SIMILARITY OF FLOWS IN NATURAL CHANNELS

HYDRAULICS

1968

SovietRxiv

Abstract

Full Text

UDC 532.501.111:551.482.211

HYDRAULICS

K. V. GRISHANIN

SIMILARITY OF FLOWS IN NATURAL CHANNELS

(Presented by Academician P. Ya. Kochina, January 2, 1967)

Modern channels of natural watercourses are formed by these same flows within the mass of their own deposits. A flow not only creates for itself a channel of definite dimensions, but also, to a certain extent, regulates its roughness—by suspending or depositing fine fractions, abrading bottom particles, and forming bed ridges.

The formation and development of natural channels cut in noncohesive soils is based on one and the same process of interaction between a turbulently moving liquid and the underlying granular medium. The universality of the process should lead to universal results—flows in natural channels should possess the properties of similarity. In particular, taking into account the interrelation among all aspects of the channel process, one may suppose that the conditions of dynamic and geometric similarity in natural flows are always satisfied jointly, or that **dynamically similar natural flows have geometrically similar channels**.

The criteria of geometric similarity of natural flows are: the ratio B/h of the channel width at the water surface to the mean depth $h = \omega/B$ (ω is the area of the wetted cross section), the ratio B/r of the channel width to the radius of curvature of the concave bank, and the ratio h/d of the mean depth to the characteristic diameter of the bed particles. The criteria of dynamic similarity are: the Froude number $\mathrm{Fr} = U^2/gh$, where $U = Q/\omega$ is the mean flow velocity (Q is the water discharge), and the relative mass content of suspended solid particles

$$\sigma \approx \frac{\rho_s}{\rho} s,$$

where ρ_s and ρ are the densities, respectively, of the solid particles and of water, and s is the volumetric content.

Thus, there must exist a functional dependence

$$f(B/h,\ B/r,\ h/d,\ \mathrm{Fr},\ \sigma) = 0. \tag{1}$$

Experience shows that the form of a channel, characterized by the parameters B/h and B/r, is more strongly connected with the Froude number than with the parameters h/d and σ. This is especially true of lowland streams with their slowly varying composition of bed deposits and insignificant content of suspended particles. Therefore, for lowland natural streams there must exist a simpler than (1), approximate dependence

$$f(B/h,\ B/r,\ \mathrm{Fr}) = 0. \tag{2}$$

On straight reaches of a channel, where the parameter $B/r = 0$, dependence (2) acquires the character of a relation between two variables. According to experimental data, the relative width of the channel increases as the Froude number decreases. Thus one may postulate the following form of the function f on straight reaches of natural lowland streams:

$$f\left(\frac{B}{h},\ 0,\ \mathrm{Fr}\right) = \frac{B}{h}\,\mathrm{Fr} - c, \tag{3}$$

where c is a constant. The physical basis of (3) may be seen in the fact that similar natural flows have the same degree of stability

with respect to random disturbances (the stability of an open flow increases with the Froude number and decreases as the channel width grows).

Expressing in (3) the velocity U through the discharge $Q = UBh$ and introducing a new constant $M = c^{-1/4}$, instead of (2) and (3) we shall have

$$h(gB)^{1/4}/Q^{1/2} = M. \tag{4}$$

To verify relation (4) and to determine the value of the constant M, data on measured water discharges published in the *Hydrological Yearbooks* were used.*

Table 1

	Q, m^3/sec	U, m/sec	B, m	h, m
Maximum	12 100	1.54	1190	10.7
Minimum	0.34	0.27	11.5	0.11

According to the yearbook for 1962 ([2]), 25 hydrometric sections were selected on 21 lowland rivers of the European territory of the USSR and Western Siberia. The choice of rivers and sections was dictated by the desire to represent channels with a wide range of absolute dimensions, as well as basins with different surface character (tundra, forest, forest-steppe, steppe). Sections were excluded from consideration that were: a) undergoing intensive channel deformations; b) with irregular flow (dead spaces); c) located in backwater; and d) overgrown with aquatic vegetation.

For each section, three water discharges were taken: the smallest, the largest, and one close to the middle of the interval of measured discharges. Thus, in all, 75 water discharges were taken. At all hydrometric sections the largest measured discharges in 1962 passed within the low-water channel. The extreme values of the hydraulic elements of the flows studied are given in Table 1.

The mean annual turbidity of the selected rivers lies approximately within the limits $25 \div 250$ g/m^3.

The calculations showed that the values of M vary around the mean value $\bar{M} = 0.904$, with a coefficient of variation of 0.175. The greatest deviations from the middle are given by the smallest discharges measured at a given section. This is natural, since unavoidable local irregularities of the sections become most appreciable at low stages. For 50 values of M, calculated for medium and large channel fillings, $\bar{M} = 0.924$ was obtained, with a coefficient of variation of 0.141.

Thus, the extensive data used confirm relation (4) with a degree of accuracy high for natural conditions. The closeness of the relation is a consequence of the fact that its variables are the principal similarity criteria of open flows: B/h and Fr.** Equation (4) expresses a statistically stable law of nature.

In calculations it is expedient to use the rounded value of the constant $M = 0.9$. Substituting this value into (4), we obtain the possibility, from any two of the three known quantities B, h, Q, of finding an approximate value of the third. In accordance with the structure of the expression for M, the mean depth can be determined with the greatest accuracy, then the water discharge, and, finally, the channel width.

* Permanently operating hydrometric sections are located, as is known, on straight pool reaches of rivers.

** An empirical formula, close in form to the initial relation (3), namely, corresponding to the replacement in (3) of the ratio B/h by the quantity

$$\frac{B}{h^{0.44} h_{\max}^{0.56}},$$

was obtained by Yu. V. Chernov ([3]) as a result of processing data for several stable reaches of rivers of the Caspian region. Strangely, this formula, undoubtedly the best of all the proposed empirical relations between the elements of the channel and the flow, did not attract wide attention and was not even mentioned in the review of works on river-channel morphometry included in ([4]).

Fig. 1. a –rivers of the USSR, b –the Mississippi River at Fulton

Figure 1: Fig. 1. a –rivers of the USSR, b –the Mississippi River at Fulton

Figure 1 shows the curves $h = h(B, Q)$ and $Q = Q(B, h)$, constructed from equation (4) for $M = 0.9$. Points of field measurements are plotted there as well. In addition to 75 measurement points on rivers of the USSR, three measurement points on the Mississippi River in the hydrometric section with very great depths are plotted (^{5}). As can be seen from the figure, they agree excellently with (4). The curve in Fig. 1b makes it possible to find an approximate value of the water discharge in a river in the complete absence not only of measured discharges, but also of information on the roughness of the channel and the slope of the free surface. If a small number of measured discharges is available, equation (4) may be used for interpolation and extrapolation of the discharge curve (within the limits of the low-water channel). In this case one may use the value of M established for the given section from the available measurements.

Fig. 1. *a* –rivers of the USSR, *b* –the Mississippi River at Fulton

Leningrad Institute
of Water Transport

Received
17 XII 1966

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Note: Figure translations are in progress. See original paper for figures.