8)$$

$$\xi_a = \xi_{i+1} + \xi_{i+2} + \dots + \xi_n \quad (9)$$

$$\xi = \xi_m + \xi_a = \frac{\sum_{i=1}^n \alpha_i/\beta_i}{\alpha_1/\beta_1} \quad (10)$$

Therefore,

$$\alpha_i = \frac{\beta_i \xi_i}{\beta_1 + \beta_2 \xi_2 + \dots + \beta_n \xi_n} \dots (11)$$

The construction cost index λ is as follows:

$$\lambda = \sum \frac{\alpha_i}{\beta_i \gamma_i} \dots (12)$$

α_i can be eliminated by using Eq (11).

$$\pi = \frac{\beta_1 + \beta_2 \xi_2 + \dots + \beta_n \xi_n}{1 + \xi_2 + \dots + \xi_n} = \frac{\sum \beta_i \xi_i}{\sum \xi_i} \dots (13)$$

$$\lambda = \frac{1 + \xi_2/\gamma_2 + \dots + \xi_n/\gamma_n}{\beta_1 + \beta_2 \xi_2 + \dots + \beta_n \xi_n} = \frac{\sum \xi_i/\gamma_i}{\sum \beta_i \xi_i} \dots (14)$$

6. Single Nationalities and Single Types of Machines

Using only Japanese employees and cranes the indices below indicate the following:

- . Work volume ratio of cranes: α
- . Work volume ratio of Japanese:

$$\alpha_1 = 1 - \alpha \dots (15)$$

- . Average productivity of cranes: β
- . Working hours of cranes: α/β
- . Performance factor of Japanese workers at the job site: δ
- . Working hours of Japanese workers: $(1-\alpha)\delta$
- . Total working hours of Japanese workers and cranes: $Y(\text{ipsilon})$:

$$Y = (1-\alpha)\delta + \alpha/\beta \dots (16)$$

- . The working hour ratio of the cranes vs. Japanese workers:

$$\xi = \frac{\alpha/\beta}{(1-\alpha)\delta} \dots (17)$$

Therefore,

$$\alpha = \frac{\beta \xi \delta}{1 + \beta \xi \delta} \dots (18)$$

- . Combined productivity, (π)

$$\pi = \frac{1}{\alpha/\beta + (1-\alpha)\delta} \dots (19)$$

- . The hourly unit cost ratio: γ
- . The construction cost index: (λ)

$$\lambda = \frac{\alpha}{\beta \gamma} + (1-\alpha)\delta \dots (20)$$

Using Eq. (18) α can be eliminated.

- . Combined productivity

$$\pi = \frac{1 + \beta \delta \xi}{\delta (1 + \xi)} \dots (21)$$

Construction cost index:

$$\lambda = \frac{\delta(\gamma + \xi)}{\gamma(1 + \beta \delta \xi)} \dots (22)$$

or

$$\lambda = \frac{1}{\pi} \cdot \frac{\gamma + \xi}{\gamma(1 + \xi)} \dots (23)$$

When γ and ξ are constant, λ and π make a hyperbola. Construction cost characteristic factors relationships are indicated in the following figures, FIG.1 thru FIG.8.

α : Work Volume Ratio

FIG. 1 α -Y curve, where $\delta=1.0$

In Figure 1, Y equals the total working hours of Japanese workers and cranes and α equals the work volume ratio of cranes. Equation (16) is used to determine Y and α .

α : Work Volume Ratio

FIG. 2 α - π curve, where $\delta=1.0$

Figure 2 shows the combined productivity, (π) and the work volume ratio (α). Equation 19 is used to calculate α and π , where δ equals 1.0.

FIG. 3 α - ξ curve
where $\delta=1.0$

Figure 3 shows the work volume ratio (α) and the working hour ratio (ξ). Eq. (8) is used to calculate α and ξ , where δ equals 1.0.

FIG. 4 (mh)-(mah) curve
where $\delta=1.0$

Figure 4 shows mh and machine hours (mah).

$$mh = (1-\alpha)\delta$$

$$mah = \alpha/\beta$$

α can be eliminated from the above equations as follows:

$$\begin{aligned} (mh) &= (1-(mah)\beta)\delta \\ (mh) &= \delta - \beta\delta(mah) \end{aligned} \quad \text{..... (24)}$$

When β and δ are constant, (mh) and (mah) have a linear relation. Decreasing (mh) means increasing (mah).

Eq. (24) is used to calculate mah and mh, where $\delta=1.0$

FIG. 5 α - λ curve
where $\delta=1.0$

Figure 5 shows the construction cost index (λ) and work volume ratio (α). Eq. (20) is used to calculate λ and α , where $\delta=1.0$ and $\gamma=80$

FIG. 6 π - ξ curve
where $\delta=1.0$

Figure 6 shows the combined productivity (π) and the working hour ratio (ξ). Eq. (21) is used to calculate π and ξ , where $\delta=1.0$.

FIG. 7 π - λ curve
where $\delta=1.0$ & $\gamma=80$

Figure 7 shows the construction cost index (λ) and the combined productivity (π). Eq. (23) is used to calculate λ and π . Eq. (23) is shown in FIG. 7, where $\delta=1.0$ and $\gamma=80$.

FIG. 8 λ - ξ curve
where $\delta=1.0$ & $\gamma=80$

Figure 8 shows the construction cost index (λ) and working hour ratio (ξ). Eq. (22) is used to calculate λ and ξ , where $\delta=1.0$ and $\gamma=80$.

7. Two Nationalities and Two Groups of Machines

Construction cost characteristic factors of Japanese and local workers and cranes and civil construction machines are shown in Table 1.

Construction Cost Characteristic Factor	Japanese	Locals	Cranes	Civil Machines
Work Volume Ratio (α)	α_1	α_2	α_3	α_4
Average Productivity (β)	β_1	β_2	β_3	β_4
Hourly Unit Cost Ratio (r)	r_1	r_2	r_3	r_4
Working Hour Ratio (ξ)	ξ_1	ξ_2	ξ_3	ξ_4

Table 1. Construction cost characteristic factors, two nationalities and two groups of machines

From Eq. (1)

$$\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 1 \quad (25)$$

From Eq. (11), the work volume ratios are:

$$\alpha_1 = \frac{\beta_1}{\beta_1 + \beta_2\xi_2 + \beta_3\xi_3 + \beta_4\xi_4} \quad (26)$$

$$\alpha_2 = \frac{\beta_2\xi_2}{\beta_1 + \beta_2\xi_2 + \beta_3\xi_3 + \beta_4\xi_4} \quad (27)$$

$$\alpha_3 = \frac{\beta_3\xi_3}{\beta_1 + \beta_2\xi_2 + \beta_3\xi_3 + \beta_4\xi_4} \quad (28)$$

$$\alpha_4 = \frac{\beta_4\xi_4}{\beta_1 + \beta_2\xi_2 + \beta_3\xi_3 + \beta_4\xi_4} \quad (29)$$

From Eq. (13), combined productivity π :

$$\pi = \frac{\beta_1 + \beta_2\xi_2 + \beta_3\xi_3 + \beta_4\xi_4}{1 + \xi_2 + \xi_3 + \xi_4} \quad (30)$$

From Eq. (14), Construction cost index λ :

$$\lambda = \frac{1 + \xi_2/\gamma_3 + \xi_3/\gamma_3 + \xi_4/\gamma_4}{\beta_1 + \beta_2\xi_2 + \beta_3\xi_3 + \beta_4\xi_4}$$

A sample of construction cost characteristic factors of two nationalities and two groups of machines in N country are shown in Table 2, where

$$\beta_1 + \beta_2\xi_2 + \beta_3\xi_3 + \beta_4\xi_4 = 757.9627$$

$$1 + \xi_2 + \xi_3 + \xi_4 = 262.505$$

$$1 + \xi_2/\gamma_2 + \xi_3/\gamma_3 + \xi_4/\gamma_4 = 3.75697$$

From Eq. (30), combined productivity (π):

$$\pi = 2.887 \quad (32)$$

From Eq. (31), construction cost index (λ):

$$\lambda = 0.004956 \quad (33)$$

Construction Cost Characteristic Factor	Japanese	Locals	Crane	Civil Machines
Working Hours	463,031MH	8,752,562MH	11,461,456HP-HR	100,871,000HP-HR
Work Volume Ratio (α)	0.001319	0.013642	0.065315	0.919724
Average Productivity (β)	1.0	0.547	2.0	3.2
Hourly Unit Cost Ratio (γ)	1.0	20.0	80.0	145.0
Working Hour Ratio (ξ)	1.0	18.903	24.753	217.849

Table 2, Construction cost characteristic factors; two nationalities and two groups of machines in "N" country.

When we consider Japanese workers and local workers as one manpower group and cranes and civil construction machines as one machine power group, construction cost characteristic factors for each group are as follows;

Work volume ratio of manpower: $\alpha_m = 0.014961$
 Work Volume ratio of machine power: $\alpha_a = 0.985\ 039$
 Average productivity of manpower: $\beta_m = 0.56976$
 Average productivity of machine power: $\beta_a = 3.077\ 562$
 Working hour ratio of manpower: $\xi_m = 19.903$
 Working hour ratio of machine power: $\xi_a = 242.602$

When the working hour ratio of manpower is assumed 1.00, the working hour ratio of machine power (ξ):

$$\xi = \xi_a / \xi_m = 12.189\ 218$$

Hourly unit manpower cost ratio: $\gamma_m = 10.233\ 437$
 Hourly unit machine power cost ratio: $\gamma_a = 133.904\ 19$

When the hourly unit manpower cost ratio is 1.00 the hourly unit machine power cost: $\gamma' = \gamma_a / \gamma_m = 13.084\ 968$

The equations in Chapter 6 can be used to simplify determination of the construction cost characteristic factors for more than one nationality and more than one kind of machine.

Table 2 is used to calculate the following construction cost characteristic factors:

$$\alpha = \alpha_a = 0.985\ 039$$

Average productivity of machines:

$$\beta = \beta_a = 3.077\ 562$$

Performance factor of men:

$$\delta = 1/\beta_m = 1.755\ 125$$

From Eq. (21), combined productivity π :

$$\pi = 2.887 \dots (34)$$

From Eq. (22), construction cost index (λ'): $\lambda' = 0.050\ 719\ 5 \dots (35)$
 λ' is based on γ' which is based on γ_m . Therefore, the construction cost index based on Japanese manpower cost (λ):

$$\lambda = \lambda' / \gamma_m = 0.004\ 956 \dots (36)$$

π in Eq. (34) and λ in Eq. (36) are the same as π in Eq. (32) and λ in Eq. (33)

8. Analysis by Computer

The construction cost characteristic factors for a multinational group of workers and multigroups of machines can be replaced with the construction cost characteristic factors for a single nationality and a single group of machines. Therefore, construction cost characteristic factors $\alpha, \beta, \delta, \gamma, \xi, \pi$, and λ which are used in high frequency all over the world can be given us output from a computer and curves or graphs can be drawn by a plotter.

FIG. 9 π - λ curve where $\delta=1.0$ & $\gamma=80$

FIG.9 shows an example of π - λ curve, where $\delta=1.0$ and $\gamma=80$.

Simulation of construction costs can be used in the future to determine minimum construction costs.

9. Conclusions

The unit rate of machine power per unit work volume will be estimated in the future the same as the unit rate of manpower. Machine hours (hp-hr) per ton of piping work will be computed with a mechanization rate as a standard unit rate. When we find an actual unit rate of machine hours rate, the performance factor of machine power will be easily computed by dividing it by the standard unit rate or the expected unit rate. A construction manager must maintain the performance factor at 1.00 or less.

Generally speaking, machines brought to job site are not always in operation full time, (refer to FIG 10). Therefore, there are three kinds of machine hours:

- (1) Holding hours: the hours during which a machine is kept idle at the job-site or in transit to the jobsite from Japan.
- (2) Rental hours: the hours during which the machine pool to construction groups.
- (3) Working hours: the actual hours of machines working including the time of transfer from the motor pool to the job site.

Working hours have a close relationship to man-hours. However, holding hours and rental hours have no relationship to man-hours.

Therefore, the working hours of machines should be recorded everyday by an hour-meter mounted on the machines. The idle hour which is the difference between the holding hours and rental hours should be controlled by a project manager. Non-working hour, which is difference between

rental hours and working hours should be controlled by a site manager or area manager. Working hours and machine performance factors should be controlled by supervisors or foremen.

If we replace mh of multinational workers with Japanese, the same principle and analysis can be applied to domestic projects.

If we have an idea about machine power and manpower utilization of foreign contractors, their performance in construction work can be easily analyzed and we can develop competing counter offers.

FIG. 10 Relationship between man-hour and machine hour

Reference

- (1) Takaiwa, K., Bulletin of JSME 28-236 (1985)