Estimation Method of Longitudinal Dispersion Coefficient

——A Case Study in the Mainstream of the Lower Yellow River

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Abstract: The general formulary form for estimating the longitudinal dispersion coefficient of the mainstream of the lower Yellow River, P.R.China, from Xiaolangdi Reservoir in Henan Province to Lijin County in Shandong Province with about a total length of 750km which has the complicated riverway characteristics and hydrology condition. is derived by calculating the longitudinal dispersion coefficient using hydrologic monitoring data and performing dimensional and correlation analysis; considering the features of the highly varying riverbed, non-straight watercourse and high sand content, theoretical values are used as sample numbers for multiple regression analysis depending on the diverse watercourse features of the studied river sections, and the empirical estimate formula that applies to each section of the mainstream of the lower Yellow River by sectioning. This formula can be used as a reference to the establishment and application of the one-dimensional water quality model in the water pollution event pre-warning and predicting system of the mainstream of the lower Yellow River.

Keywords: longitudinal dispersion coefficient; dimensional analysis; multiple regression analysis; empirical formula; lower Yellow River

Longitudinal dispersion refers to the phenomenon of longitudinal dispersion of substances in water caused by the uneven distribution of the cross sectional velocity in a natural river, while longitudinal dispersion coefficient is a parameter of such property of water body (Zhou, 1988). As an important parameter that describes the mixed transport characteristic of a natural river (Zhang, 1987), the longitudinal dispersion coefficient is mainly affected by water flow conditions, cross sectional features and the profile of watercourse, etc, and reflects the longitudinal mixed characteristic of a river (Li, 2000). At present, the generally used methods to calculate a river's longitudinal dispersion coefficient include: (1) Theoretical calculation method: When the cross sectional velocity distribution data of a river is known, the longitudinal dispersion coefficient is calculated by integration. The dispersion coefficient derived from the cross sectional velocity distribution method is purely hydraulic, and must be corrected for non-straight rivers varying greatly in cross sectional area. In an ordinary river, the lack of information on cross sectional velocity distribution and water depth restricts its applicability to some extent. (2) Empirical formula method: When the information on velocity distribution is unavailable, this method can be used for rough estimate. Its shortcoming is the estimated result is not precise enough. The empirical formula is derived from research and summarization of certain target rivers and applies only to rivers with certain watercourse cross sectional features and velocity conditions. The cross sectional features of the Xiaolangdi-Aishan watercourse in the lower Yellow River are high sand content, disordered watercourse, and greatly varying cross sectional variation and width-depth ratio. These will result in a great difference in the estimated result of the longitudinal dispersion coefficient based on the empirical formula. (3) Field tracer method: The result resulting from the field tracer experimental method is the most reliable. However, it will be effort and cost consuming to perform a large-scale tracer experiment on the watercourse of hundreds of kilometers downstream Xiaolangdi, and will be financially unaffordable.

1 Survey of Studied Area

The mainstream of the lower Yellow River is located in a semi-dry and sub-humid region, featuring the temperate sub-humid continental monsoon climate and distinct seasons, with an annual average air temperature of about 15℃. It is the coldest in January, with an average air temperature of about 5℃, and the hottest in July with an average air temperature of about 26℃. Annual average sunshine hours are 1,740-2,310h, annual average evaporation 1,000-1,200mm and annual average precipitation 580-700mm. Rainfall occurs mostly from July to September, with great year-to-year variations.

The watercourse downstream the Xiaolangdi Reservoir in the lower Yellow River takes on the features unique to the lower Yellow River. The Huayuankou-Gaocun (even Sunkou) section is a disorderly, wandering watercourse, with greatly varying river width, extremely uneven water depth distribution along the cross section, rapid variation of riverbed erosion and deposition, being a typical shallow-broad watercourse. The Aishan-Lijin section is largely a homogeneous, regular watercourse, with a stable cross sectional area, and the watercourse is generally curved. In this study, the whole lower Yellow River is divided into the two sections in Henan and Shandong Provinces respectively. The Henan section comprises the wandering watercourse between Huayuankou and Gaocun and the transitional watercourse between Gaocun and Sunkou, while the Sunkou-Lijin section is within Shandong.

The Henan section is a wandering watercourse, with a shallow-broad cross sectional profile. River width varies greatly from year to year, and surface width can be as large as nearly 10km or as small as hundreds of meters. Water depth is usually one in hundreds of surface width. Erosion occurs during the rising flood period, increasing cross sectional area. For this wandering, transitional watercourse, since the mainstream is shifting about, the water flow forms a transverse velocity gradient on the cross section, sharpening the complexity of the cross current. The regime of the Shandong watercourse is controlled and guided by the river channel, so that the water flow is stable and has little shift, which is a distinct feature from the Henan section. Water level rising rate is the smallest at the Huayuankou and Jiahetan station, slightly higher at Gaocun than at Huayuankou and Jiahetan, even higher at Sunkou, and the highest

Figure 1 Distribution of hydrologic monitoring stations between Xiaolangdi and Lijin in the lower Yellow River

in the Shandong watercourse (Liu, 2004).

Eight typical hydrologic monitoring cross sections are selected downstream the Xiaolangdi Reservoir, which are Xiaolangdi, Huayuankou, Jiahetan, Gaocun, Sunkou, Aishan, Luokou and Lijin. The river sections of simulation analysis in this study are from the upper river to 20km downstream the Xiaolangdi hydrologic cross section, and from the lower river to the Lijin cross section, with a full length of about 750km. The monitoring stations are distributed as shown in Figure 1.

2 Selection of Calculation Method

The theoretical calculation method can reflect the variation of dispersion of pollutant concentrations resulting from uneven transverse velocity distribution in a river whose width is much greater than depth reliably, and makes inference based on the precisely measured cross sectional velocity distribution information, so it is very reliable. Provided the water flow conditions and river features are known, the empirical formula can be used to calculate or estimate longitudinal dispersion coefficient values quickly, and can also predict the longitudinal dispersion coefficient. Accordingly, this study adopts a calculation method that combines theoretical calculation and empirical formula, calculates the longitudinal dispersion coefficient values of the mainstream of the lower Yellow River with the theoretical integral formula of longitudinal dispersion coefficient using the hydrologic monitoring data of the lower Yellow River. After the longitudinal dispersion coefficient values of the watercourse are calculated with the theoretical integral formula, these theoretical values are used as sample numbers for a dimensional analysis of the general expression of the calculation formula of such coefficient in conjunction with the calculated values, hydrological conditions and cross sectional features, and the correlation level between the longitudinal dispersion coefficient and the possible component factors. The highly correlated factors are combined to assume the possible longitudinal dispersion coefficient empirical formula, whose general expression is converted into a multi-variable linear equation and fitted by regression analysis to obtain the longitudinal dispersion coefficient empirical estimate formula that suits the mainstream of the lower Yellow River and can be used for prediction.

2.1 Theoretical calculation

In a natural river, river width is much greater than water depth. The longitudinal dispersion resulting from uneven transverse velocity distribution is much greater than the impact of uneven vertical velocity distribution. In view of this, Fischer, et al (1967) simplified a natural river into a two-dimensional water flow and follows the analysis method of Taylor (1954) and Elder (1959), and deduced the theoretical calculation formula of the longitudinal dispersion coefficient E_x in a natural watercourse from the transverse velocity distribution:

$$E_x = -\frac{1}{A}\int_0^B q(y)dy\int_0^y \frac{1}{D_y h(y)}dy\int_0^y q(y)dy \tag{1}$$

$$q(y) = h(y)(u(y) - U) \tag{2}$$

$$D_y = \alpha h(y)U_* \tag{3}$$

Where: A—cross sectional area , m^2; B—cross sectional width, m; $h(y)$—water depth at transverse coordinate y, m; $q(y)$—deviation of single width flow rate from average cross sectional flow rate at transverse coordinate y, $m^3 \cdot s^{-1}$; D_y—transverse dispersion coefficient, $m^2 \cdot s^{-1}$; $u(y)$—average vertical velocity at transverse coordinate y, $m \cdot s^{-1}$; U—average cross sectional velocity, $m \cdot s^{-1}$; α—coefficient, 0.1-0.2 for straight natural watercourses or 0.3-0.9 for curved watercourse; U_*—drag velocity, $m \cdot s^{-1}$; E_x—longitudinal dispersion coefficient, $m^2 \cdot s^{-1}$

2.2 Empirical formula

According to the theory of Taylor (1954), the general expression of longitudinal dispersion coefficient is:

$$E_x = \alpha H U_* , \text{ where } \alpha = a\left(\frac{B}{H}\right)^b \left(\frac{U}{U_*}\right)^c \tag{4}$$

Where: a, b, c are empirical coefficients, to be rated for different watercourse features, the other symbols are the same as above.

The longitudinal dispersion coefficient E_x relates to the width, depth, velocity, hydraulic gradient and other hydraulic and watercourse parameters of a river. When no detailed velocity distribution information is available, the empirical formula can be used for estimate. Since different types of empirical formulas are based on certain water bodies, they generally apply to rivers with certain features and are highly limited. Several typical empirical formulas of longitudinal dispersion coefficient are as follows:

Fischer, et al (1979): $E_x = 0.011\left(\frac{B}{H}\right)^2 \left(\frac{U}{U_*}\right)^2 H U_*$;

Seo, et al (1998): $E_x = 5.915\left(\frac{B}{H}\right)^{0.62} \left(\frac{U}{U_*}\right)^{1.428} H U_*$;

Iwasa, et al (1991): $E_x = 2.0\left(\frac{B}{H}\right)^{1.5}$;

and Deng Zhiqiang, et al (2001): $E_x = 0.145 + \left(\frac{1}{3520}\right)\left(\frac{B}{H}\right)^{1.38} \left(\frac{U}{U_*}\right) H U_*$.

It can be seen that these empirical formulas vary greatly and are suitable only for their respective certain water flow conditions. For the specific study conditions of the mainstream of the lower Yellow River, an empirical formula designed to predict longitudinal dispersion coefficient values specifically must be deduced.

3 Calculations

3.1 Theoretical calculated values

The longitudinal dispersion coefficient values of the six hydrologic stations in the lower Yellow River calculated from Formulas (1)-(3) are shown in Table 1-6.

Table 1 Huayuankou longitudinal dispersion coefficient calculated value

H/m	B/m	$U/(m \cdot s^{-1})$	$U_*/(m^2 \cdot s^{-1})$	B/H	$E_x/(m^2 \cdot s^{-1})$
2.50	285	0.711088	0.050618	112.7119	136956
2.26	350	0.651065	0.049348	155.096	6569
1.59	350	0.858494	0.040342	220.5882	1173350

2.09	420	1.122331	0.047043	201.1976	3954015
2.77	460	1.798211	0.054944	165.9452	102084
2.69	815	1.82407	0.05103	303.4704	3876662
2.85	475	1.637369	0.055053	166.5436	6695
2.65	435	1.412844	0.054871	164.0684	8796
2.96	450	2.00993	0.057791	152.0875	4522
1.58	450	0.803325	0.041711	284.8101	25813
1.63	390	0.731689	0.041686	239.4737	7201
1.49	363	0.757064	0.039826	243.1579	11227
1.63	515	0.800634	0.041852	316.2494	3803
1.46	365	0.595308	0.040985	249.2683	2512

Table 2 Jiahetan longitudinal dispersion coefficient calculated value

H/m	B/m	U/(m•s^{-1})	U_*/(m^2•s^{-1})	B/H	E_x/(m^2•s^{-1})
2.10	349	1.961762	0.048620	166.1905	6160
1.76	682	1.711597	0.045041	386.9504	143734
2.08	687	1.857678	0.048970	330.1373	56333
2.26	698	2.008013	0.051208	308.7776	76677
1.47	667	1.375159	0.041292	452.7149	77490
1.24	475	1.155324	0.038138	383.8384	20069
2.50	173	0.844456	0.052878	69.31553	379
2.38	214	1.430231	0.051182	89.84733	1778
1.50	306	0.902581	0.041932	203.4349	3317
2.05	326	1.388256	0.048837	159.0244	4298
1.60	316	0.800111	0.043092	196.9405	204
1.57	300	1.376284	0.041914	191.3043	2333
1.44	302	0.679591	0.040958	210.2532	346

Table 3 Gaocun longitudinal dispersion coefficient calculated value

H/m	B/m	U/(m•s^{-1})	U_*/(m^2•s^{-1})	B/H	E_x/(m^2•s^{-1})
1.49	315	0.784570	0.040993	211.7647	2897
1.73	350	0.895340	0.044247	202.2222	17905
1.46	312	0.653446	0.040992	213.1677	778
1.34	438	1.227068	0.039439	327.4766	37859
1.75	465	1.559100	0.044409	266.2996	24098
2.09	475	2.265321	0.049236	227.0221	7647
2.65	491	2.149848	0.055306	185.0145	25707
2.64	495	2.322947	0.055507	187.6093	24652
1.98	484	1.957531	0.047843	244.6209	10588
1.58	351	1.396969	0.042878	222.8571	6576
1.86	343	0.814109	0.044343	184.6923	18019
1.26	483	1.265517	0.037991	382.0339	83472
1.35	445	1.393871	0.039175	328.6154	52507

Table 4 Sunkou longitudinal dispersion coefficient calculated value

H/m	B/m	U/(m•s^{-1})	U_*/(m^2•s^{-1})	B/H	E_x/(m^2•s^{-1})
1.57	423	0.712468	0.042437	270	8345

1.44	423	0.803468	0.040561	293.4104	8404
1.43	327	0.711702	0.039984	229.4737	5308
1.45	312	1.47624	0.040726	215.8491	1774
1.60	471	2.147157	0.002859	294.375	3782
2.57	481	2.015986	0.054307	187.4026	6384
2.68	482	2.218583	0.055538	180.1869	3403
2.75	462	2.465027	0.056359	168	10331
1.98	471	1.195236	0.046952	238.481	25772
1.33	432	1.38745	0.039573	324	6330
1.85	260	0.990974	0.045522	140.1961	5982
2.18	204	0.902896	0.049883	93.5	454
1.99	191	0.757943	0.047959	95.93607	272

Table 5 Aishan longitudinal dispersion coefficient calculated value

H/m	B/m	U/(m•$\mathrm{s^{-1}}$)	U_*/($\mathrm{m^2}$•$\mathrm{s^{-1}}$)	B/H	E_x/($\mathrm{m^2}$•$\mathrm{s^{-1}}$)
2.84	242	0.66007	0.052605	85.21127	5727
2.77	268	0.882376	0.052986	96.7509	7584
2.96	154	0.72993	0.054832	52.10526	2185
3.34	170	1.341052	0.058184	50.95368	1484
3.67	335	1.80045	0.062575	91.29979	2510
4.09	336	2.076013	0.066757	82.13333	4736
4.73	337	1.806306	0.072121	71.24736	2987
5.48	338	1.981948	0.078085	61.64134	1295
3.66	332	1.388812	0.062335	90.75171	4596
3.68	202	1.270099	0.061144	54.8913	3965
3.37	130	0.900475	0.056997	38.57567	1074
5.81	67	0.791315	0.079925	11.63289	34
3.64	131	1.067998	0.060491	36.025	1676
3.82	128	1.182716	0.063642	33.52381	3030

Table 6 Luokou longitudinal dispersion coefficient calculated value

H/m	B/m	U/(m•$\mathrm{s^{-1}}$)	U_*/($\mathrm{m^2}$•$\mathrm{s^{-1}}$)	B/H	E_x/($\mathrm{m^2}$•$\mathrm{s^{-1}}$)
4.29	97	0.78879	0.067512	22.62391	61
5.20	110	0.812371	0.076151	21.15385	34
3.93	93	0.803714	0.060989	23.66412	25
3.54	116	1.336766	0.063528	32.72727	45
5.51	227	1.669457	0.079427	41.19782	787
6.22	225	1.835381	0.084932	36.17363	906
4.08	177	1.218281	0.065766	43.38235	437
3.96	104	0.702943	0.068013	26.29213	35
3.33	201	0.64788	0.059514	60.40984	1517
3.44	110	1.232725	0.062696	31.93548	92
2.98	126	1.730287	0.058275	42.28188	61

3.2 Fitting of empirical formula

The dimension of HU, BU is $\mathrm{m^2}$•$\mathrm{s^{-1}}$, U/U_*, and B/H is a non-dimensional number. Through dimensional analysis and correlation analysis, the correlation chart between E_x and

HU, *BU*, *U/U*∗, *B/H* is drawn and the correlation coefficient determined. The results are shown in Figures 2, 3, 4 and 5.

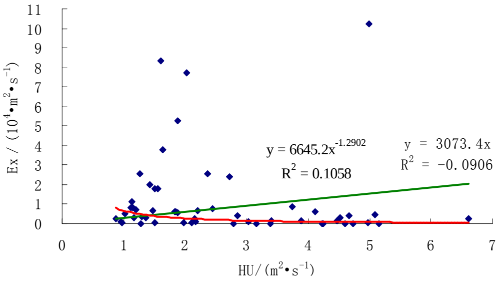

Figure 2 Huayuankou-Luokou

E_x-*HU* relation curve

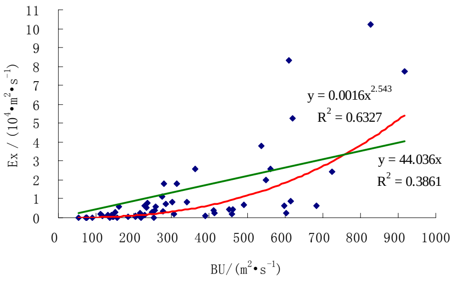

Figure 3 Huayuankou-Luokou

E_x-*BU* relation curve

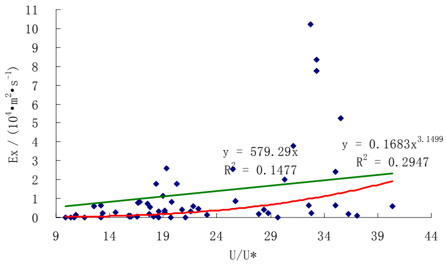

Figure 4 Huayuankou-Luokou

E_x-*U/U*∗ relation curve

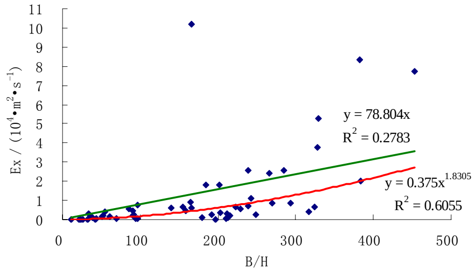

Figure 5 Huayuankou-Luokou

E_x-*B/H* relation curve

The results indicate, E_x is negatively correlated with *HU* and is in good power correlation with *B/H*. If we look at the lower watercourse as a whole, correlation is not ideal and theoretical values vary greatly, which is closely associated with the watercourse features. If it is considered separately by the Henan and Shandong sections, the width-depth ratio at the Luokou monitoring cross section in the Shandong section ranges from 21 to 61, and is less correlated with the parameters at Sunkou and Aishan, so its empirical formula is fit separately. Through multiple regression analysis, the empirical formula longitudinal dispersion coefficient is as follows:

Huayuankou-Gaocun in Henan:

$$E_x = 2.1BU\frac{U}{U_*}, \quad R^2=0.46 \tag{5}$$

Sunkou-Aishan in Shandong:

$$E_x = 1.344\left(\frac{B}{H}\right)^{1.803}\left(\frac{U}{U_*}\right)^{0.425} HU_*, \quad R^2=0.76 \tag{6}$$

Downstream Luokou in Shandong:

$$E_x = 0.038\left(\frac{B}{H}\right)^{2.402}\left(\frac{U}{U_*}\right)^{0.232} HU_*, \quad R^2=0.79 \tag{7}$$

3.3 Result analysis

The Xiaolangdi-Lijin section in the lower Yellow River is 750km long, with greatly varying watercourse features and dispersion coefficient values. It is unsuitable to fit a correlation formula uniformly. Depending on watercourse features, a long series of measured cross sectional and velocity distribution information is used to determine the empirical formula of each section respectively. These empirical formulas usually apply to a certain range of cross sectional width-depth ratio and a water flow rate of below 500m^3/s.

In the Henan section, the longitudinal dispersion coefficient values calculated from the measured hydrologic and cross sectional velocity distribution information vary sharply in amplitude (within 200-3,950,000m^2/s), and the longitudinal dispersion coefficient calculated form the estimate formula is also high (mostly within 10^3-10^{4}m^2/s), largely fitting the practical situation. The width-depth ratio of the Shandong section is slightly smaller than that of the Henan section but still higher than the corresponding values of other rivers worldwide, the theoretical values of longitudinal dispersion coefficient fall into 25-10,000m^2/s, and the estimated values are mostly within 30-5,000m^2/s, fitting the practical situation.

For the Huayuankou, Jiahetan and Gaocun cross sections of the wandering shallow-broad watercourse in the Henan section, all the estimated values derived from Formula (5) are below 60,000m^2/s. When cross sectional water flow rate is less than 500m^3/s, the theoretical values of these three cross sections have the same trend of variation as the estimated values from Formula (5) and are almost equal to the latter, showing a good estimate; when cross sectional water flow rate is greater than 500m^3/s, the estimate at Huayuankou is poor, but trend of variation is consistent at Jiahetan and Gaocun, with little difference.

In the Sunkou-Luokou section in the Shandong section with a small width-depth ratio and a fast water velocity, the fit correlation coefficient of the empirical formula is high, and 99% of the estimated values are below 8•10^{3}m^2/s. For the Sunkou, Aishan and Luokou cross sections, when cross sectional water flow rate is less than 500m^3/s, the measured values have the same trend of variation as the estimated values from Formulas (6) and (7) and are almost equal to the latter, showing a good estimate; when cross sectional water flow rate is greater than 500m^3/s, the estimated value of the Luokou cross section is greater than the measured value, while those at Aishan and Sunkou are smaller than the measured values, showing a poor estimate.

3.4 Error analysis

The statistical method based on deviation ratio DR is used. The formula is as follows:

$$DR = \log_{(10)} \frac{E_{xp}}{E_{xm}} \qquad (8)$$

Where: E_{xp}—estimated value of longitudinal dispersion coefficient derived from empirical formula; E_{xm}—theoretical value of longitudinal dispersion coefficient derived from integral formula.

When the formulas of Kashefipour, et al (2002) and Fischer(1975) and Empirical Formulas (5)-(7) are used, the distribution of DR values is shown in Table 7-9, and the percentage of DR values distributed within (-0.3, 0.3) is shown in Table 10.

Table 7 DR value distribution between Huayuankou and Gaocun

	<-1.0	(-1.0, -0.3)	(-0.3, 0.0)	(0.0, 0.3)	(0.3, 1.0)	>1.0
Kashefipour	17	6	4	0	0	0
Fischer	0	1	4	6	13	3
E.F.(5)	0	0	10	3	9	5

Table 8 DR value distribution between Sunkou and Aishan

	<-1.0	(-1.0, -0.3)	(-0.3, 0.0)	(0.0, 0.3)	(0.3, 1.0)	>1.0
Kashefipour	7	8	5	0	0	1
Fischer	0	3	4	6	5	3
Exp(6)	0	4	7	5	5	0

Table 9 DR value distribution downstream Luokou

	<-1.0	(-1.0, -0.3)	(-0.3, 0.0)	(0.0, 0.3)	(0.3, 1.0)	>1.0
Kashefipour	0	1	0	0	3	4
Fischer	0	0	1	0	4	4
E.F. (7)	0	2	2	5	0	0

Table 10 Percentage of DR values within (-0.3, 0.3)

	Huayuankou -Gaocun	Sunkou –Aishan	Downstream Luokou
Kashefipour	14.81%	23.81%	0
Fischer	37.04%	47.62%	11.11%
E.F. (5)-(7)	48.15%	57.14%	77.78%

4 Conclusion

Irregularities of a natural river make the river’s longitudinal dispersion complicated and changeful. The course of impact of such irregularities on the dispersion coefficient is unknown yet (Gu, 2007). When the dimensional analysis and multiple regression analysis methods are used, in the estimate formulas of longitudinal dispersion coefficient for different sections in the lower Yellow River deduced from the measured hydrologic information of the lower Yellow River, correlation coefficient is high at the Shandong section and a good estimated value can be obtained, while correlation coefficient is low at the Henan section, showing a poor estimate.

The longitudinal dispersion coefficient values in the Henan section of the lower Yellow River varies sharply and frequently in amplitude, reflecting the special hydrologic and hydraulic features in the lower Yellow River, such as large watercourse width-depth ratio, high sand content, serious riverbed erosion and deposition, great variation in water cross section, and poor reproducibility of watercourse variation. Even if the field tracer method is used to determine longitudinal dispersion coefficient values, the long-term effectiveness of the results cannot be assured. It is to be further studied how to eliminate or weaken the impact of these factors, so that the dispersion coefficient estimated from the resulting empirical formula is highly correlated with the corresponding factors.

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