Medium Head Hydro Power House Concrete Volumes

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Summary

Equations are developed for rapid estimation of medium head power house concrete volumes for conventional surface power houses containing vertical axis, Francis, Kaplan, or fixed-blade propellor turbines with steel spiral casings.

Introduction

During the design of a hydropower project, there are various methods whereby an engineer can determine whether optimum use has been made of the materials for each component, in order to obtain the most economic project layout. For example, the design of a dam can be optimized on the basis of attaining the required factors of safety for stability. Similarly a penstock can be optimized based on the estimated installed cost and the capitalized hydraulic losses. However, for a power house substructure, as in Fig. 1, there are no guidelines available to determine whether maximum usage has been made of the concrete substructure. There are recognized criteria for stability and flotation, but adherence to these criteria will not ensure the most economic layout since a different layout may result in less use of concrete, and still satisfy stability requirements.

If a simple measure of the required substructure concrete volume could be developed, then at least an engineer will have a yardstick against which he can compare his own or alternate designs. Furthermore, such a measure would be useful in feasibility and prefeasibility studies, where much time is spent on calculating power house quantities.

Development of Formula

For many years, the author has used the following formula to extrapolate from one power house size to another:

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$$V_u = K\, d^{2.5} \quad \text{(1)}$$

The exponent, at a value of 2.5, was rationalized as half way between 2, which would represent a hollow cube with constant wall thickness, and 3, which would represent a solid cube. The constant, K, was obtained by substituting the substructure volume and turbine throat diameter in the existing power house. The volume for the new power house was then obtained by calculating the new turbine throat diameter, (Fig. 1(*a*)) and substituting into the formula. Over the years, this formula worked well and was expanded to include the number of units and the effect of an erection bay, when it was found that concrete required for an erection bay generally represented about half the concrete required for one unit. This resulted in the following formula:

$$V_t = K(N + 0.5)\, d^{2.5} \quad \text{(2)}$$

However, the author has never been fully satisfied with the rather arbitrary selection of 2.5 for the exponent; thus, it was decided to undertake a mor detailed analysis, to try to include other factors which affect concrete volum in the power house substructure.

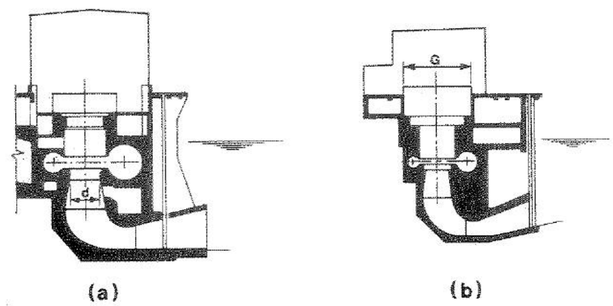

FIG. 1.—Typical Sections through Power House: (*a*) with Head below Approx 100 m; (*b*) with Head above Approx 100 m

Eq. 2 takes into account the physical size of the turbine, the number of units, and an allowance for the erection bay. Other factors which affect the concrete volume are:

1. Size of the generator casing.
2. Runner submergence below tail water.
3. Tail water level at flood.
4. Foundation geology and topography.
5. Size of erection bay.
6. Layout of equipment.
7. Requirement for a penstock valve.

To try to develop a formula which takes all the foregoing factors into account would be time consuming, but could probably be accomplished, provided sufficient data were available. Unfortunately, a search of published literature has revealed little useful data, thus, some of the factors could not be included in the evaluation.

These factors, and their effect on concrete volumes are discussed in the following paragraphs.

Size of Generator.—An article published by Taylor (9) has indicated that unit spacing will be dictated by the generator, when unit speed is 428 rpm or more, and by the turbine, when unit speed is 375 rpm or less. Due to the advances which have been made in equipment design, since the article was published in 1969, and due to the different criteria used by the various designers for equipment layout, a different answer has been obtained from an analysis of existing power house layouts. It has been found that the generator begins to affect the unit spacing when the head exceeds about 100 m. This will be discussed in more detail later. For an initial appraisal, units where head exceeds 100 m have been designated in Table 1.

Runner Submergence Below Tail Water.—Most turbine units are now set with center line of the spiral casing at, or a few meters below, low tail water level; thus, it was reasoned that within this narrow range of settings, unit submergence will have but a minor effect on overall power house concrete volume. Therefore, unit setting was not considered further.

Tail Water Level at Flood.—As tail water levels increase, the downstream wall of the power house must be reinforced to resist the higher water pressure, and mass has to be added to the substructure to counteract any tendency towards flotation. Since most of the data available to the author were for power houses with a normal range of tail water levels from about spiral case center line level up to about the elevation of the top of the generator, it was decided to exclude this factor from the analysis.

Foundation Geology and Topography.—Most power houses are located on a bedrock foundation, and since the foundation loading imposed by a power house is relatively small, it was reasoned that for competent foundations the foundation geology will have but a minor effect on power house concrete volume. Therefore, this effect was not considered further. However, it can have a marked effect where adverse topography, rock levels, or geologic conditions are encountered.

Size of Erection Bay.—The length and number of erection bays has a distinct effect on the power house concrete. Since previous experience has indicated that erection bays contain about half the concrete per meter length as contained per meter length in a turbine unit, it was decided to measure the total length of erection bays in a power house, and obtain the "equivalent unit" by dividing the erection bay length by the unit width, and by a factor of 2. Thus, an erection bay having a length equal to one unit width, would have an "equivalent unit" value of 0.5. Table 2 shows the results of this analysis. (In all tables, the projects are listed in alphabetical order.) For multiple unit plants, the unit width was taken as the unit spacing. For single unit plants, the drawings were examined to determine what the unit spacing would have been if a second unit had been installed and the repair bay length was then calculated as the total power house length minus the multiple of number of units times unit width. It is interesting to note the wide variation in repair bay equivalent unit ratio from a minimum of 0.18 at Brazeau, where the generators are serviced in place (4) and the turbine is removed through the generator rotor, minimizing repair bay area, to a maximum of 1.62 at the Grand Coulee third power house, where there are two repair bays, one of which will be required for the power

TABLE 1.—Power House Substructure Concrete Statistics

Project name (1)	Valve (2)	Turbine D^3, in cubic meters (3)	Number of units (4)	$N + R/2S$ (5)	Concrete, in volume times cubic meters (6)	$V/(N + R/2S)$ (7)
Aviemore	No	125	4	4.75	116,000	24,420
Bayano	No	115	4	5.07	52,800[d]	10,410
Bay D'Espoir 1–6[a]	Yes	14	6	7.35	22,800	3,100
Bay D'Espoir 7[a]	No	41	1	1.50	5,350	3,570
Bighorn	No	34	2	2.65	8,350	3,150
Boysen	Yes	11	2	2.57	9,800	3,810
Brazeau 1–2[a]	No	78[c]	2	2.18	9,900	4,540
Charlot River	No	5.6	2	2.54	1,420	560
Chute Georges[a]	Yes	8.4	2	2.46	2,800	850
Chute Willson	Yes	27	1	1.50	2,780	1,850
Coteau Creek	No	95	3	3.46	33,000	9,540
Dadin Kowa	No	25	2	2.54	5,000	1,970
Davis	No	112	5	6.74	82,300	12,200
Glen Canyon[a]	No	62	8	8.40	152,260	18,130
Grand Coulee[a]	No	774	6	7.62	413,165	54,220
Hart Jaune	Yes	18	3	3.25	4,860	1,500
Hinds Lake[a]	No	9.9	1	1.50	3,350	2,230
Horsechops	Yes	1.9	1	1.64	400	250
Jebba	No	358	6	6.70	101,800	15,190
Kingston Mills	No	1.3	1	1.00	110	110
Kootenay Canal	No	116	4	4.97	38,230	7,690
La Grande 3	No	178	12	13.20	116,000	8,790
La Grande 4[a]	No	171	9	10.10	80,500	7,970
Mayo 2	Yes	1.3	1	1.00	210	210
Outardes 2	Yes	114	3	3.74	44,800	11,980
Peace Canyon	No	512	4	4.80	107,040	22,300
Pelton	No	40	3	3.46	12,480	3,610
Pocaterra	Yes	9.7	1	1.26	900	720
Rattling Brook[a]	Yes	1.2	2	2.62	630	240
Sandy Brook	No	4.3	1	1.44	420	290
Seven Mile	No	221	4	4.97	67,740	13,630
Smelter	No	16.2	1	1.50	3,160	2,110
Snare Falls	No	15.1	1	1.15	1,310	1,140
Spray 2[a]	Yes	3.8	1	1.00	410	410
Taltson	No	32	1	1.36	3,060	2,250
Waterloo	No	15.1	1	1.20	1,160	970
Wells	No	127	2	2.43	16,390	6,740
Whatshan[a]	Yes	10.5	1	1.52	3,820	2,513
Whitehorse 1–2	No	11	2	2.07	2,020	980
Whitehorse 3	No	22	1	1.00	1,530	1,530
Yellowtail[a]	No	17.4	4	4.46	17,400	3,900
Yellowtail[a]	No	17.4	4	6.78[e]	17,400	2,570

[a] Unit where head exceeds (328 ft) 100 m.
[b] Has dismantling sections for closure by bulkhead.
[c] Average of throat diameters 4.07 and 4.47 in.
[d] Includes concrete for future units 3 and 4.
[e] Including equivalent repair bay length.
Note: 1 m^3 = 1.31 cubic yards.

TABLE 2.—Determination of Erection Bay Factor

Project (1)	Unit width, S, in meters (2)	Erection bay length, R, in meters (3)	$R/2S$ (4)
Aviemore	23	34	0.74
Bayano	20.1	43.1[a]	1.07
Bay D'Espoir 1–6	12.8	34.5	1.35
Bay D'Espoir 7	18.3	18.3	0.50
Bighorn	12.2	15.9	0.65
Boysen	12.2	14.0	0.57
Brazeau 1–2	15.9	5.8	0.18
Charlot River	7.9	8.5	0.54
Chute Georges	9.8	9.0	0.46
Chute Willson	13.4	13.4	0.50
Coteau Creek	19.8	18.3	0.46
Dadin Kowa	12.5	13.4	0.54
Davis	22.0	76.5	1.74
Glen Canyon	19.8	15.7	0.40
Grand Coulee	36.3	117.6	1.62
Hart Jaune	11.6	5.8	0.25
Hinds Lake	13.4	13.4	0.50
Horsechops	5.0	6.4	0.64
Jebba	27.9	39.0	0.70
Kingston Mills	5.8	—[b]	0.0
Kootenay Canal	22.0	42.7	0.97
La Grande 3	21.6	51.8	1.20
La Grande 4	21.3	46.6	1.10
Mayo 2	7.9	—[b]	0.00
Outardes 2	20.1	29.6	0.74
Peace Canyon	30.5	48.8	0.80
Pelton	16.6	15.2	0.46
Pocaterra	8.8	4.6	0.26
Rattling Brook	5.8	7.2	0.62
Sandy Brook	7.2	6.3	0.44
Seven Mile	25.6	49.7	0.97
Smelter	9.8	9.8	0.50
Snare Falls	10.4	3.1	0.15
Spray 2	9.7	—[b]	0.0
Taltson	12.8	9.1	0.36
Waterloo	9.6	3.8	0.20
Wells	20.7	18.0	0.43
Whatshan	14.0	14.6	0.52
Whitehorse 1–2	10.7	1.4[c]	0.07
Whitehorse 3	13.2	—[b]	0.0
Yellowtail	11.6	10.7	0.46
Yellowtail[a]	11.6	32.3	2.78

[a]Including equivalent repair bay length.
[b]Power house extension, no repair bay required.
[c]Repair space available between units.
Note: 1 m = 3.28 ft.

house extension. Also, some explanation is required for the two dimensions given for Yellowtail, where there are four units separated by 11.6 m and 12.5 m at a construction joint. At Yellowtail, there are two hollow jet valves in an outlet structure at the east end of the powerhouse. The service bay has a nominal length of 11.6 m, and the power house crane rails extend through the service bay into the outlet structure. Total length of power house and service bay is 78.7 m, for which an "equivalent repair bay" length has been calculated by subtracting four unit widths at 11.6 m from the total power house length.

Layout of Equipment.—It was decided that it would be impossible to quantify equipment layout in a rational manner, so that it could be included in a formula. Accordingly, it was discarded from further analysis.

Requirement for a Penstock Valve.—A control valve on the penstock upstream from the turbine will increase power house concrete, thus, it was decided to include this factor by assigning a different designation to those power houses containing valves, when plotting the data.

Unit Spacing Set by Turbine

Based on inclusion of the repair bay length, Eq. 2 can now be changed to the following:

$$V_t = K\left(N + \frac{R}{2S}\right) d^x \qquad (3)$$

in which K and x are to be determined. Data for 40 power plants was then assembled and is reproduced in Table 1, and the concrete volume per unit has been plotted on log-log paper against the cube of the turbine throat diameter as in Fig. 2.

An examination of Fig. 2 indicates that, as would be expected, there is a wide variation in unit concrete, which can be almost 4:1 as indicated by the difference between Waterloo and Bay D'Espoir units 1 to 6 which both have turbines with almost identical throat diameters, but operate under different heads, which are only 21 m at Waterloo compared with 173 m at Bay D'Espoir. Most interesting is a line can be drawn which represents a minimum volume of concrete per unit. The equation of this line is

$$V_u = 130\, d^{2.4} \qquad (4)$$

A total of 18 power plants fall on or near this line, not counting the three small power plants which have less unit concrete. An examination of the features common to these power plants indicates that:

1. All are located on competent rock foundations with the rock level near or above repair bay floor level.
2. None have tail water levels at flood above the level of the top of the generator.
3. With one exception, at Spray 2, all have turbine rated heads less than 120 m.
4. Three of the power plants have valves, which indicates that the addition of a valve need not significantly affect unit concrete volume.
5. All have turbines with spiral cases set at or near low tail water level.

6. Four of the units have generators with extra inertia. The additional inertia is 185% at Charlot, 105% at Whitehorse, 136% at Taltson, and 70% at Dadin Kowa (6). However, these four units operate at heads of less than 30 m. Even with additional inertia in the generator, the turbine spiral case still determines unit spacing and concrete requirements in the powerhouse substructure.

Based on the foregoing, it is evident that powerhouse layouts for units which fall within the above constraints, can be developed to limit the volume of concrete

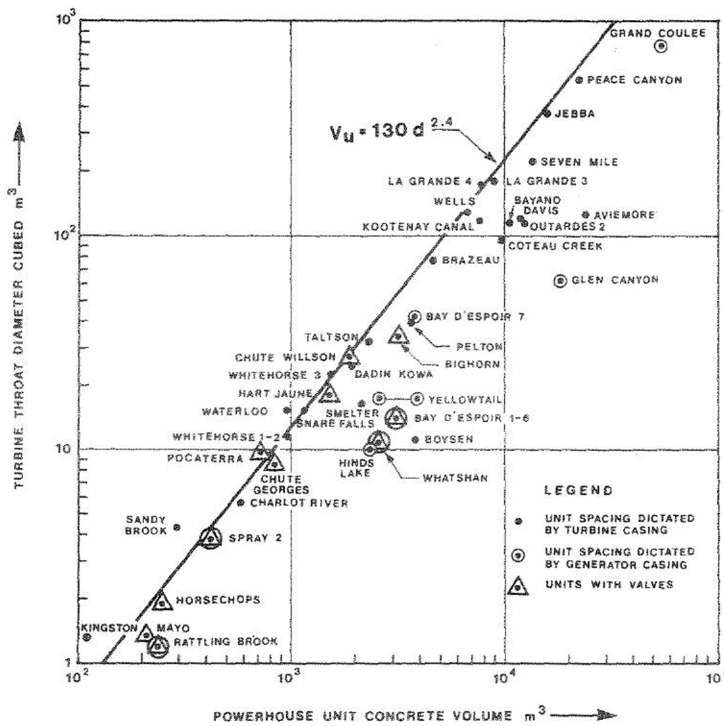

FIG. 2.—Relationship between Power House Concrete Volume and Turbine Throat Diameter

to that indicated by the following equation:

$$V_t = 130\left(N + \frac{R}{2S}\right) d^{2.4} \quad \text{. . . . .} \quad (5)$$

Turning now to some of the units which do not fall on the minimum line, the reasons for less concrete being used at four of the power plants are:

1. Kingston is a small, 500-kW unit with a vertical steel cone draft tube. There is only sufficient concrete to surround the unit as described by Newbury and Hutt (8).

2. Sand Brook, Waterloo, and Pocaterra are small single unit plants where bedrock was found at repair bay floor level, requiring only a thin covering

of concrete. At these plants, rock excavation was just sufficient to accommodate the unit, thus, minimizing concrete requirements.

As for the units which exceed the minimum line:

1. At Rattling Brook, Hinds Lake, Bay D'Espoir units 1–6 and unit 7, Whatshan, Grande Coulee, Glen Canyon, and Yellowtail, all have generator sizes which affect unit spacing.
2. Smelter includes a substantial concrete superstructure, and additional concrete in the substructure required to bridge a cavity in the rock foundation.
3. Bighorn includes additional concrete in the substructure along with a post-tensioned anchorage system, to overcome a tendency towards sliding on a buried coal seam, as described by Thicke and Bakar (10).
4. At Glen Canyon, where approx 12–15 m of mass concrete was required below the powerhouse, Aviemore, and Boysen, foundation rock is located several meters below the bottom of the draft tube.
5. Davies has a conservative design, two pier draft tubes producing a wide unit spacing, an outdoor type design with a concrete floor several meters above the generator, and substantial concrete in the repair bay areas—all of which contribute to a large unit concrete value.
6. Coteau Creek power house rests on a soft expansive shale foundation, and contains large water holding tanks to balance load on the foundation and keep the units vertical (1).
7. Bayano was built on a soft tufaceous siltstone, having an unconfined compressive strength ranging between 100 and 140 kg/cm^2, which required additional concrete and keying of the substructure concrete into the rock foundation.

Based on these few examples, it is evident that the adverse foundation conditions can double, or even quintuple, the volume of concrete in a power house.

Unit Spacing Set by Generator

Turning to the problem of estimating concrete volumes for power plants where the unit spacing is dictated by generator space requirements, it was decided to determine, first, whether there is a simple parameter used to distinguish between power plants where unit spacing will be established by the generator, from those where spacing will be determined by the turbine. A comparison of unit spacing to turbine throat diameter was made for the multi-unit power plants, lying closest to the minimum unit concrete volume line in Fig. 2. This is shown in Table 3 which indicates that unit spacing is about 3.8 times throat diameter for power plants where the turbine throat diameter is more than approx 3 m, and between 4.4 and 4.8 times throat diameter where this is less than approx 3 m.

The Brazeau power plant has a unit spacing 3.9 times the throat diameter of the first unit, and any increase in size of the generator casing would have required an increase in unit spacing (5). If unit spacing of about 3.9 d is accepted as a practical minimum, then the ratio of generator casing size to the throat diameter at Brazeau of 3.0 can be regarded as a practical maximum, beyond which the generator will affect unit spacing. (It is interesting to note that the same conclusions can be reached on the La Grande 4 power house layout.) Accordingly, the ratio of generator casing size to turbine throat diameter was determined for those power plants where unit spacing was established by the

TABLE 3.—Effect of Turbine on Unit Spacing

Project (1)	Unit spacing, *S*, in meters (2)	Turbine, *d*, in meters (3)	*S/d* (4)
Brazeau I	15.9	4.07	3.9
Charlot	7.9	1.77	4.5
Chute Georges	9.8	2.03	4.8
Dadin Kowa	12.5	3.21	3.9
Hart Jaune	11.6	2.62	4.4
Jebba	27.9	7.10	3.9
La Grande 3	21.6	5.63	3.8
La Grande 4	21.3	5.55	3.8
Peace Canyon	30.5	8.00	3.8
Wells	20.7	5.03	4.1
Whitehorse 1–2	10.7	2.23	4.8

Note: 1 m = 3.28 ft.

TABLE 4.—Effect of Generator on Unit Spacing

Project (1)	Unit: Speed, in revolutions per minute (2)	Unit: Head, *h*, in meters (3)	Diameter: Generator, *G*, in meters (4)	Diameter: Turbine, *d*, in meters (5)	*G/d* (6)
Bay D'Espoir 1–6	300	173	9.1	2.41	3.8
Bay D'Espoir 7	225	173	10.8	3.45	3.1
Brazeau	164	118	12.2	4.07	3.0
Glen Canyon	150	174	13.3	3.96	3.4
Grand Coulee[a]	85.7	105	28.9	9.18	3.1
Hinds Lake	360	214	9.5	2.15	4.4
La Grand 4	128.6	117	16.5	5.55	3.0
Rattling Brook	514	101	3.6	1.06	3.4
Spray 2	450	273	7.1	1.56	4.6
Whatshan	327.3	168	8.8	2.19	4.0
Yellowtail	225	147	8.7	2.59	3.4

[a]Allis Chalmers unit speed, maximum head.
Note: 1 m = 3.28 ft.

generator. This is shown in Table 4 where the generator casing size, *G*, (Fig. 1(*b*)) has been defined as the outside diameter of the circular steel casing or the distance across outside flat concrete or steel surfaces in a rectangular casing.

Taylor (9) undertook a similar analysis, using certain assumptions, one of which was that the generator diameter was equal to the rotor diameter plus a constant of 4.17 m, based on data by Walker (15). If instead it is assumed that the generator diameter is some function of the rotor diameter, then Eqs. 2 and 12 in Taylor's article can be combined to show that the G/d ratio is a function of head divided by speed, with unit size cancelling out. Table 4 lists both head and speed, and an examination of Table 4 will indicate that in all cases the G/d ratio exceeds 3.0 and reaches a maximum of 4.6. No relationship was found between G/d and h/rpm; however, it can be seen from the tabulation that the G/d ratio tends to increase with the increasing head, as indicated in Fig. 5, as would be expected.

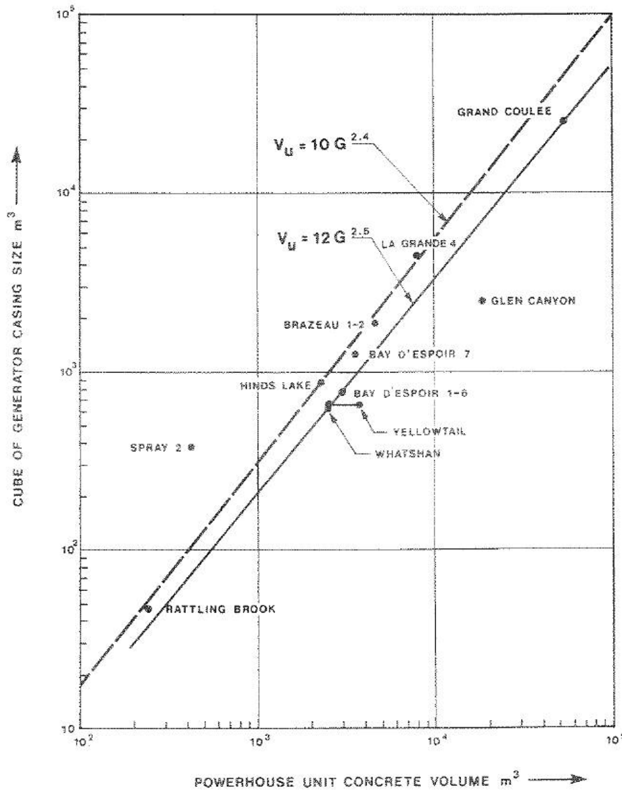

FIG. 3.—Relationship between Power House Concrete Volume and Generator Casing Size

Based on the foregoing, power plants with a G/d ratio below approx 3.0 will have a unit spacing established by the turbine, and power plants with G/d ratio over approx 3.0 will have a unit spacing established by the generator. Also, power plants likely to have unit spacing established by the generator are those where the head exceeds approx 100–120 m, depending on design of the generator, for generators with standard inertia, and at lower heads for power plants with generators having extra inertia, depending on whether the additional inertia has been obtained by increasing the rotor diameter, or adding to the rotor weight.

Since it was found that power plant concrete volume was a function of turbine throat diameter in Fig. 2, it was decided to plot the unit concrete volume against the cube of the generator casing size as shown in Fig. 3.

From Fig. 3, it is apparent, based on the examples listed in Table 5, that power house concrete volume is a function of generator casing size. The exceptions can be explained as follows:

1. Spray 2, is a small single unit addition to an existing power house with competent rock at generator level, where controlled blasting was used during construction, both to minimize overbreak and prevent damage to the adjacent operating unit. A measure of the care used in excavation can be obtained from the estimate for concrete, which was 695 m^3, where only 405 m^3 was poured.

2. Glen Canyon includes a large volume of mass concrete within the power house foundation.

3. Yellowtail includes an outlet structure; however, when the unit concrete olume is reduced to allow for the outlet structure concrete, a more satisfactory result is obtained.

TABLE 5.—Power House Concrete and Generator Casing Comparison

Project name (1)	Unit, in megawatts (2)	Casing G^3 (3)	Unit concrete volume, in cubic meters (4)
Bay D'Espoir 1–6	75	750	3,100
Bay D'Espoir 7	150	1,260	3,570
Brazeau 1–2	153	1,820	4,540
Glen Canyon	112.5	2,350	18,130
Grande Coulee	650	24,140	54,220
Hinds Lake	75	860	2,230
La Grande 4	300	4,490	7,970
Rattling Brook	6.4	47	240
Spray 2	47	360	410
Whatshan	50	668	2,513
Yellowtail	62.5	658	2,570
Yellowtail	62.5	658	3,900

Note: 1 m^3 = 1.31 cu yd.

From Fig. 3 it will be observed that two equations can be derived. For a minimum concrete volume the following equation should be used:

$$V_u = 10\,G^{2.4} \quad (6)$$

From this, the total minimum concrete volume in the power plant can be obtained from the following equation:

$$V_t = 10\left(N + \frac{R}{2S}\right) G^{2.4} \quad (7)$$

A more conservative (higher) estimate of the concrete volume can be obtained from

$$V_u = 12\ G^{2.5} \quad (8)$$

From which a conservative estimate of the total concrete volume in the power plant can be derived from the following equation:

$$V_t = 12\left(N + \frac{R}{2S}\right) G^{2.5} \quad (9)$$

It should be noted that Eqs. 7 and 9 will include the effect of additional inertia in the generator rotor since power house concrete volume is derived as a function of generator casing diameter, which, in turn, is a function of generator rating, speed, and rotor inertia. For example, the unit at Hinds Lake contains 145% additional inertia (6), yet still plots on Fig. 4 in the minimum area. Furthermore, it is interesting to note that Eqs. 5 and 7 are identical when $G = 2.9\ d$. In other words, for the power plants investigated, the generator size begins to affect unit spacing when the generator casing size exceeds 2.9 times the turbine throat diameter.

Preliminary Estimates

Since the formulas developed so far are relatively simple, it would appear worthwhile to continue the investigation further, in order to substitute other dimensions for G and d since both of these dimensions require a fair amount of effort in their determination. For power plants operating under a head of less than 100–120 m, the concrete volume is a function of turbine throat diameter. If an average throat velocity of 9.0 m/s is assumed, then throat diameter can be converted into flow, which in turn can be converted into a function of power and head. In this manner, Eq. 5 can be converted into the following formula, assuming a turbine efficiency of 90%, and adding an extra 15% to allow for the fact that Eq. 5 gives a minimum concrete volume

$$V_t = 1.05\left(N + \frac{R}{2S}\right)\left(\frac{\text{kW}}{h}\right)^{1.2} \quad (10)$$

In order to determine whether this equation is accurate, the power as expressed in kilowatts per meter head was calculated for the developments shown in Table 6 and is plotted against the unit concrete volume in Fig. 4, from which it will be noted that Eq. 10 gives a conservative value for the unit substructure concrete volume. The five developments which have substantially more concrete in the substructure than indicated by the formula, are those at Smelter, Bayano, Coteau Creek, Davis, and Boysen.

Eq. 10 can also be used to obtain an appreciation of the advances in power house substructure and turbine design which have been made over the past 40 yr, by comparison with similar data developed by Creager and Justin (3), based on 84 power houses, 38 of which have heads between 20 and 100 m, and were built in the United States between 1921 and 1943. The curve shown in Ref. 3 which shows power house substructure concrete in cubic yards per horsepower per unit plotted against head in feet can be converted to the following formula:

$$V_t = 4.2 \frac{\text{kW}}{h^{0.92}} \quad (11)$$

for the range of heads between 20 and 100 m. Eqs. 10 and 11 can be compared

TABLE 6.—Power per Meter Head and Substructure Concrete Volume

Project name (1)	Unit capacity, in megawatts (2)	Turbine head, in meters (3)	Capacity per head, in kilowatts per meter (4)	Unit concrete volume, in cubic meters (5)
Bayano	75.0	50.0	1,500	10,410
Bighorn	55.0	74.7	740	3,150
Boysen	7.5	29.3	260	3,810
Brazeau	153.0	117.7	1,300	4,540
Charlot River	5.5	28.0	200	560
Chute Georges	25.5	103.0	250	845
Chute Wilson	60.0	78.9	760	1,850
Coteau Creek	55.0	52.7	1,040	9,540
Dadin Kowa	17.0	29.4	580	1,970
Davis	45.0	36.6	1,230	12,200
Hart Jaune	16.0	37.5	430	1,500
Horsechops	7.3	84.1	90	250
Jebba	88.0	27.7	3,180	15,190
Kingston Mills	0.5	12.2	40	110
Kootenay Canal	132.0	74.7	1,770	7,690
La Grande 3	192.0	79.3	2,420	8,790
La Grande 4	300.0	116.7	2,570	7,970
Mayo 2	2.5	33.5	80	210
Outardes 2	151.0	82.9	1,830	11,980
Peace Canyon	175.0	39.6	4,420	22,300
Pelton	40.0	46.3	860	3,610
Pocaterra	13.4	56.4	240	720
Sandy Brook	6.0	33.5	180	290
Seven Mile	175.0	57.9	3,020	13,630
Smelter	31.0	86.2	360	2,110
Snare Falls	6.7	19.2	350	1,140
Talston	18.5	29.9	620	2,250
Waterloo	8.0	21.3	380	970
Wells	100.0	62.2	1,610	6,740
Whitehorse 1-2	5.5	18.6	300	980
Whitehorse 3	8.0	17.1	470	1,530

Note: m^3 = 1.31 cu yd.

and it will be seen that Eq. 10 gives lower substructure volumes for units smaller than about 100 MW, with the difference increasing with increasing head. At a head of 57 m and a generator capacity of 25 MW, the average head and capacity of the 36 plants included in the Creager data, about half of the difference in the substructure volumes can be accounted for by the higher turbine throat velocities and efficiencies in modern turbines, thus, reducing turbine size and, therefore, substructure concrete volume, and the other half of the difference is, therefore, due to the more efficient use of substructure concrete in current power house designs.

From Ref. 3 it is interesting to note that the power house substructure volume

TABLE 7.—Generator Casing Size—Turbine Head Relation

Project (1)	$G/2.9d$ (2)	Turbine head, in meters (3)
Bay D'Espoir 1-6	1.30	173
Bay D'Espoir 7	1.08	173
Brazeau	1.03	118
Glen Canyon	1.16	174
Grand Coulee	1.09	108
Hinds Lake	1.52	214
La Grande 4	1.03	117
Rattling Brook	1.17	101
Spray 2	1.57	273
Whatshan	1.39	168
Yellowtail	1.16	147

Note: 1 m = 3.28 ft.

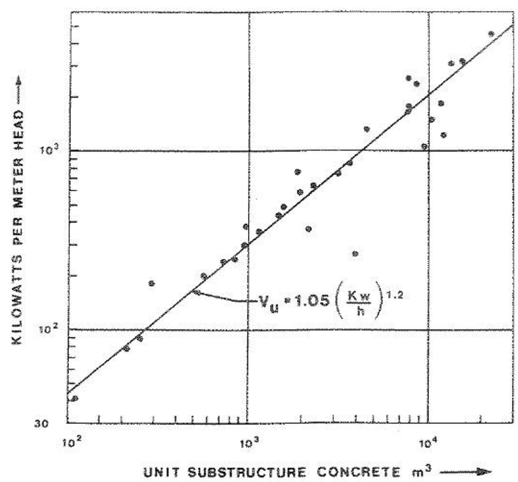

FIG. 4.—Relationship between Power, Head, and Substructure Concrete

is independent of head, for heads in excess of 110 m, thus, confirming the previous finding that the turbine ceases to influence substructure concrete volumes, at heads in excess of about 100–120 m. For these higher head power plants, conversion of Eq. 7 into a function of head and power is somewhat more imprecise, but can be accomplished. Since it has been determined that the generator begins to affect concrete volume when G is greater than 2.9

d, a relationship between generator size and head can be obtained by comparing h with the ratio $G/2.9d$, in Table 7 and as plotted in Fig. 5, from which the following formula has been derived:

$$\frac{G}{2.9d} = 0.10\,h^{0.5} \quad (12)$$

The value of G obtained in Eq. 12 can then be substituted into Eq. 9, and, using the same relationship between turbine throat diameter, d to power and head as outlined previously, it will be found that head cancels out, producing

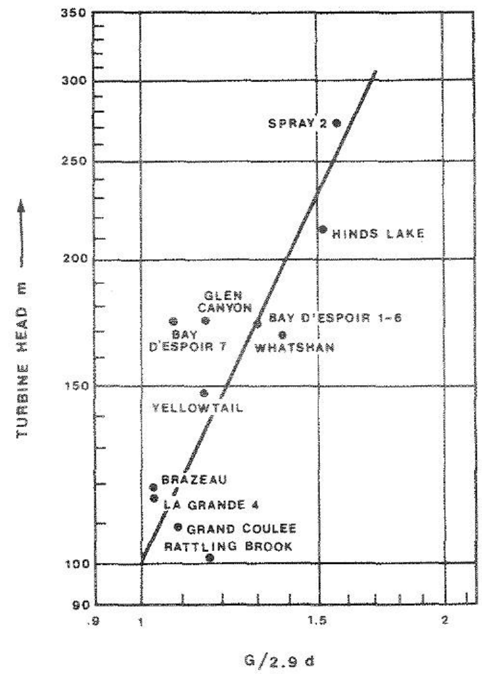

FIG. 5.—Relationship between Generator Casing Size, Turbine Throat Diameter, and Head

the following formula which is a function of capacity only:

$$V_t = 17\left(N + \frac{R}{2S}\right) \mathrm{MW}^{1.25} \quad (13)$$

In order to determine whether this formula was accurate, it was decided to plot unit capacity as indicated in Table 5, against unit concrete volume as in Fig. 6, from which the following minimum volume formula has been derived:

$$V_t = 46\left(N + \frac{R}{2S}\right) \mathrm{MW}^{0.91} \quad (14)$$

Equation 13 is also plotted on Fig. 6, from which it will be seen that Eq.

13 produces a maximum power house substructure concrete volume.

Equation 14 can be compared with the Creager data (3) which indicates that for heads in excess of 110 m, the substructure unit concrete volume is about 0.05 cu yd/hp which can be expressed as:

$$V_u = 51 \text{ MW} \quad \text{(15)}$$

Equation 15 is also shown in Fig. 6, from which substructure concrete volumes based on Eq. 14 will be about 27% lower at 10 MW capacity, increasing to about 40% lower at 100 MW capacity when compared with the Creager data.

It must be emphasized that Eqs. 10 and 13 or 14 will only give a preliminary estimate of the power house concrete volume, and their use should, therefore, be confined to prefeasibility work. They eliminate dimensions G and d in favor

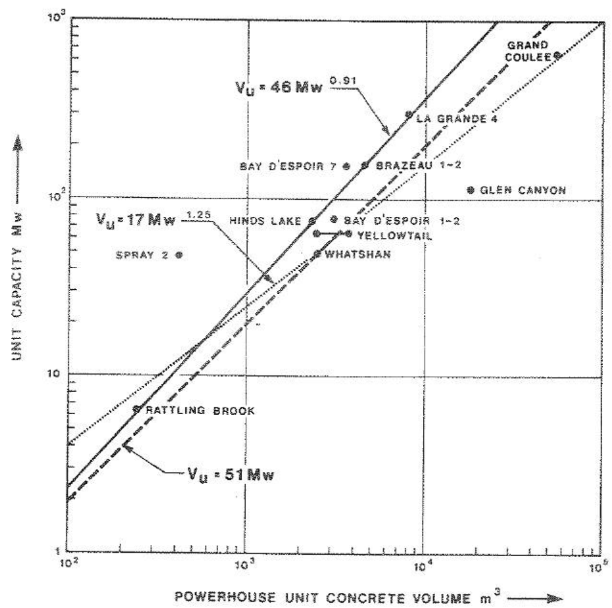

FIG. 6.—Relationship between Power House Concrete Volume and Generator Capacity

of power and head, and, since the turbine throat velocity can vary between about 7.5 and 9.8 m/s, substantial errors can be introduced. Moreover, these formulas do not take into account the effect of extra generator inertia on casing diameter, which can be significant.

Finally, the formulas can be used to determine the "power house layout efficiency," a measure of the effective use of concrete in the substructure. Assuming that there are no adverse foundation conditions present, the layout efficiency can be determined by dividing the theoretical minimum concrete volume as given by Eqs. 5 or 7, by the estimated unit concrete volume. For example, the layout efficiency of the La Grande 3 power house can be calculated from Eq. 5 as 8,208 divided by 8,790 or 93%. Bearing in mind that Eq. 5 gives a minimum volume, and requirements for storage space, access to equipment, etc., a layout efficiency in excess of about 80% can be regarded as the best attainable.

Conclusions

An estimate of minimum power house concrete volumes can be obtained from Eq. 5 when the ratio of generator casing size, G, to turbine throat diameter, d, is less than about 2.9. For larger values of this ratio, use Eqs. 7 or 9. Adverse geological and foundation conditions may have a significant effect on concrete volumes, increasing these by a factor of up to 4 or 5. For prefeasibility estimates, an approximation of power house concrete volume can be obtained from Eqs. 10 or 13 or 14. Equation 10 should be used where the turbine head is less than 110 m, and Eq. 13 or 14 where the turbine head is over 110 m.

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Appendix II.—Notation

The following symbols are used in this paper:

- d = turbine throat diameter, in meters;
- G = generator casing size measured to outside diameter or to outside concrete casing surface, in meters;
- h = rated turbine head, in meters;
- MW, kW = generator rating, in Megawatts and kilowatts;
- N = number of units in a power house;
- R = erection bay length, in meters;
- S = distance between unit center lines, in meters;
- V_t = total power house concrete, in cubic meters; and
- V_u = concrete volume per unit, in cubic meters.

16728 CONCRETE IN HYDROELECTRIC POWERHOUSE

KEY WORDS: Capacity; Casings; **Concrete; Design; Estimates; Hydroelectric powerplants;** Power series; Turbines

ABSTRACT: The volume of concrete in a hydroelectric powerhouse varies by a large amount, depending mostly on the size of turbine, size of generator, and the foundation conditions. An analysis based on data from 40 powerplants ranging in unit size from 0.5 Mw up to 600 Mw, and operating under heads ranging from 12.2 m up to 273 m is presented. Formulae are developed for estimating concrete volume for outdoor powerhouses containing vertical shaft reaction turbines with steel spiral casings based spiral on turbine throat diameter for heads less than about 110 m, and on generator casing diameter for heads above 110 m. Formulae for use in preliminary estimates are also developed based on unit capacity and head, where head is below 100 m, and on unit capacity only where head is above 110 m. All formulae include a factor for the erection bay size.

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