Energy dissipation in gabion weirs

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Abstract. The present study investigates the effect of hydraulic jumps as criteria for representation of the energy dissipation of flow in gabion weirs. A set of 25 laboratory experiments and 188 operation tests were carried out using a laboratory flume with dimensions 10 m long by 0.3 m wide, and 0.5 m high. The tested gabion weir had different five possible lengths, 0.4 m, 0.6 m, 0.8 m, 1.0 m, and 1.2 m, and the filling material used was natural quarry mono-graded gravel in five different sample sizes of average equivalent diameter 11.75 mm, 16.50 mm, 22.00 mm, 31.25 mm, and 43.75 mm. Operation discharge values ranged between 0.7 to 15.0 l/s. The data set was subject to dimensional analysis to generate dimensionless groups, and correlated using the Buckingham Pi-Theorem. The results of this analysis showed that the distance of hydraulic jump has a direct relationship with discharge and an inverse relationship with the diameter of the gravel in the sample. For specified discharges, the distance of hydraulic jump had an inverse relationship with the length of the gabion weir and a direct relationship with the proposed energy dissipation parameter.

Keywords: dimensional analysis; energy dissipation; gabion weir; hydraulic jump; physical models.

1. Introduction

A hydraulic jump may be defined as the turbulent transition from a high velocity flow to slower flow [1]. Uses of hydraulic jumps in hydraulic structures are diverse, and may serve purposes such as the self-aeration of water flow to increase water quality [2], managing the turbulent intensity and scales of turbulence after a hydraulic jump location where there is intensive turbulent mixing within the hydraulic jump that generates macro-eddies of small sizes [3], the construction of downstream protection works, where the jump location downstream of hydraulic structure outlets is an important parameter for design and construction purposes [4], and evaluation of the hydraulic performance and efficiency of using direction diverting blocks fixed on spillway surfaces to reduce the acceleration and energy dissipation of the incoming supercritical flow [5]. Movable weirs have been developed to address the weaknesses of conventional fixed weirs, and ascertaining the formation and location of hydraulic jumps helps in the assessment and solving of problems caused by riverbed protection placed downstream of movable weirs.
such as scour and deformation of structures. In most cases, these structures are designed using the same criteria as for fixed weirs [6]. Gabions are common construction materials globally, especially for spillways, as gabion spillways are structurally stable, resistant to water loads, efficient energy dissipaters, and more practical than small earth dams, being of relatively standardised design [7]. The present study thus aims to investigate the effect of hydraulic jumps as representative criteria of energy dissipation of flow in such gabion weirs.

2. Laboratory work

All tests were carried out in the hydraulic laboratory of the College of Engineering, Babylon University, Iraq. The laboratory has a tilting flume of 10 m length, 0.3 m width and 0.5 m height. The bed of the flume is fabricated from iron plates and the flume side walls are made of anti-crush glass supported by stainless steel bars. The physical models used have lengths of 0.4, 0.6, 0.8, 1.0, and 1.2 m, and these were assigned as G.W.No.I, (Gabion Weir Number I), G.W.No.II, G.W.No.III, G.W.No.IV, and G.W.No.V, respectively. All models had a constant cross-section (width 0.3 m and height 0.4 m). The gravel samples used as filling material for the physical models were five mono-sized gravel samples with diameters 9.5 to 14 mm, 14 to 19 mm, 19 to 25 mm, 25 to 37.5 mm, and 37.5 to 50 mm, labelled as G.S.No.I, (Gravel Sample Number I), G.S.No.II, G.S.No.III, G.S.No.IV, and G.S.No.V, respectively. The frame of the gabion weir, G.W., was made of thin steel plated bars, covered by a wire mesh fixed inside the flume by silicone glue. A photo of G.W.No.I with G.S.No.I is provided in figure 1. A centrifugal pump with a rated capacity of 40 l/s was used to deliver flow to the flume. Two movable carriages, as shown in figure 2, with point gages mounted on brass rails at the top of flume sides, which have an accuracy of 0.1 mm, were used to measure the depth of water. The first was located at the upstream side of the G.W. to measure the upstream water depth at equal six distances starting from the upstream face of the G.W. to 1.0 m before its location during each operation test. The other was at the downstream side of G.W. to measure the downstream water depths before and after the hydraulic jump location during each single operation test. A total of 188 operation tests were carried out and the variation between the minimum and maximum values of discharges were recorded as being from 0.7 to 15.0 l/s.

Figure 1. G.W.No.I with G.S.No.I.
3. Dimensional analysis
The interrelationships between different variables can be represented either by standard equations [8], [9], [10], [11], [12], and [13]; empirical formulas [14], [15], [16], [17], and [18]; direct relationships [19]; or correlations drawn from dimensional analysis [20], [21], [22], [23], [24], and [25]. In general, the hydraulic and geometric variables of the rectangular shape of G.W. which the hydraulic jump depends on may be expressed functionally as

\[ f_1(DHJ, y_o, y_1, q, d_{GS}, L, \rho_w, g) = 0 \]  

(1)

where \( DHJ \) is the distance of hydraulic jump formed at the downstream side of G.W. measured by length unit (L); \( y_o \) and \( y_1 \) are the depths of water at upstream and downstream sides of G.W. respectively (L); \( q \) is discharge per unit width, (L^3/T/L); \( d_{GS} \) is the equivalent diameter of the used gravel sample (L); \( L \) is the G.W. length (L); \( \rho_w \) is the mass density of water (M/L^3); and \( g \) is the gravitational acceleration (L/T^2).

The difference in water depth between two sides of G.W. can be written as

\[ \Delta y_{G.W.} = y_o - y_1 \]  

(2)

Accordingly, equation (1) can be rewritten as:

\[ f_2(DHJ, \Delta y_{G.W.}, q, d_{GS}, L, \rho_w, g) = 0 \]  

(3)

4. Results and discussions
In order to represent the discharge-distance of hydraulic jump relationship, q-DHJ, a direct style was used for this representation, as shown in Figures 3, 4, 5, 6, and 7. In these figures, the distance of hydraulic jump is directly proportional to the discharge in general form, and the best representation of this proportion varied between the exponential form for G.W.No.I, G.W.No.II, G.W.No.III, and G.W.No.IV, and the power form for G.W.No.V. Microsoft Excel was used to graph these figures and find the best trend line; the resulting equations were thus (For G.W.No.I, G.W.No.II, G.W.No.III, and G.W.No.IV.)

\[ DHJ = c_1 * e^{k_1 * q} \]  

(4)

(For G.W.No.V.)

\[ DHJ = c_2 * q^{k_2} \]  

(5)
where \(c_1\), \(c_2\), \(k_1\), and \(k_2\) are constants. These figures show little intersection and overlap for the values of DHJ at low values of discharge due to the low velocity of flow, which allows smooth passage for water flows through the voids between gravel particles with little or insufficient friction on their surfaces. The value of DHJ also decreases with increases in the equivalent diameter of the used gravel samples due to the increment in volume of such voids, which leads to increases in the amount of water passing throughout the body of the weir at lower velocity. Tables 1, 2, 3, 4, and 5 present the values of constants \(c_1\), \(c_2\), \(k_1\), and \(k_2\) in the \(q\)-DHJ relationship for all G.W. physical models. At a constant discharge, the reduction in distance of hydraulic jump toward the G.W. toe affects the value of \(\Delta y_{G.W.}\) which mainly affects the difference in energy head between the G.W. sides. For this reason, two applied discharges, 0.7 l/s and 3.6 l/s were chosen to determine the effect of G.W. length on the values of DHJ, to represent the dissipated energy of flow by determining the percentage of reduction in DHJ, and to formulate a relationship between the percentage of reduction in distance of hydraulic jump and \(\Delta y_{G.W.}\) in order to obtain the effects of DHJ on the difference in energy.

Figure 3. Variation of unit discharge values with distance of hydraulic jump values for operation tests of G.W.No.I.

Figure 4. Variation of unit discharge values with distance of hydraulic jump values for operation tests of G.W.No.II.
Figure 5. Variation of unit discharge values with distance of hydraulic jump values for operation tests of G.W.No.III.

Figure 6. Variation of unit discharge values with distance of hydraulic jump values for operation tests of G.W.No.IV.

Figure 7. Variation of unit discharge values with distance of hydraulic jump values for operation tests of G.W.No.V.
**Table 1.** Values of constants $c_1$, $k_1$ and $R^2$ of trend line equation of unit discharge-distance of hydraulic jump relationship for G.W.NO.I.

| $d_{GS}$ (mm) | $c_1$  | $k_1$  | $R^2$ |
|---------------|--------|--------|-------|
| 9.5-14        | 0.5235 | 78.615 | 0.92  |
| 14.0-19.0     | 0.3277 | 56.698 | 0.98  |
| 19.0-25.0     | 0.2240 | 59.162 | 0.98  |
| 25.0-37.5     | 0.3085 | 39.465 | 0.93  |
| 37.5-50.0     | 0.1900 | 53.993 | 0.93  |

**Table 2.** Values of constants $c_1$, $k_1$ and $R^2$ of trend line equation of unit discharge-distance of hydraulic jump relationship for G.W.NO.II.

| $d_{GS}$ (mm) | $c_1$  | $k_1$  | $R^2$ |
|---------------|--------|--------|-------|
| 9.5-14        | 0.3424 | 69.360 | 0.94  |
| 14-19         | 0.3190 | 51.034 | 0.90  |
| 19-25         | 0.3460 | 41.426 | 0.92  |
| 25-37.5       | 0.3478 | 28.453 | 0.76  |
| 37.5-50.0     | 0.2554 | 48.836 | 0.98  |

**Table 3.** Values of constants $c_1$, $k_1$ and $R^2$ of trend line equation of unit discharge-distance of hydraulic jump relationship for G.W.NO.III.

| $d_{GS}$ (mm) | $c_1$  | $k_1$  | $R^2$ |
|---------------|--------|--------|-------|
| 9.5-14        | 0.3365 | 58.988 | 0.98  |
| 14-19         | 0.3640 | 33.334 | 0.95  |
| 19-25         | 0.3663 | 24.423 | 0.89  |
| 25-37.5       | 0.3174 | 32.889 | 0.70  |
| 37.5-50.0     | 0.3262 | 32.206 | 0.84  |

**Table 4.** Values of constants $c_1$, $k_1$ and $R^2$ of trend line equation of unit discharge-distance of hydraulic jump relationship for G.W.NO.IV.

| $d_{GS}$ (mm) | $c_1$  | $k_1$  | $R^2$ |
|---------------|--------|--------|-------|
| 9.5-14        | 0.3735 | 50.970 | 0.97  |
| 14-19         | 0.3101 | 64.870 | 0.85  |
| 19-25         | 0.2978 | 51.505 | 0.94  |
| 25-37.5       | 0.2924 | 47.080 | 0.88  |
| 37.5-50.0     | 0.3375 | 32.235 | 0.92  |

**Table 5.** Values of constants $c_1$, $k_1$ and $R^2$ of trend line equation of unit discharge-distance of hydraulic jump relationship for G.W.NO.V.

| $d_{GS}$ (mm) | $c_2$  | $k_2$  | $R^2$ |
|---------------|--------|--------|-------|
| 9.5-14        | 44356  | 2.7016 | 0.99  |
| 14-19         | 14722  | 2.5983 | 0.96  |
| 19-25         | 21419  | 2.4079 | 0.87  |
| 25-37.5       | 4175.6 | 2.6876 | 0.88  |
| 37.5-50.0     | 6497.4 | 3.0784 | 0.93  |
Tables 6, 7, 8, 9, and 10 summarize the values of DHJ at 0.7 l/s and 3.6 l/s applied discharges for all G.W. physical models. In this series of tables, the value of DHJ at minimum applied discharge varied between 0 to 0.5 m, and at 3.6 l/s, between 0.015 and 1.585 m. These tables verify the intersection for data at the minimum value of applied discharge, making it clear that DHJ value ranges between 40 cm and 42.5 cm for most tests. This indicates that both the gradation of gravel samples and G.W. length have a little effect on the DHJ value for low discharge values. At this value of discharge, there is a slightly increase in the DHJ value with G.S.No.V compared to the other models; in addition, the DHJ value is 0 for G.W.No.V at the minimum value of applied discharge, which suggests that the high resistance of flow for this physical model leads to a minimisation of the amount of energy at this section, accordingly minimising DHJ. For 3.6 l/s applied discharge with the same gravel sample, as the length of G.W. increases, the DHJ reduces.

Table 6. Values of DHJ at minimum and 3.6 l/s applied discharges measured for G.W.NO.I.

| dGS (mm) | DHJ at minimum applied discharge (m) | DHJ at 3.6 l/s applied discharge (m) |
|---------|-------------------------------------|-------------------------------------|
| 9.5-14  | 0.500                               | 1.585                               |
| 14-19   | 0.415                               | 0.610                               |
| 19-25   | 0.220                               | 0.490                               |
| 25-37.5 | 0.390                               | 0.450                               |
| 37.5-50 | 0.140                               | 0.430                               |

Table 7. Values of DHJ at minimum and 3.6 l/s applied discharges measured for G.W.No.II.

| dGS (mm) | DHJ at minimum applied discharge (m) | DHJ at 3.6 l/s applied discharge (m) |
|---------|-------------------------------------|-------------------------------------|
| 9.5-14  | 0.400                               | 0.620                               |
| 14-19   | 0.415                               | 0.530                               |
| 19-25   | 0.400                               | 0.450                               |
| 25-37.5 | 0.425                               | 0.440                               |
| 37.5-50 | 0.335                               | 0.410                               |

Table 8. Values of DHJ at minimum and 3.6 l/s applied discharges measured for G.W.No.III.

| dGS (mm) | DHJ at minimum applied discharge (m) | DHJ at 3.6 l/s applied discharge (m) |
|---------|-------------------------------------|-------------------------------------|
| 9.5-14  | 0.415                               | 0.645                               |
| 14-19   | 0.420                               | 0.520                               |
| 19-25   | 0.420                               | 0.440                               |
| 25-37.5 | 0.415                               | 0.440                               |
| 37.5-50 | 0.420                               | 0.430                               |

Table 9. Values of DHJ at minimum and 3.6 l/s applied discharges measured for G.W.No.IV.

| dGS (mm) | DHJ at minimum applied discharge (m) | DHJ at 3.6 l/s applied discharge (m) |
|---------|-------------------------------------|-------------------------------------|
| 9.5-14  | 0.425                               | 0.615                               |
| 14-19   | 0.420                               | 0.500                               |
| 19-25   | 0.400                               | 0.440                               |
| 25-37.5 | 0.400                               | 0.430                               |
| 37.5-50 | 0.415                               | 0.430                               |

Table 10. Values of DHJ at minimum and 3.6 l/s applied discharges measured for G.W.No.V.

| dGS (mm) | DHJ at minimum applied discharge (m) | DHJ at 3.6 l/s applied discharge (m) |
|---------|-------------------------------------|-------------------------------------|
| 9.5-14  | 0.000                               | 0.400                               |
The percentage of reduction in distance of hydraulic jump can be calculated as

$$\text{PRDHJ} = \left( \frac{\text{DHJ}_{\text{Max.}} - \text{DHJ}}{\text{DHJ}_{\text{Max.}}} \right) \times 100\%$$

(6)

where PRDHJ refers to percentage of reduction in distance of hydraulic jump, DHJ\text{Max.} is the maximum distance of hydraulic jump measured in all physical models in the operation tests (L).

The difference in specific energy head on both G.W. sides depends functionally on $\Delta y_{G.W.}$ as in equations (7), (8), and (9):

$$E_0 = y_0 + \left( \frac{q^2}{2gy_0^2} \right)$$

(7)

where $E_0$ is the specific energy head at the upstream side of G.W. in length units (L), and

$$E_1 = y_1 + \left( \frac{q^2}{2gy_1^2} \right)$$

(8)

where $E_1$ is the energy head at the downstream side of G.W. in length units (L). Simplification of equations (7) and (8) at a constant discharge offers

$$\Delta E_{G.W.} = \Delta y_{G.W.} + (C \times \left( \frac{y_1^2 - y_0^2}{y_0^2 y_1^2} \right))$$

(9)

where $C$ is a constant equal to $\left( \frac{q^2}{2g} \right)$. Mathematically, $\Delta E_{G.W.}$ thus depends mainly on $\Delta y_{G.W.}$. Accordingly, $\Delta y_{G.W.}$ is a function of energy dissipation such that, at any PRDHJ value there will be a square difference in water depth between two sides of G.W., $\Delta(\Delta y_{G.W.})$, which may be written as $\Delta^2 y_{G.W.}$. Thus, $\Delta E_{G.W.}$ values depend on $\Delta^2 y_{G.W.}$ values. The value of $\Delta^2 y_{G.W.}$ can be calculated as

$$\left( \frac{\Delta^2 y_{G.W.})_{\%}}{\Delta y_{G.W.,A.}} \right) = \left( \frac{\Delta y_{G.W.,A.} - \Delta y_{G.W.,B.}}{\Delta y_{G.W.,A.}} \right)$$

(10)

where $\Delta y_{G.W.,A.}$ is the square difference in water depth calculated at the maximum value of DHJ (L).

Tables 11, 12, 13, 14, and 15 present the values of both of PRDHJ and $\Delta^2 y_{G.W.}$ at 3.6 l/s applied discharge. It is clear that the value of PRDHJ fluctuates between 59.306% and 61.199% for G.W. lengths 0.6, 0.8, and 1.0 m, suggesting that increasing of length of G.W. does not affect PRDHJ value for the first gravel sample used with these lengths. The PRDHJ value increases slightly for G.W. lengths 0.6, 0.8, and 1.0 m for both the second and third gravel samples suggesting the first evidence of an effect of G.W. Length on PRDHJ value. The PRDHJ value returns to fluctuation behaviours with the increase of G.W. length from 0.4 m to 1.0 m for the fourth gravel sample used, and there is an absence of effect of G.W. length on PRDHJ value for the last, biggest, gravel sample. PRDHJ value has a clear increase at the biggest G.W. length for all gravel samples used and increasing with increases in value of d for all G.W. lengths in general form. A reduction in DHJ was noticed in G.W.No.V with G.S.No.V. The value of $\Delta^2 y_{G.W.}$% showed an undulation with increases of G.W. length value for small values of $d_{GS}$ and decreases with increasing G.W. length value for medium and large values of $d_{GS}$. Finally, the value of $\Delta^2 y_{G.W.}$% increased with increases in the value of $d_{GS}$ for every single G.W. length value.

Figure 7 shows the PRDHJ-$\Delta^2 y_{G.W.}$% relationship for the physical models based on the data recorded in tables 11, 12, 13, 14, and 15 respectively. A direct relationship between PRDHJ values and $\Delta^2 y_{G.W.}$%
values can be observed, and this relationship varies between the power form for G.W.No.I, G.W.No.II, G.W.No.III, and G.W.No.IV, and the exponential form for G.W.No.V as shown in equations (11) and (12).

(For G.W.No.I, G.W.No.II, G.W.No.III, and G.W.No.IV.)

\[ \text{PRDHJ} = c_3 \times (\Delta^2 y_{G,W,\%})^{k_3} \quad (11) \]

(For G.W.No.V.)

\[ \text{PRDHJ} = c_4 \times e^{(k_4 \times (\Delta^2 y_{G,W,\%}))} \quad (12) \]

where \( c_3, c_4, k_3, \) and \( k_4 \) are constants. This figure also shows that the value of PRDHJ decreases with increases in the equivalent diameter of the gravel used. Table 16 presents the values of constants \( c_3, c_4, k_3, \) and \( k_4 \) of PRDHJ-\( \Delta^2 y_{G,W,\%} \) relationship for all G.W. physical models at the chosen comparison discharge.

| Table 11. Values of both of PRDHJ and \( \Delta^2 y_{G,W,\%} \) at 3.6 L/S applied discharge measured for G.W.NO.I. |
|---|---|---|
| \( d_{GS} \) (mm) | PRDHJ | \( \Delta^2 y_{G,W,\%} \) |
| 9.5-14 | 00.000 | 00.000 |
| 14-19 | 61.514 | 41.625 |
| 19-25 | 69.085 | 54.500 |
| 25-37.5 | 76.656 | 59.625 |
| 37.5-50 | 72.871 | 62.875 |

| Table 12. Values of both of PRDHJ and \( \Delta^2 y_{G,W,\%} \) at 3.6 L/S applied discharge measured for G.W.NO.II. |
|---|---|---|
| \( d_{GS} \) (mm) | PRDHJ | \( \Delta^2 y_{G,W,\%} \) |
| 9.5-14 | 60.883 | 24.500 |
| 14-19 | 66.562 | 38.125 |
| 19-25 | 71.609 | 48.625 |
| 25-37.5 | 77.918 | 56.500 |
| 37.5-50 | 74.132 | 62.500 |

| Table 13. Values of both of PRDHJ and \( \Delta^2 y_{G,W,\%} \) at 3.6 L/S applied discharge measured for G.W.NO.III. |
|---|---|---|
| \( d_{GS} \) (mm) | PRDHJ | \( \Delta^2 y_{G,W,\%} \) |
| 9.5-14 | 59.306 | 27.750 |
| 14-19 | 67.192 | 37.625 |
| 19-25 | 71.609 | 43.250 |
| 25-37.5 | 70.347 | 50.250 |
| 37.5-50 | 72.871 | 56.500 |

| Table 14. Values of both of PRDHJ and \( \Delta^2 y_{G,W,\%} \) at 3.6 L/S applied discharge measured for G.W.NO.IV. |
|---|---|---|
| \( d_{GS} \) (mm) | PRDHJ | \( \Delta^2 y_{G,W,\%} \) |
| 9.5-14 | 61.199 | 13.125 |
| 14-19 | 68.454 | 27.500 |
| 19-25 | 72.240 | 39.625 |
| 25-37.5 | 72.871 | 49.250 |
| 37.5-50 | 72.871 | 56.250 |

| Table 15. Values of both of PRDHJ and \( \Delta^2 y_{G,W,\%} \) at 3.6 L/S applied discharge measured for G.W.NO.V. |
|---|---|---|
| \( d_{GS} \) (mm) | PRDHJ | \( \Delta^2 y_{G,W,\%} \) |
| 9.5-14 | 74.763 | 18.750 |
The Buckingham Π-Theorem, [26] and [27], was then used to represent the dimensionless parameters of this study:

$$\text{DHJ/L} = f_3 \left( \frac{\Delta y_{\text{G.W.}}}{L} \right), \left( \frac{d_{GS}}{L} \right), \left( \frac{L^3 * g}{q^2} \right)$$

By using multi-linear regression for the data set to correlate the dependent parameters with the independent ones [28], equation (13) can be re-written as:

$$\text{DHJ/L} = c_5 \left( \frac{\Delta y_{\text{G.W.}}}{L} \right)^{k_5} + c_6 \left( \frac{d_{GS}}{L} \right)^{k_6} + c_7 \left( \frac{L^3 * g}{q^2} \right)^{k_7} + c_8 \quad R^2 = 0.89$$

Table 16. Values of constants $c_3$, $c_4$, $k_3$, $k_4$ and $R^2$ for trend line equation PRDHJ-$\Delta^2 y_{\text{G.W.}}$% relationship for all physical models.

| G.W.No. | $c_3$ | $k_3$ | $R^2$ |
|---------|-------|-------|-------|
| I       | 0.023 | 1.280 | 0.88  |
| II      | 7E-05 | 3.137 | 0.87  |
| III     | 6E-06 | 3.702 | 0.92  |
| IV      | 3E-13 | 7.658 | 0.93  |
| V       | 1.386 | 0.034 | 0.82  |

Table 17. Values of constants $c_5$, $c_6$, $c_7$, $c_8$, $k_5$, $k_6$, and $k_7$ as used in equation (14).

| $c_5$ | $c_6$ | $c_7$ | $c_8$ |
|-------|-------|-------|-------|
| 4.1307| 1.5114| -0.0158| 0.5322|
| $k_5$ | $k_6$ | $k_7$ |       |
| 3     | 0.5   | 0.25  |       |
5. Conclusion

The present study aimed to investigate the effect of the distance of hydraulic jump on energy dissipation representation parameters. Relationships between parameters were made either directly or in a comparison state, while the dimensionless form was used to correlate all parameters. Within the limitations of this study, it is thus concluded that

1. The distance of hydraulic jump is directly proportional to the discharge.
2. The effect of gradation of gravel samples and gabion weir lengths on the distance of hydraulic jump is insignificant for small values of discharge.
3. The distance of hydraulic jump is inversely proportional to the equivalent diameter of the gravel used.
4. At the same gravel sample diameter and chosen discharge rate, the distance of hydraulic jump is inversely proportional to the length of the gabion weir.
5. A dimensionless equation can be used to express the relationships that combine all parameters of this study.
6. The illustrated relationship between the proposed energy dissipation parameter and the depth parameter is directly proportional.

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