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HORIZONTAL TURBULENCE AND ALTERNATE BARS

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SYNOPSIS

The occurrence of alternate bars has been explained by means of horizontal turbulence. This explanation, which is analogous to that for the occurrence of dunes, rests largely on the identity between the length of alternate bars and the length of horizontal bursts - alternate bars are thus treated as the "imprints" of horizontal bursts on the deformable surface of a mobile bed. It has been established that the bed forms generated by a rough turbulent open-channel flow should be classified according to the width-to-depth ratio and the relative roughness. The upper and lower limits of the alternate bar region are revealed on the basis of all the available field and laboratory data.

1. INTRODUCTION

Much has been contributed by the Japanese researchers to the discovery of open-channel turbulence (Refs. [44], [39], [28], [29], [30], [31], etc.) and to the exploration of alternate- and multiple bars (Refs. [25], [27], [19], [21], [37], [26], etc.). Hence the authors thought that the Journal of Hydroscience and Hydraulic Engineering should be a suitable medium to publish this paper where an attempt is made to explain the occurrence of alternate bars by means of horizontal turbulence.

Following the works of Hansen 1967 [14] and Callander 1969 [4], a large number of valuable contributions to the study of alternate bars has been produced on the basis of stability analysis, rendering it the most popular research method in the field (see e.g. [9], [32], [15], [7]). However, in spite of its deserved popularity, the stability analysis basically is a mathematical method, and consequently its utilization is necessarily associated with certain idealizations of the actual conditions. And it is apparently owing to this reason that, in their (very prominent) work [7], Colombini et. al. acknowledge that the results of the linear stability analyses "are far from being conclusive" and that they allow the prediction in "gross terms" only. With regard to their non-linear approach they state that it "has various limitations which need further attention". A further investigation of alternate bars can thus not be regarded as superfluous and a different approach may also prove to be rewarding. The present physical study of these bed forms by turbulence is not in conflict with

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their study by the stability methods. In fact, both studies appear to be complementary.

2. LARGEST EDDIES OF HORIZONTAL TURBULENCE

Apparently the concept of "horizontal turbulence" was first introduced by Yokosi 1967 [44]. On the basis of his measurements of velocity fluctuations in the Uji River, and in a laboratory flume, Yokosi has demonstrated that, if the width-to-depth ratio B/h of an open-channel flow is sufficiently large, then the "largest eddies" of horizontal turbulence manifest themselves in the form of "horizontal disks" whose thickness is equal to the flow depth h. The plan dimensions of these disks were found to be $L_x \approx 9B$ and $L_z \approx B$. The value of L_x was determined in Ref. [44] by identifying it with the product VT_H, where V is the average velocity of the flow and T_H the period of the largest horizontal eddies. Analogous measurements were carried out also by Dementiev [8] in the Amu-Darya River (USSR) (see [12]). From the velocity fluctuation diagrams obtained from these measurements it follows that $L_x \approx 7B$. The time-space average value of the semi-random quantity L_x cannot be assessed from a limited number of measurements; and the above mentioned "samples" $\approx 9B$ and $\approx 7B$ merely suggest that the average value of L_x should be comparable with them.

3. BURST LENGTHS

From the research carried out in boundary layer flows "... it appears to be fairly well established that the burst period T scales with outer variables and the generally accepted number is $Tu_\infty/\delta \approx 6$ (Cantwell 1981 [5]). Similarly, from the research conducted in open-channel flows it follows that the average relative length L/h of "vertical bursts" can also be approximated by ≈ 6:

$$L \approx 6h, \tag{3.1}$$

the maximum extent of vertical bursts, along y, at the end of a burst cycle being $\approx h$.

The remarkable similarity between the relation (3.1) and the expressions produced for the length Λ_d of dunes, viz

$$\Lambda_d \approx 2\pi h \quad [42]; \quad \Lambda_d = 7h \quad [17]; \quad \Lambda_d = 5h \quad [43]; \quad \text{... etc.} \tag{3.2}$$

has already been used in Ref. [40] to explain the dunes as the "imprints" of vertical bursts on the deformable surface of a mobile bed.

To the authors knowledge, the horizontal bursts have not yet been explored quantitavely by special experiments. Yet, from the flow visualization studies it appears that horizontal turbulence of an open-channel flow has also its large-scale "coherent structures" which extend by several B in the flow direction x.[3] According-

[3] The authors are grateful to Prof. H. Ohnari (Tokuyama College of Technology) for supplying them with the photographs of coherent structures in open-channel flows.

ingly it would only be reasonable to assume that horizontal bursts exist and that their length L_H should be expressible (in analogy to (3.1)) as

$$L_H = \alpha B. \tag{3.3}$$

One would expect (also in analogy to vertical bursts) that the maximum extent of horizontal bursts, along z, at the end of the burst cycle should be $\approx B$.

The striking similarity between the plan dimensions of horizontal bursts and the "largest eddies" reported in the "pre-burst-era" pioneering work of Yokosi [44] suggests that the "largest eddies" of Ref. [44] are but the disturbed fluid regions occupied by horizontal bursts.

The numerous data available for alternate bars indicates (see Fig. 1) that the average bar length Λ_a and the flow width B are interrelated by the proportionality

$$\Lambda_a \approx 6B. \tag{3.4}$$

Alternate bars can occur only in turbulent flows. Yet they cannot be caused by vertical turbulence. For all large-scale lengths of vertical turbulence are proportional to h, and therefore they cannot possibly be "imprinted" as bed forms whose length is proportional to B. But this means that alternate bars must be caused by the large-scale horizontal turbulence - they must be the "imprints" of horizontal bursts:

$$\Lambda_a \equiv L_H. \tag{3.5}$$

Hence one can adopt $\alpha \approx 6$ and this value is certainly comparable with the values ≈ 9 and ≈ 7 found in Refs. [44] and [8].

Since the shear stresses $\tau_{xz} \sim (\partial u / \partial z)^2$ have their largest values at the banks - near the free surface - the disk-like structures forming horizontal bursts should originate (predominantly) at those locations. Considering this, and taking into account that the plan arrangement of alternate bars is antisymmetrical with respect to the center line of the flow, it would only be reasonable to assume that the plan arrangement of horizontal bursts should be as shown schematically in (the highly idealized) Fig. 2; the bursts being "fired" (from their sources O_i and O_i', at the banks and free surface) with the average time intervals $T_H = L_H / V$.

4. FORMATION OF ALTERNATE BARS

Since "bursts are distributed randomly in space and time" [35], neither dunes (due to vertical bursts) nor alternate bars (due to horizontal bursts) can occur if the conditions are completely uniform along x: a sequence of sand waves can then be expected to occur only if a sequence of bursts is provided first. And this can be achieved by a local "discontinuity" on the flow bed or banks, at a section $x = 0$, say, which will render the section $x = 0$ to acquire a "bias" (a "preferential status") in comparison to the rest of the flow sections. The local discontinuity (which can be an accidental ridge on the mobile bed or banks, abrupt transition from the rigid to mobile boundaries, etc.) will trigger the "eddy shedding" and, consequently, it will augment the frequency of the generation of bursts at $x = 0$. This, in turn, must lead to the generation of a burst sequence starting from $x = 0$, for the "break-up" of the first burst will induce the initiation of the second burst, ..., and so on. Although the burst sequence is attenuating (the "preferential frequency" is decreasing along x), the abrupt downstream surfaces (steps) "imprinted" by the first few bed forms will themselves act as "new" discontinuities. This will cause the burst sequence (and the emerging bed forms due to it) to propagate further and further downstream.

The occurrence of aternate bars due to a sequence of horizontal bursts can be explained with the aid of the diagrams in Fig. 3 (where the discontinuity d is at the origin O_1 of the first burst).

If the burst-forming horizontal eddies e_H and e_H' were moving without interferring with each other, then the boundaries of their modules would be the lines $\overline{O_iP_i}$ and $\overline{O_i'P_i'}$ (Fig. 3a). However, in reality, their motions interfer, and therefore $\overline{O_iP_i}$ and $\overline{O_i'P_i'}$ must deform, eventually, into a sequence of non-intersecting lines l_i and l_i' whose end points are O_i' and O_i (Fig. 3c). To put it differently, each boundary line $\overline{O_iP_i}$ must deform so that its end point P_i is "brought upstream" to the location O_i' (the analogous applies to each $\overline{O_i'P_i'}$).

If the burts *were* not interferring, then the material eroded from the (shaded) regions immediately downstream of O_i and O_i' *would have been* deposited in the areas D_i and D_i' at the end of these hypothetical burst modules (Fig. 3b). However, in actual case, the depositions cannot occur as far downstream as D_i and D_i', for an excessive advance of the depositions caused by the bursts originating from O_i will be "checked" by the stream of eddies issued from O_i': they will simply wash away any excessive deposition. Hence the actual depositions will occur in the locations $\overline{D}_i$ and $\overline{D}_i'$ (Fig. 3c), which are not as far downstream as the "intended" depositions D_i and D_i'. As a result of this, the downstream boundary of each deposition $\overline{D}_i$ caused by the bursts issued from O_i and the boundary of the (shaded) "channel" eroded by the bursts issued from O_i' form a single line (l_i') which connects O' and O. The lines l_i' (and l_i) emerge thus as the "crest-lines" of alternate bars, each bar being an erosion-deposition sequence confined between l_i and l_i'. (Fig. 3d shows schematically the time average streamlines of the flow contacting the bar surfaces).

5. EXISTENCE REGIONS OF BED FORMS

5.1 *Theoretical considerations*

On the basis of the above considerations, one can ascert that alternate bars can occur only for a limited interval of the width-to-depth-ratio B/h, the limits of the interval being certain functions of the relative roughness $k_s/h \sim D/h$ of the (flat) initial bed:

$$f_0\left(\frac{h}{D}\right) < \frac{B}{h} < f_1\left(\frac{h}{D}\right). \tag{5.1}$$

Indeed, let δ_{max} be the thickness of the largest disk-like "structures" forming a horizontal burst. If $(\delta_{max}/h) < 1$ then the disk-like "structures" (which originate near the banks and the free surface) are not "rubbing" the bed at any phase of the burst cycle. Consequently they cannot deform the mobile bed surface (as alternate bars). The bed deformation by horizontal turbulence can then be expected only if the (intended) maximum disk thickness δ_{max} is larger than h. Since δ_{max} must be proportional to the plan dimensions of the largest disk-like structures, and thus to B, and since (in the case of rough turbulent flows) the initiation of the factual interaction between the (flat) initial bed surface and the "disks" may vary depending on the bed roughness $k_s \sim D$, the alternate bars should occur only if $(\delta_{max}/h) \sim B/h$ exceeds a certain lower limit which must be expected to vary with $k_s/h \sim D/h$ ($f_0(h/D)$ in (5.1)).

On the other hand, the alternate bars cannot occur for *all* $B/h > f_0(h/D)$. For if B/h is too large, then the horizontal bursts may not be able to "reach" the opposite banks: the (bed rubbing) disk-like structures forming them may be destroyed by the bed friction before their plan dimensions reach the size $\approx B$; and the more so the larger are B/h and k_s/h. Hence the alternate bars, which extend from one bank to the other, should occur only if B/h does not exceed a certain upper limit which depends upon (and in fact decreases with) $k_s/h \sim D/h$ ($f_1(h/D)$ in (5.1)).

Consider now the B/h-regions that remain outside the "alternate bar-ribbon" (5.1).

- If $B/h > f_1(h/D)$ then the horizontal bursts emitted from O_i and O_i' may meet each other in the midst of the flow. In this case, instead of a "single-row" configuration of bursts which produces alternate bars (or "single-row" bars (Fig. 3)), the "double-row" configuration of bursts, which produces the "double-row" bars, will be present (Fig. 4a). A further increment of the bed friction effect (i.e. of B/h and k_s/h) must lead to the further reduction of the relative length $(L_H)_i/B$ of bursts (emitted from O_i and O_i'). Thus the "double-row" configuration will change into the "triple-row", "quadriple-row", ..., "N-row" configurations, where the lateral extent of each row is $B/3$, $B/4$, ..., B/N respectively (Figs. 4b and c) (the rows adjacent to the banks are formed by the horizontal bursts themselves, the rows in the central region B_c, by the (large-scale) eddies "induced" by them). Clearly the configurations mentioned will deform the mobile bed surface correspondingly, i.e. so as to produce "double-row", "triple-row" and "N-row" bars respectively, the value of N being an increasing function of B/h and $k_s/h \sim D/h$.
- If $B/h < f_0(h/D)$, then the horizontal bursts are not touching the bed. In this case the bed surface will be subjected to the action of vertical bursts only, and the formation of dunes must be expected. However, this should be so only if the flow is tranquil, i.e. if $Fr \ll 1$: otherwise, the action of the standing waves dominates and antidunes are "imprinted" instead of dunes.

5.2 *Experimental Data*

A total of 462 laboratory and natural rivers data points of all available to the authors sources are plotted in the log-log system of coordinates h/D and B/h in Fig. 5. The general behaviour of the data is consistent with the prediction above. Indeed, the alternate bar points A exhibit a clear tendency to form their existence region ("ribbon") confined between the lines $B/h = f_0(h/D)$ and $B/h = f_1(h/D)$ (see (5.1)): the region $B/h > f_1(h/D)$ is occupied by the multiple bar points C, the region $B/h < f_0(h/D)$ by the dune points D. The antidune points, which occupy the same region as dunes, are not plotted in Fig. 5. Most of the data corresponds to

$v_* D/\nu > \approx 20$ (rough turbulent flow past the flat initial bed), and therefore ripples, which might have been superimposed on dunes or bars, were either not prominent or they were not existent at all (in any event, they were not reported in Refs. used).

Although the "diffusion" of points from one region to the other is appreciable, nonetheless the following approximate forms of $f_0(h/D)$ and $f_1(h/D)$ can be suggested on the basis of Fig. 5:

$$\text{If } (h/D) < \approx 10^2, \text{ then } f_0(h/D) \approx 0.25(h/D) \text{ and } f_1(h/D) \approx 24.5(h/D)^{1/3}$$

and (5.2)

$$\text{If } (h/D) > \approx 10^2, \text{ then } f_0(h/D) \approx 25 \text{ and } f_1(h/D) \approx 120.$$

The fact that $f_1(h/D)$ must be proportional to the 1/3-power of h/D (when $(h/D) < \approx 10^2$) is demonstrated theoretically in Ref. [35]. No distinction was made in data sources used as to whether the multiple bar points correspond to double-row or triple-row bars, etc. (and therefore they are all marked by C). Consequently it was not possible to reveal the boundaries separating "various types" of multiple bars.

It should be mentioned that the parameters B/h and h/D are not suficient to determine the existence regions of ripples which are due to viscous conditions at the bed: the determination of their existence region requires the introduction of the Reynolds number $v_* D/\nu$.

The present consideration of the existence regions by means of B/h and h/D appears to be consistent with the recent trend in the field. Muramoto and Fujita 1978 [27], Tamai et al. 1978 [38] and Hayashi and Ozaki 1980 [15] have classified the existence regions with the aid of some dimensionless combinations, the interrelations between which are equivalent to the interrelations between B/h and h/D (see [35]). And in [33] (Public Works Research Institute, Ministry of Construction, Japan 1982) it is exactly the parameters B/h and h/D which were used to classify the bed forms. The earlier attempts to determine these regions by involving the (transport related) parameters, such as S, γ_s, v_*, v_{*cr}, in addition to B, h and D (Refs. [37], [20], [26], etc.) were more cumbersome but not more successful. (Take e.g. the transport-related ratio v_*/v_{*cr} which was often used in the earlier attempts mentioned. Since *all* bed forms occur only when v_*/v_{*cr} is within certain limits, the ratio v_*/v_{*cr} can indicate whether a certain bed form can or cannot be present in the course of a given experiment. It cannot, however, be of any help in determining the *type* of that "certain" bed form).

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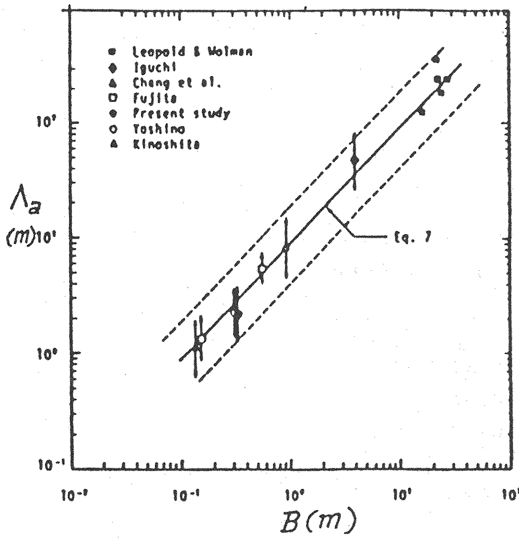
List of Symbols

a) General

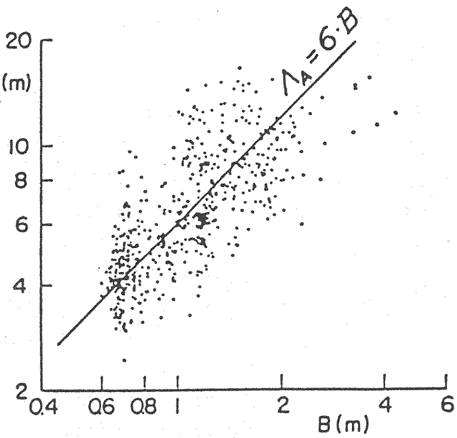
B	flow width
D	typical grain size; Deposition areas in Fig. 3.
e_H	burst-forming eddy of horizontal turbulence
Fr	Froude number
h	flow depth
k_s	equivalent (granular) sand roughness
L	burst length of vertical turbulence
L_H	burst length of horizontal turbulence
L_x, L_z	plan dimensions of the "largest eddies" along x and z respectively
N	number of horizontal burst rows
S	slope of uniform flow
T, T_H	durations of vertical and horizontal bursts respectively
u	local flow velocity along x
V	average flow velocity
v_*	shear velocity
x	direction of flow
y	direction vertically perpendicular to x
z	direction laterally perpendicular to x
γ_s	specific weight of grains in fluid
Λ_i	wave length of an alluvial form i
ν	kinematic viscosity

b) Subscripts

cr	critical stage of a quantity
a	alternate bar
d	dune



a) From Ikeda 1984 [21]



b) From Hayashi 1971 [16]

Fig. 1

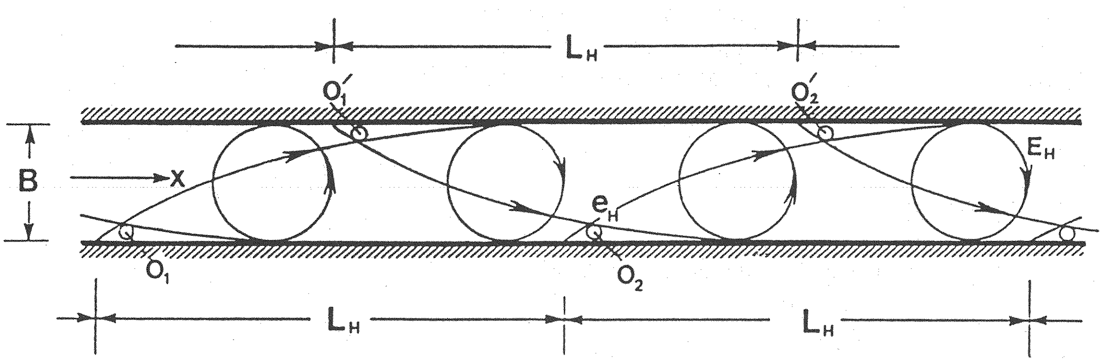
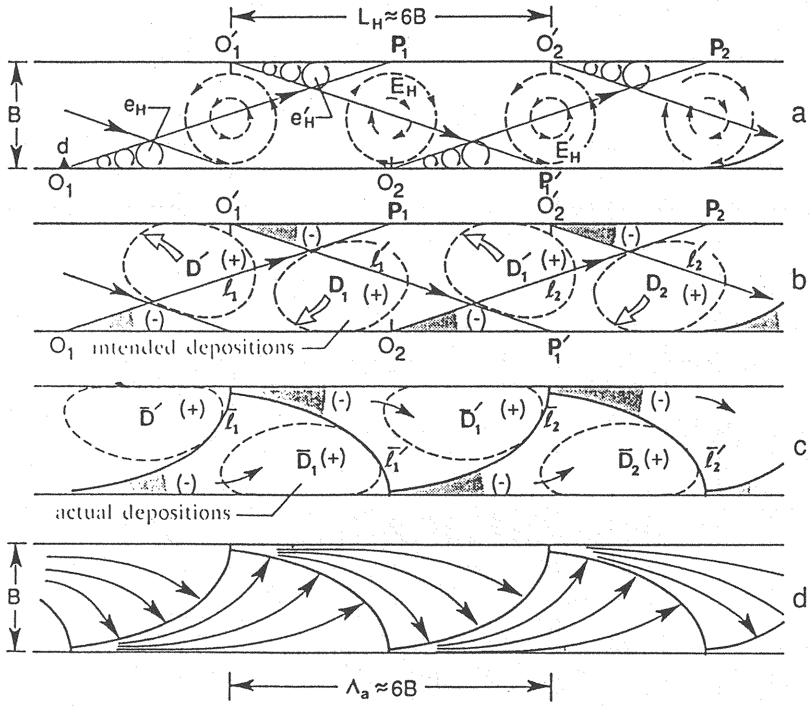
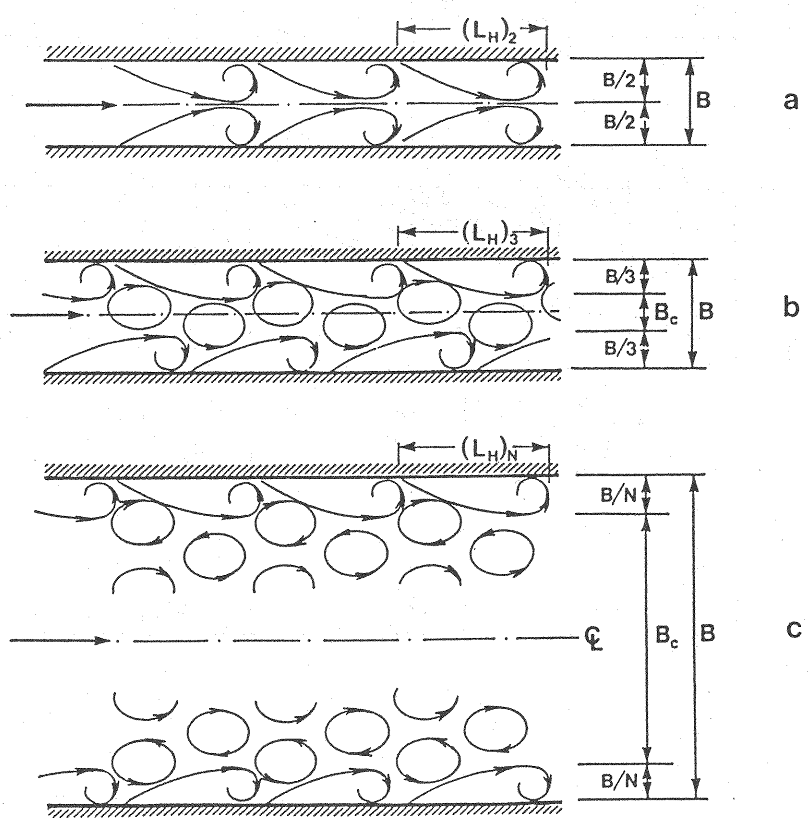


Fig. 2



L_H≈6B
O'1
P1
O'2
P2
B
e_H
e'_H
E_H
d
O1
O2
P'1
a
D' (+)
ℓ'1
ℓ1
D1 (+)
D'1 (+)
ℓ2
ℓ'2
D2 (+)
(-)
intended depositions
b
c
actual depositions
d
Λa ≈6B

Fig. 3



(L_H)2
B/2
B
a
(L_H)3
B/3
Bc
b
(L_H)N
B/N
CL
c

Fig. 4

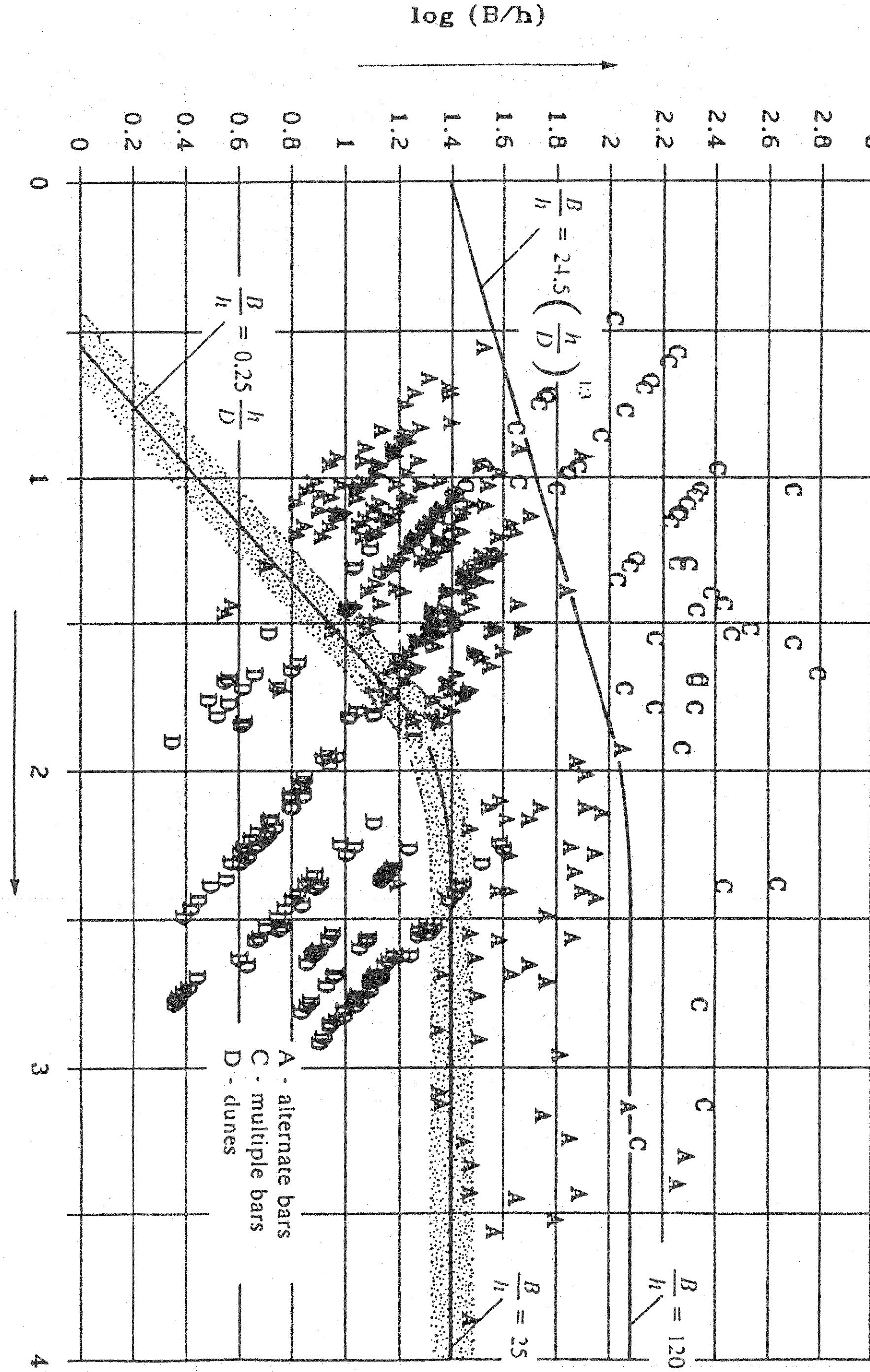


Fig. 5

A - Refs. [2], [6], [10], [18], [19], [21], [22], [24], [25], [27], [35]
B - Refs. [19], [25], [24], [27], [35]
C - Refs. [1], [3], [11], [13], [23], [34], [36], [41], [45]

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