Reflectivity Model of Low Grazing Angle Radar Sea Clutter

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Abstract The commonly used reflectivity models of radar sea clutter are summed up. Among these models, the adjusted Barton model and the adjusted Morchin model are compared. From the analysis result, the γ - p reflectivity model is presented for radar sea clutter at low grazing angle by the adjustment on the original Barton reflectivity model. The model takes into account radar frequency, grazing angle, sea condition, and polarization property. The influences on the proposed model by these factors are analyzed. The model absorbs the merits from commonly used reflectivity models of sea clutter. It introduces several researchers' opinions, and extends them. And it accounts for the reflectivity with arbitrary radar frequency from VHF to X-band, arbitrary low grazing angle, arbitrary sea condition and different polarization property. One of the main results is the proposed γ - p reflectivity model can reflect polarization' influence on sea clutter reflectivity to some extent. The proposed γ - p reflectivity model of low-angle radar-sea clutter is validated by comparing simulated and statistically experimental data.

Key words induction, low grazing angle, sea clutter reflectivity, radar frequency, sea condition, polarization

1. INTRODUCTION

In order to assess and research the performance of sea return, especially when ground-based radar against low-flying target, it is necessary to model reflectivity of sea clutter. Many researchers make research on modeling of sea clutter reflectivity. Commonly, constant-γ model is the most popular, and it is so simple that it is easy for use. In constant-γ model, Barton [1] gives an approximate equation about γ value. Song [2] makes an adjustment of the equation and the accuracy of γ is improved. The reflectivity model proposed by Morchin [3] is easy for use too, but its accuracy is not so good. Peng and Tang [4] adjust the model, and the adjusted model is useable, but still not so accurate. Petts [5] also presents a reflectivity model for sea clutter. The model [5] is simple and accurate, but its use somewhat is limited due to the variability of the parameters in the model. Thus, it is necessary to study the reflectivity model for radar sea clutter at low grazing angle, and present a relatively easy and accurate model.

Based on the character of radar sea clutter and the idea of the commonly used reflectivity models of sea clutter, the major influence factors on sea clutter reflectivity are analysed by using the method of probability statistics. Then the reflectivity model of low-angle radar-sea clutter is proposed. The proposed reflectivity model is validated by comparing simulated and statistically experimental data.

This paper is structured in the following way. The commonly used reflectivity models of sea clutter are briefly described in Section II. In Section III, the proposed sea clutter reflectivity model is shown, and the analysis of the model is made in theory. The simulated results are given in Section IV. The conclusions are given in Section V.

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2. COMMONLY USERD MODELS OF SEA REFLECTIVITY

2.1 Adjusted Barton Model [2]

Constant-γ reflectivity model for sea clutter is

$$\sigma_0 = \gamma \sin\theta$$

where γ is the parameter describing reflectivity, θ is grazing angle at sea surface. Constant-γ reflectivity model for sea clutter is set up by the assumption that sea clutter is even. In such case, sea clutter reflectivity is usually the function of grazing angle. Barton [1] gives a proximate equation for γ

$$10\lg\gamma = 6K_B - 10\lg\lambda - 64$$

where λ is radar wavelength, and is in meters, K_B is the Beaufort wind scale. So we can obtain

$$\sigma^0(\mathrm{dB}) = 6K_B - 10\lg\lambda + 10\lg\sin\theta - 64 \qquad (1)$$

Here, model of form (1) is named as Barton Model [1]. However, reflectivity data from (1) has distinct differences with experimental data, and don't include the influence of polarization type. Song [2] gives

$$\sigma^0 = \begin{cases} 6K_B - 10\lg\lambda + 10\lg\sin\theta - 10\lg(\theta_c/\theta) - 64, & \theta < \theta_c \\ 6K_B - 10\lg\lambda + 10\lg\sin\theta - 64, & \theta \geq \theta_c \end{cases} \qquad (2)$$

where θ_c, critical grazing angle, is related with sea condition [7-8]. Morchin [3] gives $\theta_c = \arcsin(\lambda/4\pi h_e)$

and $h_e \approx 0.025 + 0.046K_B^{1.72}$ that h_e shows sea surface roughness. Here, Model of form (2) is called Adjusted Barton Model [2].

2.2 Adjusted Morchin Model [4]

Peng and Tang [4] adjust sea clutter reflectivity model presented by Morchin [3].

$$\sigma_0 = \frac{4\times10^{-7}\cdot10^{0.6(K_B+1)}\sigma_c \sin\theta}{\lambda} + \cot^2\beta \exp\left[-\frac{\tan^2(\pi/2-\theta)}{\tan^2\beta}\right] \quad (3)$$

where $\beta = 2.44(K_B+1)^{1.08}/57.29$; $\sigma_c = (\theta/\theta_c)^k$ if $\theta < \theta_c$ and $\sigma_c = 1$ if $\theta \geq \theta_c$; parameter $k \in [1,4]$, and it is advised to 1.9. Here, model of form (3) is called Adjusted Morchin Model [4].

2.3 Petts Model [5]

Petts [5] presents sea clutter reflectivity model. And it is named as Petts Model [5] as follows.

$$\sigma^0(\text{dB}) = I + (3.376\Delta\lg(f/0.3132))$$

where radar frequency f is in GHz; I and Δ are parameters related with grazing angle, polarization and sea condition. Here, model of form [5] is named as Petts Model [5].

3. MODELING REFLECTIVITY

3.1 HH Model Presentation

According to [8,9], assume sea clutter reflectivity has relation with radar frequency, grazing angle, sea condition and polarization type. As a result, we get the sea clutter reflectivity model as follows.

$$\sigma^0 = T(f,\theta,K_B,p) \quad (4)$$

where $f \in X$, $X = [0.03,\ 12.5]$; $\theta \in Y$, $Y = [0, 0.174]$; $K_B \in M$, $M = \{0,1,2,3,4,5\}$; p is polarization type, and $p \in P$, $P = \{$horizontal polarization, vertical polarization$\}$; T is functional defined in X, Y, M and P. HH polarization is considered here, so (4) reduces to

$$\sigma^0 = T(f,\theta,K_B) \quad (5)$$

Among the commonly used reflectivity of sea clutter, Petts Model [5] is the most accurate, but it is limited to use for the great variation of the parameters in the model. Other models are easy to use, but they are not so accurate. Considering applicability and veracity of model , and for analyzing (5), the relation between Adjusted Barton Model [2] and Adjusted Morchin Model [4] is thought over.

The segment in Adjusted Morchin Model [4] is considered.

$$\cot^2\beta\exp\left(-\tan^2(\pi/2-\theta)/\tan^2\beta\right) = \cot^2\beta\cdot\exp(-\cot^2\theta\cdot\cot^2\beta) \quad (6)$$

In (8), let $x = \cot^2\theta$ and $y = \cot^2\beta$, we have $x \in [32.164,\ +\infty)$ and $y \in [10.82,\ 549.83]$ for $\theta \in Y$, $\beta = 0.0426(K_B+1)^{1.08}$ and $K_B \in M$. Let $A = [32.164, +\infty)$ and $B = [10.82, 549.83]$, we have

$$g(x,y) = y\cdot\exp(-x\cdot y) \quad (7)$$

where g is the functional defined in A and B. Let $C = \{z : y\cdot\exp(-x\cdot y),\ x \in A, y \in B\}$, and then $\sup C = (2.36\times10^{-150})$, $\sup C \in C$. So that $\max C$ is equal to $(2.36e-150)$, and (3) reduces to

$$\sigma^0 = (4\times10^{-7}\cdot10^{0.6(K_B+1)}\sigma_c^0\sin\theta)/\lambda \quad (8)$$

If (8) shown in decibel (dB), we obtain

$$\sigma^0 = 6K_B - 10\lg\lambda + 10\lg\sin\theta + 10\lg\sigma_c^0 - 58 \quad (9)$$

Now that we know (9) is the approximate of Adjusted Morchin Model [4] in low grazing angle. Comparing (9) and (3), it is found that Adjusted Morchin Model [4] and Adjusted Barton Model [2] have certain common relations, and the relation is shown that the two models are both based on Barton Model [1]. Furthermore, for Barton Model [2] is simple, and it accords with fact reflectivity data well when the grazing angle is between 0.0524 and 1.0472, the reflectivity of sea clutter is also based on Barton Model [1]. So we get

$$T(f,\theta,K_B) = 6K_B - 10\lg\lambda + 10\lg\sin\theta + a \quad (10)$$

where a is the adjusted value of sea clutter reflectivity. Considering the relation between wavelength λ and frequency f, this form can be transformed to

$$T(f,\theta,K_B) = 6K_B + 10\lg f + 10\lg\sin\theta + (a - 10\lg 0.3) \quad (11)$$

Equation (11) considers the total influence by every factor that affects sea clutter reflectivity. But, there have mutual effects among these influence factors [7,8]. Using modeling idea[5], the above expressions result in

$$T(f,\theta,K_B) \approx 6K_B^b + 10c\lg(df) + 10\lg\sin\theta + a - 5 \quad (12)$$

where b, c and d are the adjusted parameters, $0 < b \leq 1$, and $0 < d \leq 1$. Equation (12) can quantitatively reflect the total influence of various factors on sea clutter reflectivity by adjusting parameters a, b, c and d. In addition, the constant e(e>0) is introduced into (12) to more accurately simulate experimental reflectivity data and prevent the dB value of reflectivity from negative infinity when the grazing angle approaches to zero. Thus

$$T(f,\theta,K_B) = 6K_B^b + 10c\lg(df) + 10\lg\sin(\theta+e) + a - 5 \quad (13)$$

Define $x = (f,\theta,K_B)$ and $h = (h_1,h_2,h_3)$. In such case, $\forall f, h_1 \in X$, $\theta, h_2 \in Y$ and $K_B, h_3 \in M$, we have

$$T(x+h)-T(x)=\frac{10\cdot c}{\ln 10}\ln\frac{f+h_1}{f}+\frac{10}{\ln 10}\cdot \ln\frac{\sin(\theta+e+h_2)}{\sin(\theta+e)}+6((K_B+h_3)^b-K_B^b))$$

We can now write that

$$DT(x,h)=\left[\frac{10\cdot c}{\ln 10}\cdot\frac{1}{f}+\frac{10}{\ln 10}\cdot\cot(\theta+e)+6K_B^{b-1}\right]h$$

Thus

$$dT(x)=\nabla T(x)=(\frac{10c}{\ln 10}\frac{1}{f},\frac{10}{\ln 10}\cot(\theta+e),6K_B^{b-1}) \quad (14)$$

The above expressions result in

$$\begin{cases}\partial T(f,\theta,K_B)/\partial f>0\\ \partial T(f,\theta,K_B)/\partial\theta>0\\ \partial T(f,\theta,K_B)/\partial K_B>0\end{cases} \quad (15)$$

Consequently, sea clutter reflectivity increases with the increment of radar frequency, with the increment of the grazing angle, as well as the Beaufort wind scale. These are accordance with literatures [7-9].

From (13) and (14), by statistical data [9] and based on the method of probability statistics, we have

$$\begin{cases}a=-53.77, & b=0.88, & c=1.9\\ d=1.47, & e=7e-4\end{cases} \quad (16)$$

According to (5), (14) and (16), reflectivity model of sea clutter in HH polarization can be obtained as

$$\sigma^0=6K_B^{0.88}+19\lg(f/0.68)+15\lg\sin(\theta+(7e-4))-59 \quad (17)$$

3.2 VV Model Presentation

When the grazing angle is very small, sea clutter return has a lot of differences by the different polarization type [7-9]. Thus, reflectivity of sea clutter in VV is obtained as follows.

$$\sigma^0=-59+6K_B^{0.88}+19\lg(f/0.68)+15\lg\sin(\theta+(7e-4))+\Delta\sigma^0(P) \quad (18)$$

The difference is $\Delta\sigma^0(P)$ between (18) and (17). And $\Delta\sigma^0(P)$ reflects the difference between sea clutter reflectivity in HH polarization and sea clutter reflectivity in VV polarization state. The difference can be described by radar frequency, grazing angle and Beaufort wind scale. So that we have

$$\Delta\sigma^0(P)=T_1(f,\theta,K_B) \quad (19)$$

where T_1 is functional defined in set X, Y and M.

The main differences of sea clutter reflectivity between HH and VV are shown that the differences are obvious when radar frequency is small and the Beaufort wind scale is small; radar frequency is small and the grazing angle are relatively great [5-9]. Using the ideal of Petts Model [5], (19) may be analyzed as

$$T_1(f,\theta,K_B)=\frac{a_1+a_2K_B^{c_1}}{a_3+\theta}+\frac{(b_1+\theta)^{d_1}}{(b_2+f)^{e_1}} \quad (20)$$

where $a_1, a_2, a_3, b_1, b_2, c_1, d_1$ and e_1 are parameters that reflect the influence on sea clutter reflectivity by radar frequency, grazing angle and Beaufort wind scale in VV. $a_1>0, a_2<0, a_3>1$, $1>b_1>0$, $b_2\ge 1$, $c_1>0$, $d_1>0$, and $e_1>0$. Considering $\forall f,h_1\in X$, $\theta,h_2\in Y$, K_B and $h_3\in M$, we let $x=(f,\theta,K_B)$ and $h=(h_1,h_2,h_3)$. For $X\subset R$, $Y\subset R$, and $M\subset R$, thus we can get

$$T_1(x+h)-T_1(x)=\frac{a_1+a_2(K_B+h_3)^{c_1}}{a_3+\theta+h_2}+\frac{(b_1+\theta+h_2)^{d_1}}{(b_2+f+h_1)^{e_1}}-\frac{a_1+a_2K_B^{c_1}}{a_3+\theta}-\frac{(b_1+\theta)^{d_1}}{(b_2+f)^{e_1}}$$

We can write that

$$DT_1(x,h)=\left(\frac{-e_1(b_1+\theta)^{d_1}}{(b_2+f)^{e_1+1}},\frac{d_1(b_1+\theta)^{d_1-1}}{(b_2+f)^{e_1}}-\frac{a_1+a_2K_B^{c_1}}{(a_3+\theta)^2},\frac{a_2c_1K_B^{c_1-1}}{a_3+\theta}\right)h$$

Thus

$$dT_1(x)=\nabla T_1(x)=\left(\frac{-e_1(b_1+\theta)^{d_1}}{(b_2+f)^{e_1+1}},\frac{d_1(b_1+\theta)^{d_1-1}}{(b_2+f)^{e_1}}-\frac{a_1+a_2K_B^{c_1}}{(a_3+\theta)^2},\frac{a_2c_1K_B^{c_1-1}}{a_3+\theta}\right) \quad (21)$$

The above expressions result in

$$\begin{cases}\partial T_1(f,\theta,K_B)/\partial f<0\\ \partial T_1^2(f,\theta,K_B)/\partial f\partial\theta=\dfrac{-e_1d_1(b_1+\theta)^{d_1-1}}{(b_2+f)^{e_1+1}}<0\\ \partial T_1(f,\theta,K_B)/\partial K_B<0\end{cases} \quad (22)$$

As a result, according to from (20) to (22), we get that in various polarization state, sea clutter reflectivity decreases with the increment of radar frequency, which accords with the statistical measuring data [9]; under relatively small radar frequency and great grazing angle, sea clutter reflectivity varies much with the variation of polarization type, which accords with literatures [7-9]; when the Beaufort wind scale is relatively small, sea clutter reflectivity in HH polarization state is less than that in VV polarization state, the speed that the increment sea clutter reflectivity in HH polarization state increase with the increment of the Beaufort wind scale is more rapid than that in VV polarization state, and so in the state of rough sea surface there has few difference of reflectivity between HH and VV, which accords with literature [8].

From (20) and (21), by statistical data [9], and based on the method of probability and statistics, we get

$$\begin{cases} a_1 = 100, & a_2 = -30, & a_3 = 10, & b_1 = 0.01 \\ b_2 = 1, & c_1 = 0.74, & d_1 = 1.1, & e_1 = 0.5 \end{cases} \quad (23)$$

According to from (18) to (20) and (23), reflectivity model for sea clutter in VV polarization is obtained

$$\sigma^0 = 19\lg(f/0.68) + 15\lg\sin(\theta + 7\times10^{-4}) + 6K_B^{0.88}\frac{(10-3K_B^{0.74})}{(1+0.1\theta)} + \frac{(0.01+\theta)^{1.1}}{(1+f)^{0.5}} - 59 \quad (24)$$

4. SIMULATION REFLECTIVITY

In order to validate the applicability and veracity of our reflectivity model of sea clutter in low grazing angle, experimental data [9] are used to analyze. The analyzed results are shown in Table 1 and 2. In Table 1 and 2, * and ‡ denote data with about negative five dB error and negative eight dB error [9] respectively.

Table 1: The average values of sea clutter reflectivity in HH polarization

	f_L, f_S, f_C, f_X / GHz			
K_B	1.25	3.0	5.6	9.3
	0.1° grazing angle			
0	—	-90*/-86/-93/-96	-87*/-81/-90/-95	—
1	—	-80/-80/-92/-40	-75/-75/-89/-97	-71*/ -71/-87/-95
2	-90*/-82/-93/-46	-75*/-75/-90/-42	-67*/-69/-87/-99	-59*/-65/-85/-97
3	-82*/-71/-90/-45	-68*/-70/-86/-41	-69*/-65/-84/-98	-53*/-61/-82/-96
4	-74*/-77/-86/-43	-63*/-65/-83/-99	-60/-60/-80/-96	-48/ -56/-78/-94
5	-70‡/-68/-82/-41	-63*/-61/-79/-98	-58*/-56/-76/-94	-42*/ -52/-74/ -92
	0.3° grazing angle			
0	—	-83*/-80/-84/-84	-79/-75/-81/-81	-74*/-71/-79/ -79
1	—	-74/-74/-82/-86	-68/-69/-79/-84	-66*/-65/-77/ -81
2	—	-66*/-69/-80/-88	-60/-64/-77/-85	-56*/-59/-75/ -83
3	-68*/-71/-81/-91	-60*/-64/-77/-87	-50/-59/-74/-84	-46/-55/-72/-82
4	—	-55*/-60/-73/-85	—	-42/-50/-68/ -80
5	-64*/-63/-73/-87	-52*/-55/-68/-83	-44*/50/-66/-80	-39/-46/-64/-78
	1° grazing angle			
0	-80*/-80/-77/-72	-75*/-73/-73/-69	-70*/-68/-70/-66	-60*/-63/-68/-64
1	-73*/-74/-75/-75	-66/-67/-72/-71	-56/-61/-69/-68	-51/-57/-67/-66
2	-65*/-69/-73/-77	-55/-62/-70/-73	-48/-56/-67/-70	-46/-52/-65/-68
3	-60*/-64/-70/-76	-48/-57/-66/-72	-43/-52/-64/-69	-40/-47/-62/-67
4	-56*/-59/-66/-74	-45/-55/-63/-70	-39/-47/-60/-67	-36/-43/-58/-65
5	-50*/-55/-62/-72	-42/-48/-59/-68	-36/-43/-56/-65	-34/-38/-54/-63
	3° grazing angle			
0	-72*/-73/-71/-65	-68*/-66/-67/-61	-63*/-61/-64/-58	>-58*/-57/-62/-56
1	-63*/-67/-66/-61	-59/-60/-62/-57	-54/-55/-59/-55	-50/-50/-57/ -52
2	-59/-62/-64/-63	-53/-55/-60/-59	-48/-49/-57/-56	-43/-46/-55/-54
3	-55*/-57/-61/-62	-46/-50/-57/-58	-42/-45/-54/-55	-39/-41/-52/ -53
4	-48*/-52/-57/-60	-41/-45/-53/-56	-38/-40/-53/-54	-35/-36/-48/ -51
5	-46/-48/-53/-58	-40/-41/-49/-54	-36/-36/-46/-51	-33/-32/-44/-49
	10° grazing angle			
0	-60*/-65/-65/-59	—	—	>-56*/-49/-57/ -51
1	-56*/-59/-59/-53	—	-53/-47/-53/-47	- 51/-43/-51/ -45
2	-53/-54/-53/-48	-51/-47/-50/-44	-48/-42/-47/-41	-43/-38/-45/-39
3	-58/-50/-50/-47	-46/-42/-44/-43	-40/-37/-44/-40	-37/-33/-42/-48
4	-45/-45/-46/-45	-40/-38/-43/-41	-36/-33/-40/-38	-34/-29/-38/-36
5	-43/-41/-42/-43	-38/-34/-39/-39	-36/-28/-36/-36	-30/-24/-34/-34

Note: Literature [9]/ γ - p Model/Adjusted Barton Model [2]/Adjusted Morchin Model [4]

5. CONCLUTIONS

In this paper, based on the commonly used radar reflectivity models of sea clutter, sea clutter reflectivity $\gamma - p$ model in the low grazing angle is proposed by considering radar frequency, grazing angle, sea condition, and polarization.

Simulation results are shown that as follows:

(1) The calculated reflectivity data of sea clutter obtained with $\gamma - p$ model compares favorably with statistically experimental data obtained under conditions similar to those modeled.

(2) $\gamma - p$ model is more easy to use than other commonly used models.

(3) $\gamma - p$ model reflects the influence on reflectivity by polarization type, and most of all, the model is easy.

Table2: The average values of sea clutter reflectivity in VV polarization

K_B	f_L, f_S, f_C, f_X / GHz 1.25	3.0	5.6	9.3
	0.1° grazing angle			
0	—	—	—	—
1	—	-80*/-73/-92/-40	-72*/-68/-89/-97	-65*/-64/-87/-95
2	-87*/-77/-93/-46	-75*/-70/-90/-42	-67/-65/-87/-99	-56/-60/-85/-97
3	-82*/-74/-90/-45	-75*/-67/-86/-41	-60*/-62/-84/-98	-51/-57/-82/ -96
4	-78*/-71/-86/-43	-67*/-64/-83/-99	-58*/-59/-80/-96	-48/-54/-78/ -94
5	-70‡/-68/-82/-41	-63*/-61/-79/-98	-55*/-56/-76/-94	-44/-51/-74/-92
	0.3° grazing angle			
0	-83‡/-78/-87/-88	—	—	—
1	-78*/-75/-86/-90	-64*/-77/-82/-86	-60/-62/-79/-84	-58/-57/-77/-81
2	-73*/-72/-84/-92	-62*/-64/-80/-88	-55/-59/-77/-85	-52/-55/-75/-83
3	-68*/-71/-81/-91	-60*/-64/-77/-87	-50/-59/-74/-84	-46/-55/-72/-82
4	-65/-65/-77/ -89	-55*/-60/-73/ -85	—	-42/-50/-68/-80
5	-64*/-63/-73/-87	-52*/-55/-68/ -83	—	-39/-46/-64/-78
	1° grazing angle			
0	-68*/-70/-77/-72	—	—	-60*/-54/-68/-64
1	-65*/-67/-75/-75	-56/-63/-72/-71	-53/-58/-69/-68	-50/-50/-67/-66
2	-58*/-64/-73/-77	-53/-60/-70/-73	-47/-55/-67/-70	-44/-57/-65/-68
3	-54*/-60/-70/-76	-48/-56/-66/-72	-43/-52/-64/-69	-39/-44/-62/-67
4	-45/-58/-66/-74	-42/-53/-63/-70	-39/-48/-60/-67	-37/-41/-58/-65
5	-43/-54/-62/-72	-38/-47/-59/-68	-35/-42/-56/-65	-33/-38/-54/-63
	3° grazing angle			
0	—	—	-60*/-52/-64/-58	>-56*/-48/-62/-56
1	-53*/-59/-66/-61	-52/-53/-62/-57	-49/-48/-59/-55	-45/-44/-57/ -52
2	-50/-56/-64/-63	-49/-49/-60/-59	-45/-45/-57/-56	-41/-41/-55/-54
3	-43*/-55/-61/-62	-43/-46/-57/-58	-40/-41/-54/-55	-38/-37/-52/ -53
4	-38/-49/-57/-60	-38/-42/-53/-56	-36/-38/-53/-54	-35/-34/-48/-51
5	-38/-46/-53/-58	-35/-39/-49/-54	-35/-35/-46/-51	-33/-31/-44/-49
	10° grazing angle			
0	-45*/-52/-65/-59	—	-44*/-43/-59/-53	>-47*/-40/-57/ -51
1	-39/-47/-59/-53	-40/-42/-56/-50	-41/-39/-53/-47	-42/-35/-51/-45
2	-37/-43/-53/-48	-38/-38/-50/-44	-39/-35/-47/-41	-36/-31/-45/-39
3	-34/-39/-50/-47	-34/-34/-44/-43	-34/-31/-44/-40	-32/-28/-42/-48
4	-31/-36/-46/-45	-31*/-31/-43/-41	-32/-27/-40/-38	-29/-24/-38/ -36
5	-30/-32/-42/-43	-28/-27/-39/-39	-28/-23/-36/-36	-25/-20/-34/-34

Note: Literature [9]/ γ - p Model/Adjusted Barton Model [2]/Adjusted Morchin Model [4]

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