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Multi-factor dynamic analysis of the deformation of a coal bunker in a coal preparation plant

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Abstract To assess the deformation of a coal bunker and propose effective preventative measures for such, a real-time monitoring system was designed. Moreover, methods were proposed for monitoring the coal-bunker inclination, settlement, groundwater level, temperature, and material level. By using a vector autoregression model and time-series data for the coal-bunker deformation, a long-term equilibrium relationship was derived between the coal-bunker inclination and settlement and their influencing factors. The dynamic effects of each factor on the coal-bunker inclination and settlement and how the contribution of each factor changes were revealed by using an impulse response function and variance decomposition. The results show that the coal-bunker inclination and settlement vary hysteretically. Groundwater level has constant and small negative effects on the coal-bunker inclination and settlement, and temperature has continuous and significant negative effects; however, material level has constant positive effects on the coal-bunker settlement and slightly influences the eastward inclination while significantly influencing the northward inclination of the coal bunker. Also, unbalanced loading has little influence on the coal-bunker settlement and eastward inclination but significant influence on its northward inclination. Therefore, monitoring of the coal-bunker deformation should be strengthened in summer, and sudden changes in material level and unbalanced loading should be avoided during production. Moreover, the coal-bunker inclination can be adjusted by unbalanced loading in the reverse direction.

Keywords Coal bunker · Settlement · Influence factor · Dynamic analysis

1 Introduction

Coal bunkers (CBs) help to regulate and buffer the production system of a coal preparation plant to ensure stable production. A CB is affected by many factors, such as groundwater level, temperature, material level, and unbalanced loading, all of which act to deform it. If CBs are deformed too much or too rapidly, then they crack, incline, and settle, thereby influencing their normal use and even threatening production safety, and therefore resulting in significant economic losses (Liu et al. 2019; Lv et al. 2009; Wang et al. 2019).

To ensure the operational safety of CBs, scholars have studied the flow states and accumulation of coal in CBs and how they influence CB deformation (Li et al. 2014a, b; Lu et al. 2012; Song and Oloya 2014). By using a three-dimensional particle flow code (PFC3D), Wang and Xu (2014) built a discrete-element model of a CB and bulk coal and analyzed factors influencing the flow state and mechanical behavior of bulk coal therein. Zhao (2014) investigated the distribution and accumulation of coal layers in a CB with one or more feed ports. Using finite-element analysis software, Wang et al. (2016) simulated the stress and deformation characteristics of the soil and support structures in the foundation pits of CBs under

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abnormal conditions. Zhao et al. (2012) used independent component analysis to analyze CB settlement data, and the results showed that of material level, temperature, and unbalanced loading, material level influences CB settlement the most. Furthermore, Li et al. (2014a, b) divided CB settlement into two stages, namely static settlement and dynamic settlement; the former decreases gradually with time, while the latter changes with loading, and considered that CB safety is influenced mainly by factors such as unbalanced loading and material level. Given the potential for large CB settlement, Wei (2011) presented the reasons for CB foundation settlement and overall inclination by analyzing how CB foundation settlement changed during construction, preliminary coal storage, and after emptying.

Some scholars have also studied methods for predicting and monitoring CB deformation (Liu and Xu 2014; Lv 2017; Wang et al. 2015). Lin et al. (2019) developed a method for predicting CB settlement based on a fuzzy clustering loop iteration model, and Li et al. (2004) analyzed using a high-precision electronic level to observe CB settlement. To realize real-time monitoring of the temperatures in CBs, Cao et al. (2017) designed a CB temperature monitoring system based on Web Access. Aimed at the usually poor site environment of CBs, Jiang (2016) designed a set of real-time monitoring devices to detect CB coal level based on counterweight principles.

The aforementioned studies revealed the settlement and deformation law of CBs and analyzed how factors such as material level, temperature, and unbalanced loading influence CB settlement and deformation. Moreover, methods were designed to monitor CB settlement and coal level. However, the aforementioned studies did not quantify how each factor influences CB settlement and deformation, nor did they reveal (i) the strength of each factor in influencing CB deformation in different periods and (ii) how the contributions of each influencing factor change dynamically.

To overcome the above limitations, a vector autoregression (VAR) model is introduced herein to quantify the dynamic effects of key factors on CB settlement and deformation. First, a monitoring system is developed in combination with engineering examples. Second, based on monitoring data and the VAR model, lag terms of CB inclination and settlement as well as their influencing factors are used to constitute a set of equations, thereby improving the effectiveness of the estimated results. Finally, by using tools such as an impulse response function and variance decomposition, the dynamic effects of factors such as groundwater level, temperature, material level, and unbalanced loading on CB inclination and settlement and changes in the contributions of each factor are evaluated.

The contributions of this paper are as follows. Theoretically, by introducing the VAR model, a quantitative method is proposed for analyzing the dynamic law governing CB settlement deformation, thereby revealing systematically (i) the dynamic effect path, (ii) the rule governing how the dynamic effect degree changes, and (iii) the process by which the contribution rates of key factors to CB settlement deformation change. Practically, the results provide insights into the development of practical and feasible measures for preventing CB deformation, and they present changes of direction and strength of influences of the implementation of stabilizing measures. This provides a reference for adjusting these measures dynamically in the future.

2 Engineering context

In China, open-pit coal mines are found mainly in Inner Mongolia, Xinjiang, Shanxi, and other northwest regions, where the climate is mostly the same. To ensure that the present research results have a certain reference value, the chosen coal preparation plant belongs to an open-pit coal mine located in the northeast of the Ordos Plateau in the Inner Mongolia Autonomous Region of China. With a typical continental climate, this region has four distinct seasons and a large temperature range, being cold and windy in winter while experiencing concentrated rainfall in summer. The coal preparation plant has a total production capacity of 30 Mt per annum, and its processes include jigging and dense-, medium-, and shallow-slot washing. There are nine coal warehouses with a height of 37.3 m and a diameter of 20.59 m and nine finished-product warehouses with a height of 22.4 m and a diameter of 14.86 m. The latter are arranged in a row and numbered C1–C9 from west to east (see Fig. 1). The coal warehouses are arranged in two rows: those in the northern row are numbered M1–M4 from west to east, while those in the southern row are numbered M5–M9 (see Fig. 1).

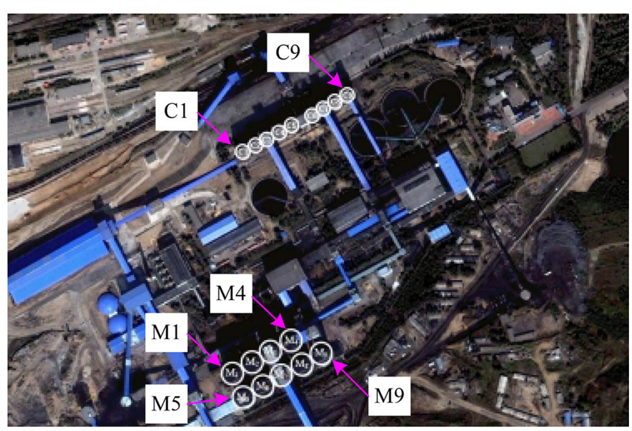


Fig. 1 Plan positions of coal bunkers (CB) in open-pit coal mine

The coal warehouses and finished-product warehouses are inclined during use. Therefore, to take rational engineering measures to ensure CB safety, it is necessary to understand the main causes of this CB inclination and analyze the correlations therein.

3 Methods

Established based on statistical data, the VAR model takes each variable in the system as a function of lagged values of all variables in the system, thereby extending the univariate autoregressive model to VAR composed of variables in multivariate time series. By using an impulse response function and variance decomposition, the VAR model can dynamically analyze the degree of influence of independent variables on dependent variables and is used widely for analyzing multivariate time series (Tiwari et al. 2019; Zhao et al. 2019).

The general VAR (P) model is given by (Yang et al. 2017)

$$\begin{pmatrix} \mathrm{NIN}_t \\ \mathrm{WL}_t \\ T_t \\ \mathrm{ML}_t \\ \mathrm{UL}_t \end{pmatrix} = \phi_{2,0} + \phi_{2,1} \begin{pmatrix} \mathrm{NIN}_{t-1} \\ \mathrm{WL}_{t-1} \\ T_{t-1} \\ \mathrm{ML}_{t-1} \\ \mathrm{UL}_{t-1} \end{pmatrix} + \phi_{2,2} \begin{pmatrix} \mathrm{NIN}_{t-2} \\ \mathrm{WL}_{t-2} \\ T_{t-2} \\ \mathrm{ML}_{t-2} \\ \mathrm{UL}_{t-2} \end{pmatrix} + \cdots \phi_{2,p} \begin{pmatrix} \mathrm{NIN}_{t-p} \\ \mathrm{WL}_{t-p} \\ T_{t-p} \\ \mathrm{ML}_{t-p} \\ \mathrm{UL}_{t-p} \end{pmatrix} + \begin{pmatrix} \varepsilon_{2,1,t} \\ \varepsilon_{2,2,t} \\ \varepsilon_{2,3,t} \\ \varepsilon_{2,4,t} \\ \varepsilon_{2,5,t} \end{pmatrix} \tag{1}$$

where, Y_t is the column vector of k-dimensional endogenous variables, p is the lag order, T is the number of samples, $\phi_1,\ldots,\phi_p$ are the coefficient matrix to be estimated, which are $k \times k$-dimensional matrixs, and ε_t is the series of k-dimensional disturbance terms. Equation (1) can be expanded to

$$Y_t = \begin{pmatrix} Y_{1t} \\ Y_{2t} \\ \vdots \\ Y_{kt} \end{pmatrix} = \phi_0 + \phi_1 \begin{pmatrix} Y_{1t-1} \\ Y_{2t-1} \\ \vdots \\ Y_{kt-1} \end{pmatrix} + \phi_2 \begin{pmatrix} Y_{1t-2} \\ Y_{2t-2} \\ \vdots \\ Y_{kt-2} \end{pmatrix} + \cdots + \phi_p \begin{pmatrix} Y_{1t-p} \\ Y_{2t-p} \\ \vdots \\ Y_{kt-p} \end{pmatrix} + \begin{pmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \\ \vdots \\ \varepsilon_{kt} \end{pmatrix} \tag{2}$$

which can be transformed simply as

$$Y_t = c_t + \sum_{i=1}^{p} \beta_i Y_{t-i} + \varepsilon_t \tag{3}$$

where, c_t is the intercept vector of the VAR model, and the $k \times k$-dimensional matrix β_i is the coefficient matrix to be estimated.

To explore the law governing the CB deformation in the coal preparation plant in more detail, the settlement (SM), northward inclination angle (NIN), and eastward inclination angle (EIN) of the CB are used to measure the CB deformation characteristics. From existing research results and theoretical analysis, four indices (groundwater level WL, temperature T, material level ML, and unbalanced loading UL) are selected as the main influencing factors of CB deformation. These are selected for the following reasons.

(1) Groundwater level. When the groundwater level changes, so do the pore water pressure and the effective stress in the soil, thereby producing a dynamic buoyancy force that deforms the foundation and leads to CB settlement and inclination (Zhao et al. 2012).
(2) Temperature. Increasing temperature increases the excess static pore pressure in the foundation, thereby causing the foundation to rebound and decreasing the CB settlement and inclination (Li et al. 2014a, b).
(3) Material level. Increased coal loading leads directly to elastic settlement of the CB and so increases the concomitant settlement. When the loading decreases, because the foundation is relatively stable, it rebounds and the settlement decreases (Wang et al. 2015).

(4) Unbalanced loading. Uneven loading position leads to unbalanced loading, resulting in non-uniform stress and settlement of the CB and so inclination thereof (Li et al. 2014a, b).

Consequently, three VAR models comprising VAR1 (Eq. (4)), VAR2 (Eq. (5)), and VAR3 (Eq. (6)) are built to analyze how the values of WL, T, LM, and OL influence those of SM, NIN, and EIN of a CB:

$$\begin{pmatrix} \mathrm{SM}_t \\ \mathrm{WL}_t \\ T_t \\ \mathrm{ML}_t \\ \mathrm{UL}_t \end{pmatrix} = \phi_{1,0} + \phi_{1,1} \begin{pmatrix} \mathrm{SM}_{t-1} \\ \mathrm{WL}_{t-1} \\ T_{t-1} \\ \mathrm{ML}_{t-1} \\ \mathrm{UL}_{t-1} \end{pmatrix} + \phi_{1,2} + \begin{pmatrix} \mathrm{SM}_{t-2} \\ \mathrm{WL}_{t-2} \\ T_{t-2} \\ \mathrm{ML}_{t-2} \\ \mathrm{UL}_{t-2} \end{pmatrix} + \cdots \phi_{1,p} \begin{pmatrix} \mathrm{SM}_{t-p} \\ \mathrm{WL}_{t-p} \\ T_{t-p} \\ \mathrm{ML}_{t-p} \\ \mathrm{UL}_{t-p} \end{pmatrix} + \begin{pmatrix} \varepsilon_{1,1,t} \\ \varepsilon_{1,2,t} \\ \varepsilon_{1,3,t} \\ \varepsilon_{1,4,t} \\ \varepsilon_{1,5,t} \end{pmatrix} \tag{4}$$

$$\begin{pmatrix} NIN_t \\ WL_t \\ T_t \\ ML_t \\ UL_t \end{pmatrix} = \phi_{2,0} + \phi_{2,1} \begin{pmatrix} NIN_{t-1} \\ WL_{t-1} \\ T_{t-1} \\ ML_{t-1} \\ UL_{t-1} \end{pmatrix} + \phi_{2,2} + \begin{pmatrix} NIN_{t-2} \\ WL_{t-2} \\ T_{t-2} \\ ML_{t-2} \\ UL_{t-2} \end{pmatrix} + \cdots \phi_{2,p} \begin{pmatrix} NIN_{t-p} \\ WL_{t-p} \\ T_{t-p} \\ ML_{t-p} \\ UL_{t-p} \end{pmatrix} + \begin{pmatrix} \varepsilon_{2,1,t} \\ \varepsilon_{2,2,t} \\ \varepsilon_{2,3,t} \\ \varepsilon_{2,4,t} \\ \varepsilon_{2,5,t} \end{pmatrix} \tag{5}$$

$$\begin{pmatrix} EIN_t \\ WL_t \\ T_t \\ ML_t \\ UL_t \end{pmatrix} = \phi_{3,0} + \phi_{3,1} \begin{pmatrix} EIN_{t-1} \\ WL_{t-1} \\ T_{t-1} \\ ML_{t-1} \\ UL_{t-1} \end{pmatrix} + \phi_{3,2} + \begin{pmatrix} EIN_{t-2} \\ WL_{t-2} \\ T_{t-2} \\ ML_{t-2} \\ UL_{t-2} \end{pmatrix} + \cdots \phi_{3,p} \begin{pmatrix} EIN_{t-p} \\ WL_{t-p} \\ T_{t-p} \\ ML_{t-p} \\ UL_{t-p} \end{pmatrix} + \begin{pmatrix} \varepsilon_{3,1,t} \\ \varepsilon_{3,2,t} \\ \varepsilon_{3,3,t} \\ \varepsilon_{3,4,t} \\ \varepsilon_{3,5,t} \end{pmatrix} \tag{6}$$

To avoid spurious regression, in Sects. 5.1 and 5.2 sample data are used to test the stationarity and co-integration relationship of each series and to determine the lag order of the model. Thus, the specific form of the VAR model is further determined, and its stability is tested.

By using the established monitoring system, the values of WL, T, ML, UL, SM, NIN, and EIN can be collected automatically, and it is easy to collect enough valid historical data. By collecting the above CB data from different coal mines, the VAR model can be used to analyze dynamically the degree of influence of each of the main influencing factors of CB deformation on the CB deformation characteristics. Also, the numbers of independent and dependent variables in the model can be increased or decreased according to the actual situation. Thus, the VAR model in this paper can be extended to different coal mines and has universal applicability.

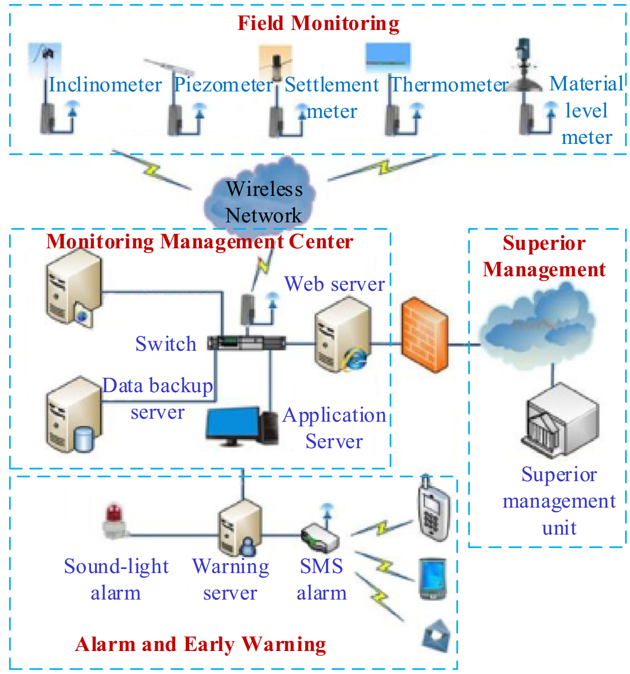


Fig. 2 Structure of real-time monitoring system for CB deformation

4 Data sources

4.1 Design of real-time monitoring system for coal-bunker deformation

The main monitoring parameters of the real-time monitoring system for CB deformation are inclination, settlement, groundwater level, temperature, and material level. The system has three parts: sensor systems at monitoring points on site, a monitoring center, and a data transmission system (Fig. 2).

Fixed-in-place inclinometers are used to monitor the CB inclination in real time, while the CB settlement is monitored through hydrostatic leveling. Moreover, groundwater level and temperature are monitored by using a vibrating-wire piezometer and a vibrating-wire thermometer, respectively. The material level is monitored with an ultrasonic coal-level monitor.

The system transmits data effectively through wired 422/485, optical fibers, and wireless GPRS/CDMA and a

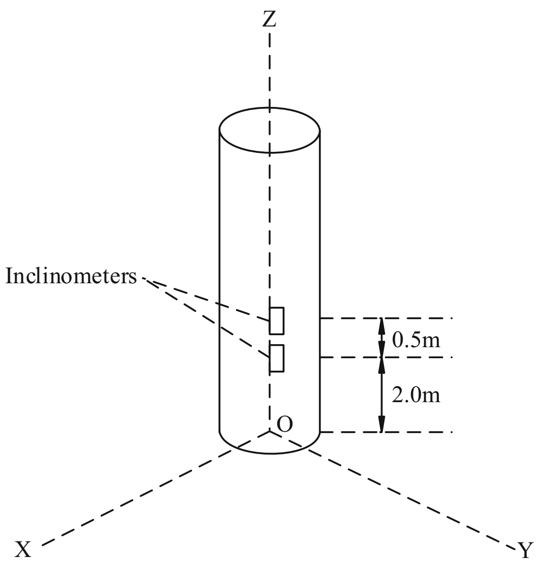


Fig. 3 Installation positions of biaxial inclinometers

wireless network, thereby transmitting the sensor data collected on site to the monitoring center. The monitoring center comprises hardware systems, including a server, an exchanger, a memory, supply and distribution facilities, firefighting facilities, lightning protection facilities, and a software system comprising an integrated monitoring platform. In this way, automatic acquisition, transmission, storage, processing, and analysis of monitoring data as well as comprehensive warning and web publishing are realized.

Fig. 4 Installation of biaxial inclinometers

4.2 Monitoring principles and system installation

4.2.1 Inclination

Biaxial inclinometers were selected that can measure inclination angles simultaneously in two vertical planes, namely the *XOZ* and *YOZ* planes. One inclinometer was installed in the CB at a height of 2 m above the ground, and the other inclinometer was installed 0.5 m above the first (Fig. 3).

The distance between the inclinometers is known, so the CB inclination angle can be obtained; the inclination at each position in the CB is found using Pythagorean geometry. Type BGK-6150–2 fixed inclinometers were used, and their actual installation is shown in Fig. 4.

A positive inclination angle of the positive axis A + (Fig. 7) of the inclinometers on the CB represents northward inclination (NIN), while a positive inclination angle of the positive axis B + indicates eastward inclination (EIN).

4.2.2 Settlement

As a precision system for measuring liquid levels, a hydrostatic leveling system for settlement monitoring was designed to measure the relative settlement at multiple measuring points. Several sensor containers are connected in series by breather pipes, and the liquid level in each container is measured by using a precision vibrating-wire sensor with a buoy. When the liquid level in the containers changes, the instrument senses the buoyancy. The components of the hydrostatic leveling system are shown in Fig. 5.

BGK-4675 hydrostatic levels were set on the CB (Fig. 6). By combining their data with the CB inclination as measured by the inclinometers, the settlement at any position can be obtained (positive values represent settlement, while negative values indicate rising).

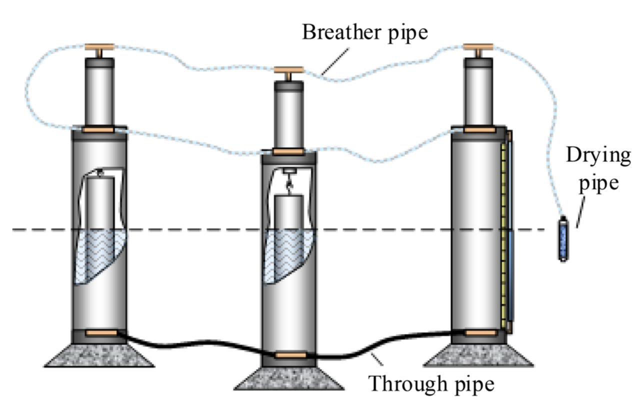


Fig. 5 Schematic of components of hydrostatic leveling system

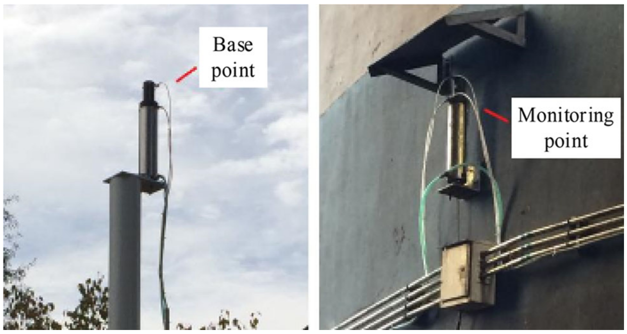
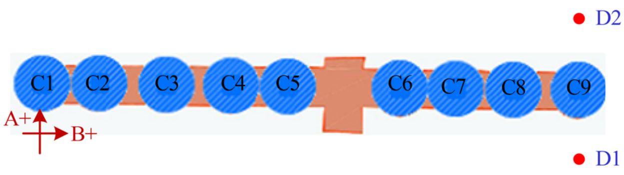
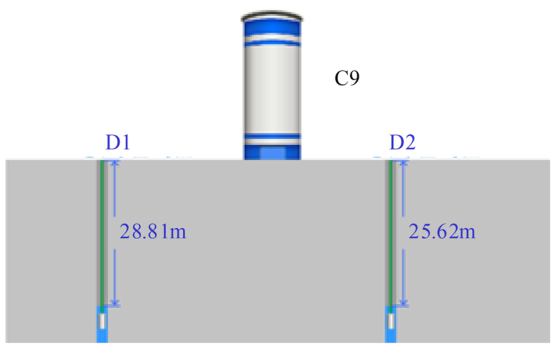


Fig. 6 Installation of hydrostatic leveling system



(a) Schematic of plane positions



(b) Schematic of section positions

Fig. 7 Installation positions of vibrating-wire piezometers

4.2.3 *Groundwater level*

The groundwater level is monitored by vibrating-wire piezometers placed in boreholes (combined with piezometric tubes). By measuring the pressures at the piezometers and converting them into heads of water, the elevation of the groundwater surface can be obtained by combining the data with the installation depths and the elevation at the mouth of each borehole. The measurement accuracy depends on the accuracy of the piezometers, and the error here is less than 10 mm.

Two boreholes for observing groundwater level were opened, and BGK-4500S piezometers were installed therein (Fig. 7). The groundwater level is taken as the mean of the two measured groundwater levels.

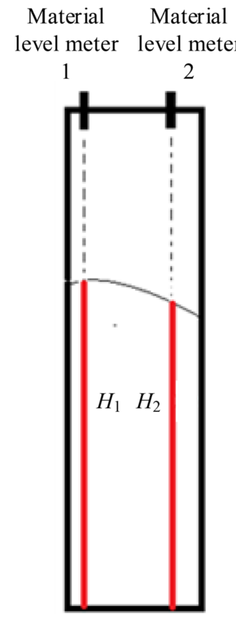


Fig. 8 Schematic of monitoring of material level

4.2.4 *Temperature*

The temperature is monitored by a BGK-3700 vibrating-wire thermometer that was fixed directly on the outer wall of the CB using expansion bolts.

4.2.5 *Material level*

Two material-level meters (ultrasonic level meters) were installed in the CB (Fig. 8). Through converting units, these meters convert a current of 4–20 mA into integer values that are stored in the OLE for Process Control (OPC) server. The software reads these values from the OPC server and converts them into CB material levels. The average of the two measured material levels is taken as the CB material level, and the difference indicates the magnitude of the unbalanced load.

4.3 Monitoring data

By using the established monitoring system and analysis software, data were collected from 23 April to 30 December 2018. One set of monitoring data was collected every hour. Data were missing in part of the period affected by equipment failure, and abnormal data were removed. In total, 5825 groups of data were collected. As for the VAR model, it belongs to high-frequency large sample data, which is enough to ensure the accuracy of the model. Although the data cover less than a whole year, they contain various groundwater-level, temperature, material-level, and unbalanced-loading conditions that are

Table 1 Partial monitoring data from real-time monitoring system

No.	Date and time	WL (m)	*T* (°C)	ML (m)	UL (m)	SM (mm)	Inclination angles ($10^{-3°}$)	
							NIN	EIN
1	2018/5/1 1:39	969.56	11.20	12.58	− 0.15	0.84	2.50	− 17.50
2	2018/5/1 2:39	969.56	11.60	15.96	0.87	1.49	2.50	− 18.00
3	2018/5/1 3:39	969.57	11.50	14.57	1.66	1.55	1.00	− 17.00
4	2018/5/1 4:39	969.57	7.50	15.83	1.40	1.14	2.00	− 16.00
5	2018/5/1 5:39	969.57	7.20	18.79	1.00	0.98	2.50	− 14.00
6	2018/5/1 6:39	969.58	6.90	19.06	0.29	0.37	2.50	− 14.50
7	2018/5/1 7:39	969.59	6.80	11.66	− 0.25	1.42	− 0.50	− 16.00
8	2018/5/1 8:39	969.57	7.00	7.40	3.43	1.38	− 2.00	− 17.00
9	2018/5/1 9:39	969.55	8.10	3.01	4.07	1.30	0.50	− 17.50
10	2018/5/1 10:39	969.56	11.20	12.58	− 0.15	0.84	2.50	− 17.50

Table 2 Results of unit root test

Variable	ADF test	ERS test	PP test	Conclusion
WL	− 3.35**	− 2.60	− 3.16**	Stationary
T	− 2.29	− 1.90**	− 7.67***	Stationary
ML	− 16.22***	− 14.91***	− 12.37***	Stationary
UL	− 21.98***	− 21.66***	− 22.80***	Stationary
SM	− 10.76***	− 7.73***	− 13.80***	Stationary
NIN	− 3.45***	− 2.80	− 1.84**	Stationary
EIN	− 3.44**	− 1.95	− 8.60***	Stationary

Note: *** and ** denote significance at 5% and 1% levels, respectively; when three results of a test differed, the consistent result of two of them was chosen

representative and can be used to test empirically the rules governing how various factors influence CB deformation. The monitoring data for finished-product warehouse 9 are taken as an example, some of which are listed in Table 1.

5 Empirical analysis

5.1 Unit root test

To test the stationarity of the series, three-unit root tests (augmented Dickey–Fuller (ADF) test, Elliott–Rothenberg–Stock (ERS) test, and Phillips–Perron (PP) test) were performed on each series, the results are shown in Table 2. According to Table 1, each variable is a stationary series at significance levels of 1% and 5%. A co-integration test is not required, and the original series can be used directly to build the model.

5.2 VAR specifications

By selecting four indices (groundwater level WL, temperature *T*, material level ML, and unbalanced loading UL) three VAR models—VAR1, VAR2, and VAR3—were built to analyze how these indices influence the settlement (SM), northward inclination angle (NIN), and eastward inclination angle (EIN) of the CB.

Table 3 Selection criteria of lag order on models VAR1, VAR2, and VAR3

Lag order	VAR1			VAR2			VAR3		
	AIC	SC	HQ	AIC	SC	HQ	AIC	SC	HQ
0	22.23	22.25	22.24	10.84	10.86	10.84	8.40	8.42	8.41
1	11.47	11.57	11.51	− 2.74	− 2.64	− 2.70	− 2.66	− 2.55	− 2.62
2	10.65	10.84	10.72	− 3.60	− 3.41	− 3.53	− 3.37	− 3.18	− 3.30
3	10.55	10.83*	10.66*	− 3.74	− 3.47*	− 3.65*	− 3.47	− 3.19*	− 3.37*
4	10.55	10.91	10.68	− 3.78	− 3.42	− 3.64	− 3.50	− 3.13	− 3.36
5	10.54*	10.99	10.71	− 3.80*	− 3.35	− 3.64	− 3.54	− 3.08	− 3.37

Note: “*” indicates the lag order selected by the criteria

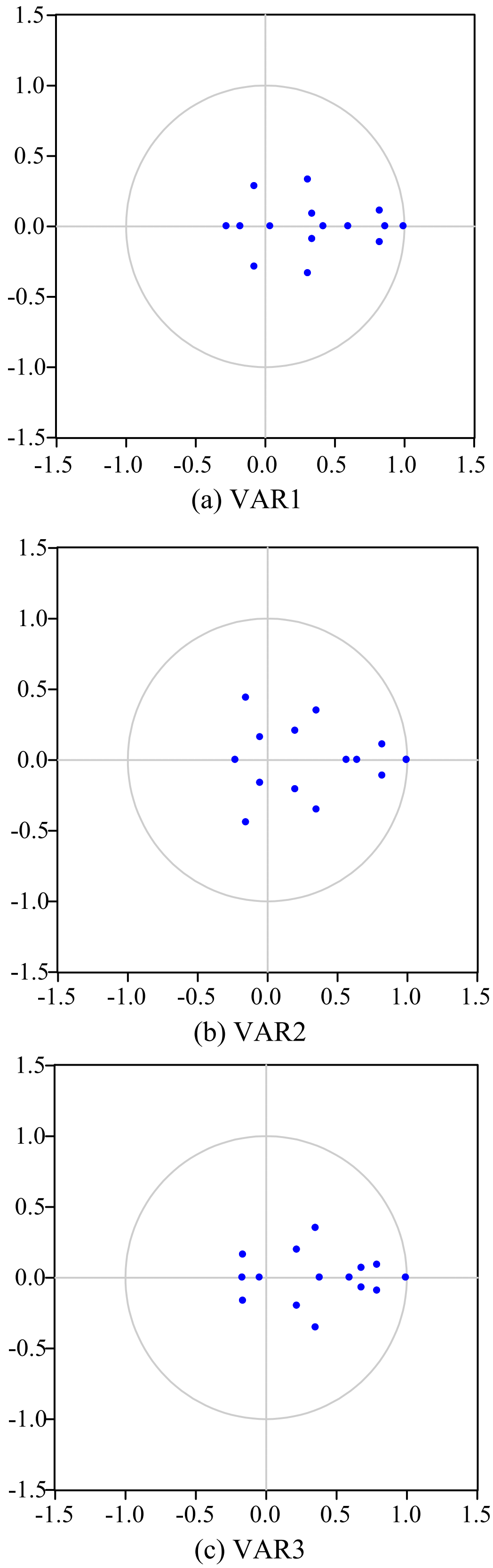


Fig. 9 Inverse roots of VAR characteristic polynomial

5.2.1 Optimal order

The larger the lag order, the more completely the dynamic characteristics of the model can be reflected; however, it also results in more parameters to be estimated and loss of higher degrees of freedom, which affects the validity of the parameters. Based on Table 3, in the three standards, the lag order obtained using two standards is 3, so it is deemed necessary to build the VAR1(3), VAR2(3), and VAR3(3) models.

5.2.2 Stability test

As shown in Fig. 9, the inverse roots of the VAR characteristic polynomial all fall within the unit circle, indicating that the three VAR models are stable and can therefore be used in the impulse response analysis.

5.3 Generalized impulse response analysis

To analyze the degrees and directions of the influences of each factor on the CB settlement and eastward and northward inclinations, a generalized impulse response analysis was conducted. The results are shown in Fig. 10, where the horizontal coordinate is period, and eight periods are used to analyze the rules governing how various factors influence the CB deformation in the next eight hours.

Based on Fig. 10, positive impacts of groundwater level constantly produce negative effects on the CB settlement and eastward and northward inclinations. The strength of these influences reaches a maximum in the first four periods and then tends to stabilize. The main reason is that when groundwater levels decrease, the pore water pressure in the soil decreases gradually and the effective stress increases: this deforms the foundation and leads to settlement and increasing inclination of the CB.

Positive impacts of temperature constantly have negative effects on the CB settlement and eastward and northward inclinations, and the strength of these influences on the CB settlement reaches a maximum in the first four periods and then tends to stabilize. The strength of the influences on the eastward inclination reaches a maximum in the first six periods and then weakens gradually. Moreover, the strength of the influences on the northward inclination is at a maximum in the first three periods and then decreases gradually. This is mainly because the increasing temperature increases the excess static pore pressure in the foundation, causing rebound of the foundation, settlement of the CB, and a reduction in the inclination.

Positive impacts of material level constantly exert positive effects on the CB settlement. The strength of these influences reaches a maximum in the third period and then

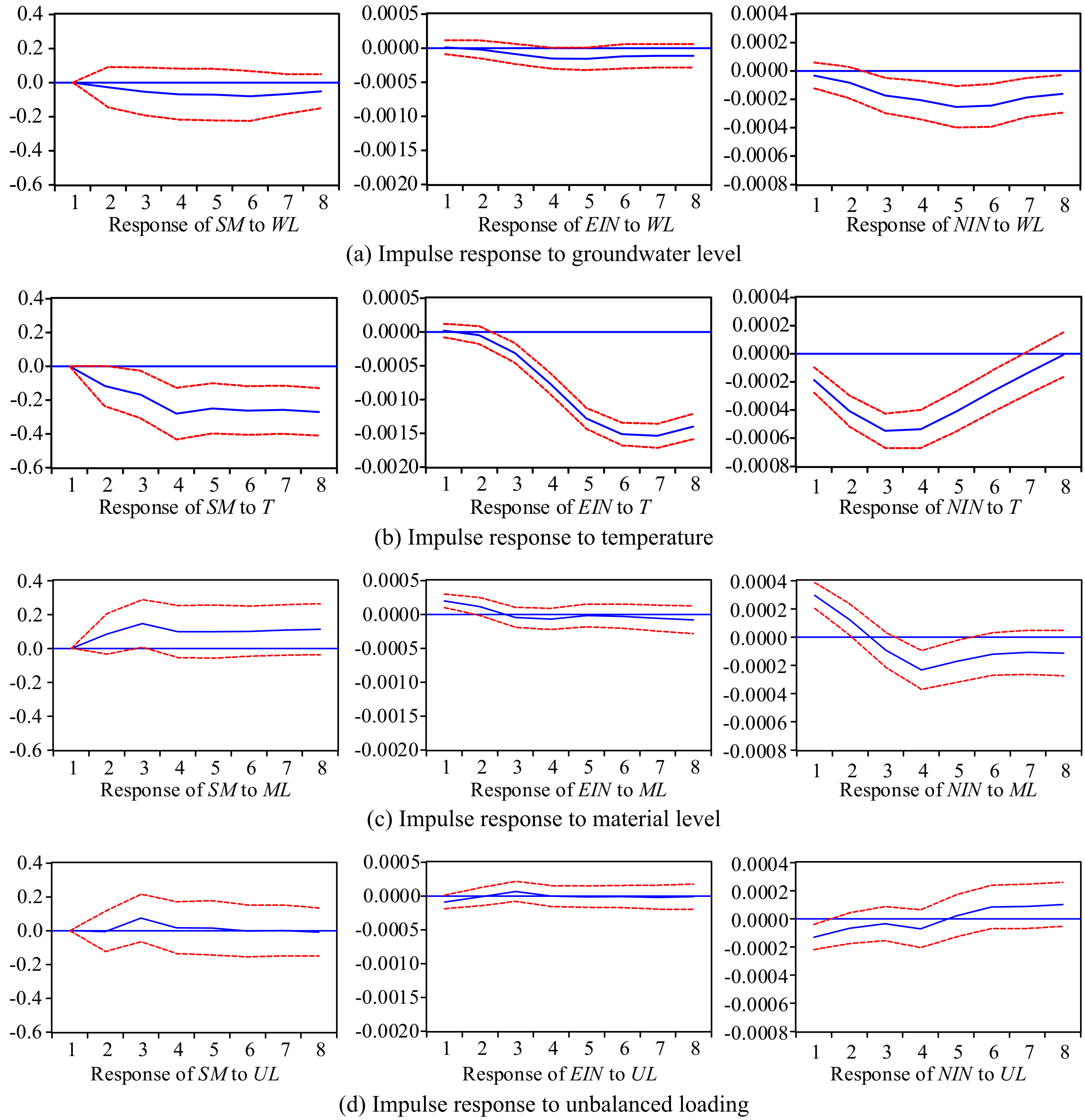


Fig. 10 Impulse response of CB deformation to each influencing factor

weakens and tends to stabilize. Positive effects are first produced on eastward inclination and reduce gradually. After the third period, weak negative effects are generated. Positive effects are first produced on the northward inclination and then weaken gradually. Negative effects begin to appear in the third period, reaching their maximum strength in the fourth period before weakening gradually and finally tending to stabilize in the sixth period. Elastic settlement of the CB is caused mainly by coal loading, and the concomitant settlement increases. When the changes in load are small, because the foundation is relatively stable, its rebounds and so reduces the CB settlement.

Positive impacts of unbalanced loading constantly positively affect the CB settlement. The strength of these influences reaches a maximum in the third period then weakens and tends to zero. For the eastward inclination, negative effects are first produced and then become positive effects in the third period. Moreover, the effects tend to

Table 4 Variance decomposition of influencing factors of CB settlement

Period	S.E.	SM	WL	*T*	ML	UL
1	2.36	99.52	0.01	0.44	0.08	0.03
2	2.82	98.67	0.02	1.09	0.19	0.03
3	3.13	97.13	0.11	2.08	0.52	0.16
4	3.35	95.78	0.17	3.14	0.75	0.16
5	3.50	94.55	0.21	4.12	0.97	0.15
6	3.62	93.48	0.23	4.98	1.16	0.15
7	3.70	92.57	0.24	5.71	1.33	0.14
8	3.77	91.84	0.24	6.30	1.47	0.14

Table 5 Variance decomposition of influencing factors of CB northward inclination

Period	S.E. (10^{-3})	NIN	WL	*T*	ML	UL
1	2.00	95.26	0.24	1.68	2.23	0.58
2	2.00	92.06	0.59	5.23	1.60	0.51
3	3.00	88.43	1.33	8.08	1.70	0.45
4	3.00	86.59	1.94	9.15	1.95	0.37
5	3.00	85.83	2.31	9.41	2.13	0.32
6	4.00	85.68	2.57	9.17	2.30	0.28
7	4.00	85.99	2.76	8.61	2.40	0.25
8	4.00	86.49	2.91	7.93	2.46	0.22

Table 6 Variance decomposition of influencing factors of CB eastward inclination

Period	S.E.(10^{-3})	EIN	WL	*T*	ML	UL
1	2.00	98.59	0.03	0.03	1.14	0.22
2	3.00	98.38	0.02	0.52	0.94	0.14
3	3.00	94.93	0.04	4.18	0.74	0.11
4	4.00	88.47	0.06	10.75	0.63	0.10
5	4.00	80.15	0.08	19.12	0.55	0.10
6	4.00	71.86	0.09	27.45	0.50	0.10
7	4.00	64.81	0.10	34.51	0.47	0.11
8	5.00	59.38	0.10	39.96	0.45	0.12

zero after the fourth period. Negative effects are first generated on the northward inclination and weaken gradually. After the fifth period, the negative effects become positive effects. After the sixth period, the influences tend to stabilize. Unbalanced loading results in non-uniform stress and settlement of the CB, thus incurring inclination. When the material level is lower (resp. higher), it has more (resp. less) influence. Unbalanced loading only affects the CB settlement slightly.

5.4 Variance decomposition

To measure the relative contributions of each influencing factor in the system to changes in the CB settlement and northward and eastward inclinations, the proportions of each factor in the prediction error variance in the eight periods were investigated (Tables 4, 5 and 6).

As shown in Table 4, regardless of time, the settlement itself contributes the most to the variations observed, with the rate of influence thereof reaching 99.52% in the first period, followed by temperature and material level, both also showing significant rising trends. The contribution rates of groundwater level and unbalanced loading are small and reach their lowest in the first three periods, at below 0.11%. From the fourth period, unbalanced loading contributes the least, with a contribution below 0.16%.

According to Table 5, regardless of time, the northward inclination itself shows the largest contribution to the variations observed, reaching 95.26% in the first period, followed by temperature. In the short term, the contribution of material level is higher than that of groundwater level, while the opposite result was obtained in the fifth period. Moreover, the contribution of unbalanced loading is the lowest, decreasing from 0.58% to 0.22%.

Based on Table 6, regardless of time, the eastward inclination itself contributes the most to the variations observed, with a rate of 98.59% in the first period. In the short term, the contributions of material level and unbalanced loading are high while their proportions show a decreasing trend. The contribution of temperature rises rapidly and ranks second in the third period, reaching 4.18%. Groundwater level contributes the least at below 0.10%.

6 Conclusions

Based on monitoring data, by constructing a VAR model, the key factors influencing CB inclination and settlement and the dynamic actions of each factor were explored. The results show the following.

Groundwater level constantly exerts negative effects on CB settlement and inclination, but its contribution is low and its influence is slight. With increasing groundwater level, CB settlement and inclination decrease slightly.

Temperature continuously shows significant negative effects on CB settlement and inclination. With increasing temperature, CB settlement and inclination decrease significantly. The decrease in settlement and eastward inclination increases, while that of the northward inclination increases initially and then decreases.

Material level has constant positive effects on CB settlement. It slightly affects the eastward inclination of the

CB, while significantly influencing the northward inclination of the CB. With increasing material level, CB settlement increases gradually, the eastward inclination changes slightly, while the northward inclination increases initially and then decreases.

Unbalanced loading influences CB settlement and eastward inclination slightly, while significantly affecting the northward inclination. With increasing unbalanced loading, the northward inclination decreases initially and then increases.

The large temperature difference in summer in the study region leads to large changes in both the settlement and inclination of the CB, so monitoring should be intensified at that time. In the production process, it is necessary to avoid sudden changes in load, so as to avoid sudden changes in pressure, which will lead to sudden local settlement and damage the CB. Uniform loading should be ensured as far as possible, especially avoiding significantly unbalanced CBs at material levels of less than 50% full. In addition, the direction of unbalanced loading should be opposite to the inclination of the CB as far as possible to offset inclination by virtue of unbalanced loading.

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Declarations

Conflict of interest The authors declare no conflict of interests regarding publication of this paper.

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