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Longwall top coal fall index from an integrated numerical and statistical analysis

Dung Tien Le [1,*], Hai Hong Mai [2]

[1]Hanoi University of Mining and Geology, Hanoi, Vietnam
[2] Dongbac Corporation, Quang Ninh, Vietnam

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ABSTRACT

Assessment of top coal fall potential is of great importance for sustainable longwall caving mining. However, available assessment tools/indices for the fall are applicable to roof rock only, and their use for top coal (whose geological structures may be different) can be inappropriate. This paper presents a new index for top coal fall in longwall mining where the fall is controlled by the cantilever effect. The index is developed from an integrated numerical and statistical analysis using the database from Ha Lam coal mine in Vietnam. The numerical analysis reveals that the strength and stiffness of in-seam discrete fractures and coal's elastic modulus are inversely proportional to top coal fall. Meanwhile, the density of discrete fractures and seam depth are found to be directly proportional to the fall. A procedure for the development of assessment equation for top coal is established using single and multiple regressions and model transformation technique. A new assessment index for longwall top coal fall named Fall Index (FI) is proposed, taking coal elastic modulus, fracture density, fracture friction angle, fracture stiffness and seam depth as input parameters. The study also reveals that statistically seam depth has the most significant effect while fracture density and fracture strength show the least significant effect on top coal fall. At the same time, coal's elastic modulus and fracture stiffness play similar roles in the fall. The results from this paper assist engineers in better assessing top coal fall potential and subsequently better controlling longwall stability for various geological conditions in mine design.

1. Introduction

Longwall is the major underground mining method producing coal in many countries such as Australia, Europe, and Vietnam (Mohutsiwa and Musingwini, 2015). In terms of geotechnics, the stability of top coal (in Longwall Top Coal Caving) or roof rock (in Single Pass Longwall) portion between coal wall (coal face line) and face support plays an important role in the successful operation of a longwall caving method (Figure 1).

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*Corresponding author
E - mail: t.d.le@humg.edu.vn

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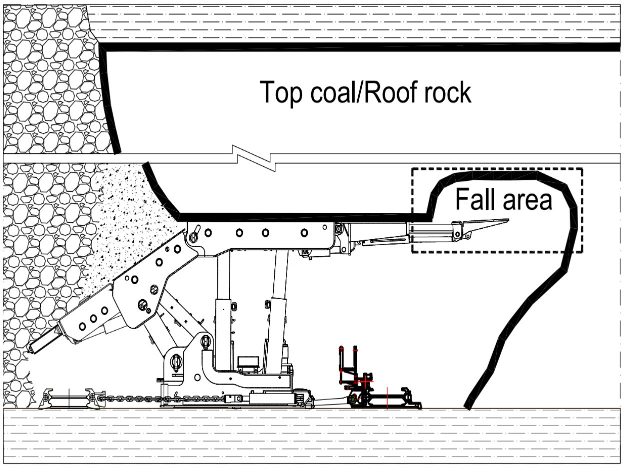

Figure 1. Conceptual model of top coal/roof rock fall in longwall mining (modified from Le et al., 2022).

Mining practices around the world show that top coal/roof rock may uncontrollably fall downwards which causes serious shearer/support damage, worker injury/fatality, and huge economic loss (Le et al., 2022). A geotechnical assessment of top coal/roof rock fall potential is therefore of importance for minimizing the above damage or loss, particularly at the early stage of a mining project.

The reliability and accuracy of a longwall top coal/roof rock fall assessment greatly depend on the understanding of fall mechanisms and the database used for assessment. As reviewed in detail in past studies (Le et al., 2022), the top coal/roof rock fall between coal wall and face support (roof cavity) is basically controlled by either top coal/immediate roof cantilever or massive roof weighting. Based on these mechanisms, several tools or indices were developed for the assessment or prediction of the fall. For example, from empirical and analytical analysis, Langosch et al. (2003) calculated an index of roof fall frequency. This index used the data of support resistance, vertical stress, fracture direction and tip-to-face distance collected from German longwalls. Similarly, Frith (2005) developed equations for calculating the potential of roof fall using panel width, extraction height, and massive strata thickness from Australia mining practice. Also from field monitoring of face support in Australia longwalls, Hoyer (2011) and Trueman and Hutchinson (2018) presented indices of roof cavity risk using leg pressure, load rate and yield cycles. Medhurst et al. (2014) used similar approach and incorporated Geophysical Strata Rating (GRS) to develop a chart for predicting roof cavity risk. Using a qualitative risk-analysis technique, Iannacchione et al. (2007) introduced a roof fall risk index based on characteristics and defects of roof conditions from US mining practice. Also using risk assessment method, Prusek et al. (2017) developed another roof fall risk index from various characteristics of roof strata, face support, panel geometry and fault orientation from Poland longwalls. Recently, Islavath et al. (2020) developed a numerical-based index for roof fall, but the simulation could not show explicit fall. Meanwhile, Małkowski and Juszyński (2021) performed a modern assessment of roof fall using an artificial neural network, but for copper mines rather than coal mines. In general, the above tools/indices are helpful for the assessment of longwall roof fall potential in various geotechnical conditions at different levels of details and cost. However, as the original database from practice for a tool/index development was limited and representative of a specific mining region, a new assessment tool/index applicable to wide range of geological conditions is recommended. More importantly, since many tools/indices are applicable to roof rock only, its use for top coal (whose geological structures may be different) can be inappropriate. Although some studies assessed top coal fall (i) separately from roof rock fall (Le et al., 2018, 2020, 2022) or (ii) as a consequence of face spall (Yao et al., 2017, Kong et al., 2019, Guo et al., 2019), a tool/index for top coal fall assessment remains unavailable and needs to be developed exclusively.

This paper presents a new index for assessment of top coal fall in longwall mining where the fall is controlled by the cantilever effect. The index is developed from an integrated numerical analysis (parametric study) and statistical analysis (multiple regression) using the database from Ha Lam coal mine, Vietnam. The index assists mining engineers in better assessment of top coal fall potential for various geological conditions at the preliminary stage of mine design.

2. Parametric study of geotechnical parameters

2.1. Numerical and parametric consideration

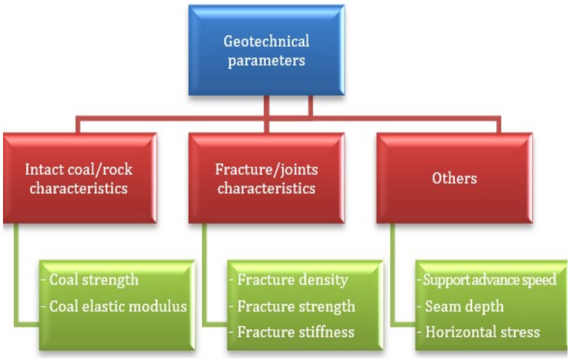

Figure 2. Geotechnical parameters affecting top coal fall.

The 2D discontinuum-based numerical code UDEC (Itasca Consulting Group, 2019) is used to develop longwall models for understanding key parameters controlling top coal fall. The code can well represent typical joints and discrete fractures in coal seam/rock strata and explicit coal/rock detachment in the fall. The geological and mining conditions from Ha Lam coal mine are used for development of a longwall model because the top coal fall is controlled by the cantilever effect. The model is then used for parametric study. The details of model development are described in (Le and Oh, 2022) and thus not presented in this paper. Considering the 2D nature of the code, computation time for each longwall mining simulation and effect of controlling parameters on top coal fall in the literature, the current paper focuses on the key geotechnical parameters, as can be classified into three groups of intact coal/rock characteristics, fracture/joint characteristics, and others (Figure 2). To quantify top coal fall, an index called top coal fall rate (%) is adopted from Le and Oh (2022). The rate is calculated by dividing the total fallen blocks from all face advances by the total of pre-mining top coal blocks. For the parametric study, a range of three to five values is assigned for each parameter to cover practical and possible values of parameters in the field.

2.2. Parametric study

Table 1. Input and result of parametric study.

Order	Coal cohesion strength (MPa)	Coal elastic modulus (GPa)	Fracture density (m/m^2)	Fracture friction angle (degree)	Fracture stiffness (GPa/m)	Support advance speed (timestep)	Seam depth (m)	Horizontal stress (MPa)	Top coal fall rate (%)
1	0.70	1.09	2.0	15	10	50	200	5.2	6.20
2	1.40	1.09	2.0	15	10	50	200	5.2	7.16
3	2.79	1.09	2.0	15	10	50	200	5.2	8.91
4	3.49	1.09	2.0	15	10	50	200	5.2	8.59
5	1.40	0.54	2.0	15	10	50	200	5.2	10.89
6	1.40	2.17	2.0	15	10	50	200	5.2	5.65
7	1.40	2.72	2.0	15	10	50	200	5.2	5.01
8	1.40	1.09	1.0	15	10	50	200	5.2	4.48
9	1.40	1.09	1.5	15	10	50	200	5.2	4.90
10	1.40	1.09	3.0	15	10	50	200	5.2	7.98
11	1.40	1.09	2.0	10	10	50	200	5.2	8.11
12	1.40	1.09	2.0	25	10	50	200	5.2	5.96
13	1.40	1.09	2.0	35	10	50	200	5.2	4.45
14	1.40	1.09	2.0	15	1	50	200	5.2	12.09
15	1.40	1.09	2.0	15	30	50	200	5.2	6.36
16	1.40	1.09	2.0	15	50	50	200	5.2	6.12
17	1.40	1.09	2.0	15	10	100	200	5.2	7.71
18	1.40	1.09	2.0	15	10	400	200	5.2	8.19
19	1.40	1.09	2.0	15	10	50	100	5.2	5.25
20	1.40	1.09	2.0	15	10	50	300	5.2	8.91
21	1.40	1.09	2.0	15	10	50	400	5.2	10.02
22	1.40	1.09	2.0	15	10	50	500	5.2	12.48
23	1.40	1.09	2.0	15	10	50	200	2.6	6.20
24	1.40	1.09	2.0	15	10	50	200	10.4	8.11

The input and result of the parametric study are presented in Table 1. The table also includes the effect of fracture characteristics which were investigated by Le and Oh (2022). In this paper, the variation in coal strength and fracture strength is represented through the variation in intact block cohesion and fracture friction angle, respectively. The results in Table 1 show that as the coal cohesion strength increases from 0.7 to 3.49 MPa, the top coal fall rate fluctuates in the range of 6.20÷8.91%. This result which is not expected as a stronger coal seam should increase its stability. One likely explanation for the result is that as top coal falls explicitly in the simulation, its fall rate is controlled by not only intact coal strength but also fracture strength (boundaries between blocks). This can be clearly seen from the results of fracture friction angle's variation. As the angle increases from 10 to 35 degrees, the fall rate clearly decreases from 8.11 to 4.45%.

The results from coal elastic modulus and fracture stiffness show consistency. That is, as the modulus and stiffness increase from 0.54 and 1 GPa to 2.72 and 50 GPa, respectively, the fall rate decreases from 10.89 and 12.09% to 5.01 and 6.12%, respectively. The results can be explained by a field observation that stiffer rock/fracture suffers more stress concentration (Calleja, 2008). This consequently causes more coal/fracture failure and fall. The role of stress concentration in top coal fall is clearly seen from seam depth and horizontal stress analyses. As the seam depth (or vertical stress) increases, the fall rate clearly increases as expected. An increase in horizontal stress from 2.6 to 10.4 MPa increases the fall rate from 6.20 to 8.11%. It should be noted that as the horizontal stress is 3D in nature, the effect of this parameter on top coal fall should be further studied using a 3D numerical code.

For the advance of face support, it is proved that before setting support at new coal wall, an amount of roof convergence occurs that needs great support capacity for resistance (Mitchell, 2009). This explains why in practice, after each face cut, a support is advanced to new coal wall after a short period of time rather than immediately. As there is no guideline for modelling this period in UDEC, the time for support advance is represented through the mechanical timestep in UDEC. The result shows that as the time for face advance increases, top coal rate also increases. This result agrees with practical mining. Note that the timestep is a function of the simulation setting, and it should not be used as an input parameter for geotechnical assessment.

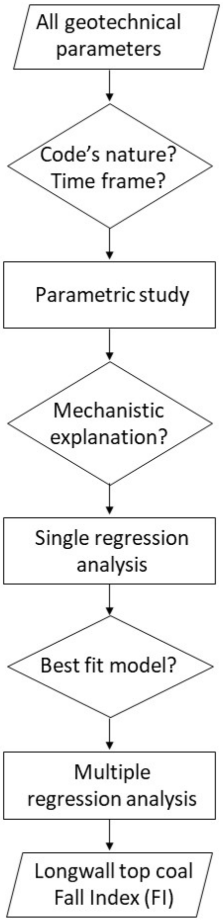

Figure 3. Procedure for development of longwall top coal fall index.

3. Top coal fall index

3.1. Statistical analysis

A procedure for the development of longwall top coal fall index (FI) is shown in Figure 3. In the first step, all geotechnical parameters affecting top coal fall are theoretically analyzed (see Section 1). Eight parameters (i.e., coal cohesion, coal elastic modulus, fracture density, fracture friction angle, fracture stiffness, timestep, seam depth and horizontal stress) that fulfill the requirements of code's nature and computation time are entered into the second step. The second step is a parametric study (see Section 2). Five parameters from the study (i.e., coal elastic modulus, fracture density, fracture friction angle, fracture stiffness and seam depth), whose effect on top coal fall is mechanistically explainable, are used in the next step.

In the third step, a single regression analysis is conducted to estimate the regression model with greatest fit for a single parameter. The finding indicates a linear relationship between fracture density, fracture friction angle, and seam depth with the top coal fall rate. The correlation has a high coefficient of determination (R square) and is consistent with field observations. At the same time, the optimal model for coal elastic modulus and fracture stiffness has a power relationship with the fall rate. The relationship well represents the role of coal elastic modulus/fracture stiffness in top coal fall, which is clearly manifested at practical values rather than high values. All the relationships are plotted in Figure 4.

In the fourth step, a multiple regression analysis is performed to form a regression equation (f) for top coal fall assessment. The regression equation (or assessment equation) is given as:

$$f = \alpha + \beta_1 E^a + \beta_2 FD + \beta_3 FF + \beta_4 FS^b + \beta_5 D \tag{1}$$

Where: E is elastic modulus of coal (GPa); FD is fracture density (m/m^2); FF is fracture friction angle (degree); FS is fracture stiffness (GPa/m); D is seam depth (m); α is intercept; β_{1-5} are

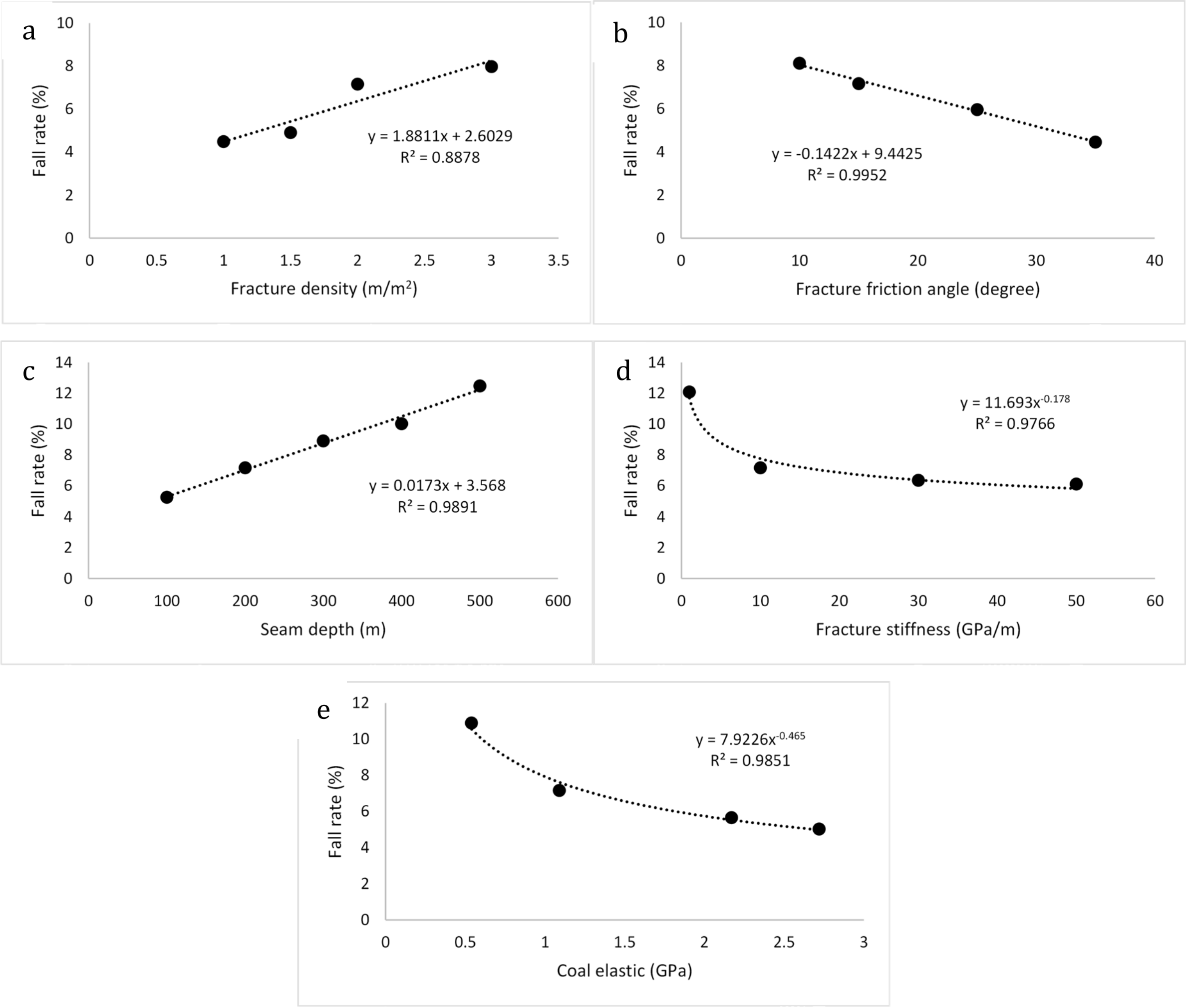

Figure 4. Relationship between five parameters and top coal fall rate.

coefficients of independent variables; a and b are power.

Since the single regression analysis shows three linear relationships and two nonlinear (power) relationships, either multiple linear or nonlinear regression model can be considered as best fit model. A multiple linear regression model is finally selected for two reasons: (i) simple use in practical assessment and (ii) limited input parameters. The power model in f is accordingly transformed into linear model by assuming specific value of power (Ryan, 2008). The specific value is adopted from single regression analysis in Figure 4. The regression equation is rewritten as:

$$\begin{aligned} f = \alpha + \beta_1 E' + \beta_2 FD + \beta_3 FF \\ + \beta_4 FS' + \beta_5 D \end{aligned} \tag{2}$$

Where: $E' = E^{-0.465}$ and $FS' = FS^{-0.178}$. The data for multiple linear regression is listed in Table 2. The coefficients are then calculated using the following matrix algebra:

$$\begin{bmatrix} f_1 \\ f_2 \\ \dots \\ f_{17} \end{bmatrix} = \begin{bmatrix} \alpha & \beta_1 E'_1 & \beta_2 FD_1 & \beta_3 FF_1 & \beta_4 FS'_1 & \beta_5 D_1 \\ \alpha & \beta_1 E'_2 & \beta_2 FD_2 & \beta_3 FF_2 & \beta_4 FS'_2 & \beta_5 D_2 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \alpha & \beta_1 E'_{17} & \beta_2 FD_{17} & \beta_3 FF_{17} & \beta_4 FS'_{17} & \beta_5 D_{17} \end{bmatrix} \tag{3}$$

The results of multiple linear regression are shown in Tables 3÷5. Table 3 shows that 93.69% of the total variance in top coal fall can be explained by the variance of the five parameters. The small difference between R square and Adjusted R square may denote that the set of five parameters is statistically suitable for development of regression model. Each independent parameter affects top coal fall with reasonable correlation. Table 4 indicates the validity of regression model because the Significance F is nearly zero with a Level of

Table 2. Data for multiple linear regression.

Order	Transformed coal elastic modulus (GPa)	Fracture density (m/m^2)	Fracture friction angle (degree)	Transformed fracture stiffness (GPa/m)	Seam depth (m)	Top coal fall rate (%)
1	0.96072	2	15	0.663743	200	7.16
2	1.331794	2	15	0.663743	200	10.89
3	0.697503	2	15	0.663743	200	5.65
4	0.627951	2	15	0.663743	200	5.01
5	0.96072	1	15	0.663743	200	4.48
6	0.96072	1.5	15	0.663743	200	4.9
7	0.96072	3	15	0.663743	200	7.98
8	0.96072	2	10	0.663743	200	8.11
9	0.96072	2	25	0.663743	200	5.96
10	0.96072	2	35	0.663743	200	4.45
11	0.96072	2	15	1	200	12.09
12	0.96072	2	15	0.545849	200	6.36
13	0.96072	2	15	0.498406	200	6.12
14	0.96072	2	15	0.663743	100	5.25
15	0.96072	2	15	0.663743	300	8.91
16	0.96072	2	15	0.663743	400	10.02
17	0.96072	2	15	0.663743	500	12.48

Table 3. Regression statistics.

Parameter	Value
Multiple R	0.967943282
R square	0.936914197
Adjusted R square	0.908238832
Standard Error	0.80036098
Observations	17

Table 4. Analysis of variance (ANOVA).

	Degree of freedom	Sum Squares	Mean Squares	F	Significance F
Regression	5	104.6484218	20.92968436	32.67313926	3.04421E-06
Residual	11	7.046354687	0.640577699		
Total	16	111.6947765			

Table 5. Coefficient of variables.

	Coefficients	Standard Error	t Stat	p-value	Lower 95%	Upper 95%
Intercept	-14.0088	2.318598	-6.04193	8.41E-05	-19.112	-8.9056
Coal elastic modulus	7.918964	1.428068	5.545227	0.000174	4.775806	11.06212
Fracture density	2.076501	0.535709	3.87617	0.00258	0.897412	3.255589
Fracture friction angle	-0.13915	0.0364	-3.82289	0.002829	-0.21927	-0.05904
Fracture stiffness	12.44001	2.038838	6.101523	7.72E-05	7.952563	16.92746
Seam depth	0.016612	0.002187	7.594993	1.07E-05	0.011798	0.021427

Significance at 0.05. Table 5 shows the validity of independent parameters. This is because all parameters have their p-value less than 0.05, and they are concluded to be statistically significant at a 0.05 Level of Significance.

3.2. Top coal fall index

The regression equation in Section 3.1 (Equation 1) can serve as an assessment index for top coal fall and is named Fall Index (FI). Using the coefficients from Table 5, the Fall Index is written as follows:

$$FI = -14 + 7.918E^{-0.465} + 2.076 - 0.139F + 12.44FS^{-0.178} + 0.016D \quad (4)$$

In order to compare the statistical significance of different parameters on top coal fall, the Standardised Multiple Regression (Kutner et al., 2005) is used. The result shows that statistically, seam depth has the most significant effect on top coal fall (28.27%). In contrast, both fracture density and fracture strength show the least significance effect on the fall (14.36 and 14.22%). At the same time, coal elastic modulus and fracture stiffness play similar roles in the fall (20.55 and 22.59%).

4. Conclusions

This paper presents a new index for assessment of top coal fall in longwall mining from an integrated numerical and statistical analysis. The numerical analysis reveals that the strength and stiffness of in-seam discrete fractures and coal elastic modulus are inversely proportional to top coal fall. Meanwhile, the density of discrete fractures and the seam depth are found to be directly proportional to the fall. A procedure for the development of an assessment equation for top coal fall is established using single and multiple regressions and model transformation technique. A new assessment index for longwall top coal fall named Fall Index (FI) is proposed, taking coal elastic modulus, fracture density, fracture friction angle, fracture stiffness and seam depth as input parameters. The study also reveals that seam depth statistically has the most significant effect while fracture density and fracture strength show the least significant effect on top coal fall. At the same time, coal elastic modulus and fracture stiffness play similar roles in the fall. Due to the limitation of the numerical code, effect of support characteristics should be further studied in future research. The results from this paper assist mining engineers in better assessing top coal fall potential and subsequently better controlling longwall stability for various geological conditions at preliminary stage of mine design.

Contribution of authors

Dung Tien Le - prepared and edits of the manuscript; Hai Hong Mai - contributes to edit the manuscrip.

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