Investigation and statistical analysis for variable material loads on formwork system during construction

Du Tao[1] Xie Nan[1] Jia Songsong[2]

([1] School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China)
([2] Tangshan Jiantou Real Estate Development Co., Ltd., Tangshan 063000, China)

Abstract: To accurately predict the variable material loads (VMLs) of concrete structures during construction, the equivalent uniformly distributed loads (EUDLs) are determined. The EUDL with the same load effects as the actual VML is produced on the shore. The VMLs of the reinforced concrete structure prior to and after concrete placement were investigated on-site and statistically analyzed. The statistical characteristics of the VML were obtained. The VML before and after concrete placements was randomly modeled to derive its spatial correlation. The finite element model of the formwork system was established. The characteristics of the influence surface for the shore axial force were analyzed using the maneuver method. Then, a random load was applied on the form surface. The EUDLs with the same load effects as the actual VML were calculated. By taking the standard value of a load, the recommended value of the VML prior to concrete placement is finally proposed. The results show that the VMLs surveyed at different construction sites vary greatly. With the increase in distance, the correlation coefficient of the random field zero-mean load gradually decreases. The recommended value of VMLs can be used to provide a reliable basis for the design and safety control of formwork systems.

Key words: formwork system; variable material loads; random field; influence surface; equivalent uniformly distributed loads

DOI: 10.3969/j.issn.1003 -7985.2023.01.003

The failures of reinforced concrete structures during construction are often attributed to the collapse of formwork systems. Based on the investigation and analysis of several collapse accidents, construction loads exceed the bearing capacity of formwork systems during the construction process, which is the main reason for the collapse of formwork systems[1-4]. Loads during construction mainly include material loads (e.g., weights of fresh concrete, reinforcement, concrete forms, and formwork components), the weight of construction personnel, the weight of construction equipment, vibration load, and impact load[5]. Construction loads are the loads imposed on the formwork system during construction. They mainly include the weight of construction personnel, equipment, and material loads. Material loads are divided into two categories: fixed material loads (FMLs) and variable material loads (VMLs). FMLs refer to loads from fixed materials in magnitude, and VMLs refer to loads from stockpiled materials that vary in magnitude[5]. With the acceleration of the construction progress, a large number of construction materials are often stockpiled on working-surfaces in advance. The resulting VMLs may make actual loads borne by the formwork system exceed the design value of the structure, which become major potential safety hazards of collapse accidents.

At present, research on loads during construction is still very limited, and a unified understanding of loads has not been formed. Chinese scholars mostly investigated the construction sites of concrete buildings, divided the working surfaces according to different sizes, and used the area average load method to deal with the investigated construction live loads[6-8]. Xie et al.[9] conducted an investigation and statistical analysis on construction live loads and concrete loads based on the influence surface method and presented the recommended values of the two forms of loads. Karshenas et al.[10-11] measured construction live loads on working surfaces before and after concrete placement and investigated the material, personnel, and construction equipment loads. Some construction load investigations directly measure the load effects of the shore[12-14]. Zhang et al.[15] investigated the shore load during and following concrete placement at three construction sites in Sydney and obtained the statistical characteristics of the dead load effect and live load effect. In addition, the assessment of load statistical information for formwork systems is important when establishing safety criteria. Jin et al.[16-17] hypothesized that loads from stockpiled materials played an important role in the formwork construction risk assessment system and studied the load probability model of the formwork system during construction based on in situ investigation and statistics

Received 2022-08-04, **Revised** 2023-01-15.

Biographies: Du Tao (1990—), male, Ph. D. candidate; Xie Nan (corresponding author), female, doctor, professor, n_xie@sina.com.

Foundation item: The National Natural Science Foundation of China (No. 51578050).

Citation: Du Tao, Xie Nan, Jia Songsong. Investigation and statistical analysis for variable material loads on formwork system during construction[J]. Journal of Southeast University (English Edition), 2023, 39(1): 17 -25. DOI: 10.3969/j.issn.1003 -7985.2023.01.003.

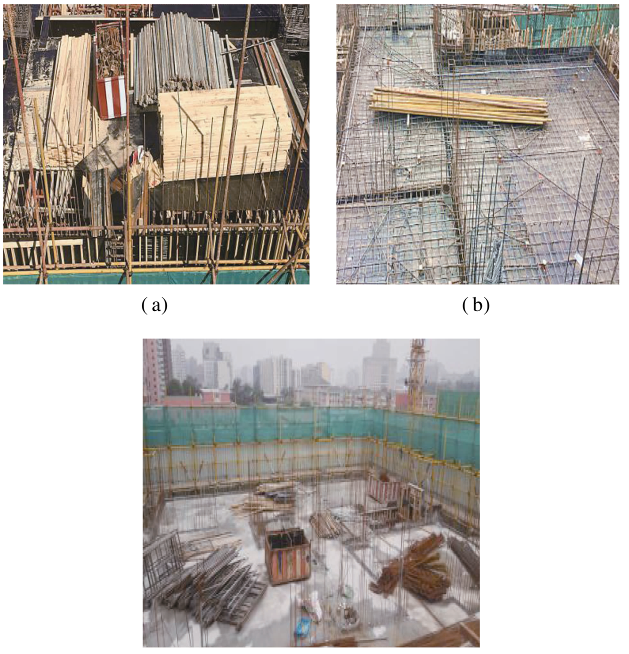
data. Rosowsky et al.[18] established a probabilistic construction load process model, which can take into account the probability distribution and time characteristics of the material stacking load.

Under different standards, the VML design of formworks may greatly vary. ASCE/SEI 37-02[5] divides the construction operation into four grades, namely, very light duty, light duty, medium duty, and heavy duty, according to the condition of working surfaces, and presents the corresponding combination values of VMLs and construction live loads, which are 0.96, 1.20, 2.40, and 3.59 kPa, respectively. The British Standard BS EN 12812:2008[19] specifies that the additional VML value can be determined between 0.75 and 1.75 kPa during concrete placement. However, in the Australian standard for concrete formwork AS 3610-1995[20], loads from stockpiled materials vary during different construction stages. For example, it can be 4.0 kPa before and after concrete placement.

As the specific conditions of a construction site have a great impact on the investigation and research of loads during the construction period, there may be great differences in the statistical parameters of VMLs. The sample quantity of the construction load investigation is not enough to determine a complete load probability model. The current research mostly simplifies the load probability model to random variables and ignores the variability of loads in space. Accordingly, the VML investigation data prior to and after concrete placements were statistically analyzed. The VML survey data prior to and after concrete placements were used to estimate the parameters of the random probability load model. Based on the influence surface method, the derived random load model was used to determine the load effects of the formwork system. The equivalent uniformly distributed load (EUDL) of the shore axial force was calculated, namely, the EUDL that produced the same load effect as the actual VML. Finally, the reasonable design value of the VML was recommended. This work can provide a reference for the design of formwork support and the reasonable and scientific arrangement of material stacking.

1 In Situ Investigation of VMLs

The VMLs considered in this work were from stockpiled materials, which mainly include the load caused by the self-weight of construction materials that have been partially in place or have been randomly stacked by construction personnel. The VMLs greatly change during the construction of the structure and are the focus of the load analysis during the construction. The investigated VMLs were from two stages: 1) prior to the concrete placement stage, including the formwork erection stage and reinforcement binding stage; 2) after concrete placement when the strength of the concrete has not reached the standard value after concrete placement. Fig. 1 presents the VMLs at different stages.



(a) (b) (c)

Fig. 1 VMLs in different stages. (a) Formwork erection stage; (b) Reinforcement binding stage; (c) After concrete placement stage

To obtain the distribution law of the loads, it is necessary to investigate some construction sites and collect enough data. When determining the construction sites to be investigated, concrete construction projects are generally selected randomly throughout the country. However, due to the influence of various factors, only a few projects have been approved for investigation. In addition, it is not feasible to attempt to investigate more projects in a short time. Therefore, the construction sites selected for investigation within a certain range should be typical and representative. The survey data in this work are from nine projects with different scales, construction periods, and characteristics, including canteens, residential buildings, and commercial buildings. The buildings are all multi-story and high-rise reinforced concrete structures. The investigated construction units have Class I construction enterprise qualifications. The construction behavior meets the requirements of industry specifications after investigation. Tab. 1 shows the types of construction sites investigated and the corresponding measured stages. After verification, the actual construction operations in situ are all in line with the construction organization plan. When investigating the VMLs, the specific conditions of the stockpiled materials on the working surfaces were recorded in detail, including the type, specification, quantity of the material, and specific location. A steel winding scale or flexible rule was used to measure the area of the material on the working surface.

The VMLs of reinforced concrete structures during con-

Tab. 1 Description of the construction sites and measured stages

No.	Description of the construction sites	Measured stages
1	Multi-story residential building in Beijing	Prior to concrete placement
2	High-rise residential building in Beijing	Prior to and after concrete placement
3	High-rise teaching office building and dormitory building in Beijing	Prior to and after concrete placement
4	High-rise residential building in Changzhou	Prior to concrete placement
5	High-rise office building and commercial building in Shenzhen	Prior to and after concrete placement
6	High-rise office building and commercial building in Beijing	Prior to and after concrete placement
7	Multi-story residential building in Beijing	Prior to and after concrete placement
8	High-rise public canteens and cross-platform building in Beijing	After concrete placement
9	High-rise residential building in Beijing	Prior to concrete placement

struction are various. Fig. 2 shows the VML investigation and standardization results of construction site 2 at the formwork erection stage.

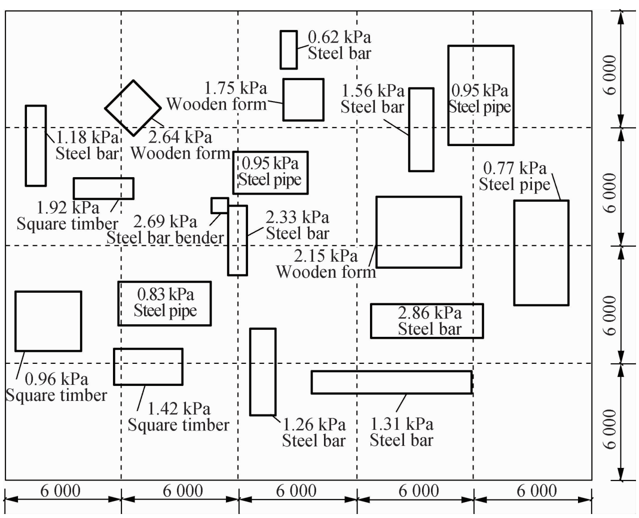


Fig. 2 VML investigation and standardization results of construction site 2 (unit: mm)

To reflect the statistical characteristics of VMLs, the area average load method was used to statistically analyze the original load data obtained from the investigation. When using the area average load method, the investigated working surface is divided into several equal grids according to the specified size, and each grid is taken as a unit. The ratio of the VMLs in the grid to the area is the load value of the corresponding unit. If there is no load in the grid, it is called a zero load unit; otherwise, it is called a non-zero load unit.

In this work, the surveyed construction plan of the VML on the working surface was divided. When the working surface is divided by a small grid size, the percentage of zero load units is relatively large; then, the average value of the unit load obtained by the statistical analysis is large[11]. Starting from the safety demand, the grid size was determined as 0.3 m × 0.3 m. After dividing the working surface, the total number of grids was 15 573. Among them, there were 3 421 non-zero load units, accounting for 22%. The surveyed results of VMLs prior to and after concrete placement were statistically analyzed. After the collation and statistical analysis of the survey data, the statistical parameters of VMLs were obtained. A chi-squared test was performed. The results show that the VMLs can be best fitted by an exponential distribution at a significance level of 5%. Tabs. 2 and 3 show the statistical results of VMLs for the construction sites prior to and after concrete placement, respectively. Tabs. 2 and 3 show that the standard deviation of VMLs is large. This is mainly due to the different construction methods, construction progress, and management level of each project, which makes the VMLs among projects vary greatly.

Tab. 2 Statistical results of VMLs prior to concrete placement

Site	Measured area/m^2	Number of grids	Mean/kPa	Standard deviation/kPa
1	257	2 322	0.593	1.330
2	484	2 705	0.498	1.273
3	109	5 238	1.025	1.293
4	200	2 137	0.657	0.873
5	126	1 125	1.282	2.026
6	48	240	0.261	0.736
7	269	2 711	0.573	2.016
9	25	272	0.147	0.528

Tab. 3 Statistical results of VMLs after concrete placement

Site	Measured area/m^2	Number of grids	Mean/kPa	Standard deviation/kPa
2	257	157	0.593	1.330
3	484	103	0.498	1.273
5	109	50	1.025	1.293
6	200	58	0.657	0.873
7	126	1 896	1.282	2.026
8	48	198	0.261	0.736

2 Stochastic Modeling of VMLs

To calculate the VMLs equivalent to the actual loads and uniformly distributed on the working surfaces, their spatial correlation must be determined. The survey data obtained from the in situ investigation and statistical analysis can be used to determine the parameters of the stochastic load model. After dividing the working surfaces at the construction sites, the strength data and relative position of the loads were obtained. Based on the random field theory and fitting method, the stochastic model of VMLs can be described.

2.1 Probabilistic model of VMLs

The distribution of VMLs during construction can be equivalent to a generalized stable and uniform random field model; that is, the distribution of load positions is random. When any position u of the load on the working face is known, the corresponding random function $X(u)$ can be obtained. The random function $W(x, y)$ of the load on the working surface can be defined as follows[21]:

$$W(x, y) = \mu_q + \gamma_p + \varepsilon(x, y) \tag{1}$$

where x and y are the coordinates at any point; μ_q is the mean of the VMLs at all surveyed construction sites; γ_p is the random variable of the difference between construction sites with zero-mean, with γ_p obeying the exponential distribution; $\varepsilon(x, y)$ is a two-dimensional stationary random field of the load intensity with a zero-mean value at a construction site. We assume that a random variable γ_p and random field $\varepsilon(x, y)$ are statistically independent.

The random variable γ_p varies greatly among projects. This variation is mainly caused by the difference in the project scale, construction site characteristics, architectural design, and other factors. If enough load data can be collected, the mean value and variance of various combinations of the above factors can be estimated, and individual design loads would be calculated according to the conditions of each group. However, if the load model is used to determine the concrete construction load specified in the code, it is better to develop one that can represent all construction sites. The established model requires appropriate sampling to ensure that the collected load data include a balanced mixture of various concrete construction projects and are not dominated by one or two construction sites. Based on the above reasons, the surveyed data from different construction sites are combined, and the load probability model that meets all construction sites is obtained.

The stationary random field $\varepsilon(x, y)$ can be considered a zero-mean random process with a non-zero spatial correlation. As a result, the formula can be obtained as follows:

$$\text{Cov}[\varepsilon(x_0, y_0), \varepsilon(x_1, y_1)] \neq 0 \tag{2}$$

where $\text{Cov}[\varepsilon(x_0, y_0), \varepsilon(x_1, y_1)]$ denotes the covariance function of two random fields, $\varepsilon(x_0, y_0)$ and $\varepsilon(x_1, y_1)$, and x_0, y_0, x_1, and y_1 are the coordinates at any two points.

The mean $E[W(x, y)]$ and variance $\delta[W(x, y)]$ of the random function $W(x, y)$ are described as follows:

$$E[W(x, y)] = \mu_q \tag{3}$$

$$\delta[W(x, y)] = \sigma_q^2 = \sigma_p^2 + \sigma_v^2 \tag{4}$$

where σ_q is the standard deviation of the VML at all surveyed construction sites, σ_p is the standard deviation of a random variable γ_p, and σ_v is the standard deviation of random field $\varepsilon(x, y)$.

In this study, Peir and Cornell's equation[22] is adopted to determine the covariance function $\text{Cov}[W(x_0, y_0), W(x_1, y_1)]$ of two random functions, $W(x_0, y_0)$ and $W(x_1, y_1)$.

$$\begin{aligned}\text{Cov}[W(x_0, y_0), W(x_1, y_1)] = \\ E[W(x_0, y_0)W(x_1, y_1)] - E[W(x_0, y_0)]E[W(x_1, y_1)] = \\ \sigma_p^2 + \text{Cov}[\varepsilon(x_0, y_0), \varepsilon(x_1, y_1)]\end{aligned} \tag{5}$$

2.2 Determination of random field parameters

The VMLs obtained through the investigation and calculation can be used to determine the parameters of the random function $W(x, y)$. To combine the measured VMLs of the various construction sites, it must be assumed that the established random field of VMLs is a generalized uniform and stable random field. Hence, the probability distribution of loads at different locations under construction is the same.

The mean μ_q is obtained as

$$\mu_q = \frac{1}{A_t}\sum_{i=1}^{n}\mu_{qi}A_i \tag{6}$$

$$A_t = \sum_{i=1}^{n}A_i \tag{7}$$

where n is the number of investigated construction sites; A_i is the measured area of construction site i; A_t is the total area of the surveyed construction sites; μ_{qi} is the mean of the random process for the VMLs at construction site i.

The standard deviation σ_p can be obtained as

$$\sigma_p = \sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n}(\mu_{qi} - \mu_q)^2} \tag{8}$$

The process is obtained by subtracting the corresponding average load from the VML of a construction site. As the measured area exceeds 0.09 m^2, the obtained process is a discrete load process. The standard deviation σ_v can be estimated as follows [18]:

$$\sigma_v = \sqrt{\frac{1}{m-1}\sum_i\sum_j\varepsilon_i^2(x_j, y_j)} \tag{9}$$

where $\varepsilon_i(x_j, y_j)$ is the zero-mean load of a 0.09 m^2 grid centered at point (x_j, y_j) of construction site i; x_j and y_j are the coordinates of the point in grid j; and m is the total number of 0.09 m^2 grids at all the surveyed construction sites.

Taking the data from Tabs. 2 and 3 into Eqs. (6) to (9), μ_q prior to and after concrete placement can be calculated as 0.638 and 0.485 kPa, respectively; σ_p prior to and after concrete placement can be calculated as 0.373 and 0.338 kPa, respectively; and σ_v prior to and after concrete placement can be calculated as 1.452 and 1.962 kPa, respectively.

2.3 Covariance function

The load random field $\varepsilon(x, y)$ is a zero-mean generalized stationary and uniform random field, which can only be described incompletely by the correlation function. To estimate the correlation function of the load random field $\varepsilon(x, y)$, the correlation coefficient $\rho(r)$ can be obtained as[21]

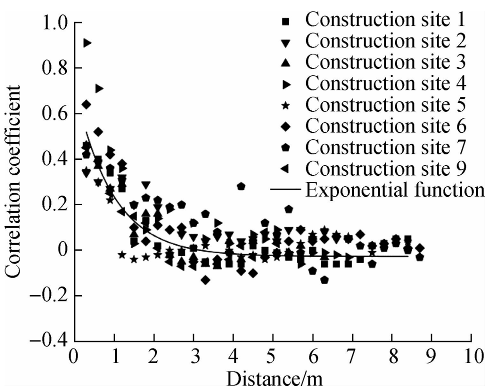
$$\rho(r) = \frac{\sum \varepsilon_i(x_j, y_j)\varepsilon_i(x_k, y_k)}{n\sigma_v^2} \tag{10}$$

where r is the distance between two points (x_j, y_j) and (x_k, y_k); $\varepsilon_i(x_j, y_j)$ and $\varepsilon_i(x_k, y_k)$ are the zero-mean loads of grids j and k at the construction site i, respectively; x_k and y_k are the coordinates of the point in grid k; and n is the number of loads multiplied by two zero-mean loads.

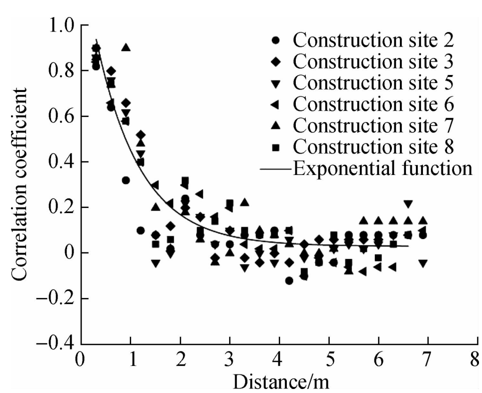
The distance can be obtained as follows:

$$r = \sqrt{(x_j - x_k)^2 + (y_j - y_k)^2} \tag{11}$$

According to Eqs. (10) and (11), the correlation coefficient $\rho(r)$ can be computed. Fig. 3 shows the relationship between the correlation coefficient $\rho(r)$ and distance r prior to and after concrete placement. The figure shows that the correlation coefficient $\rho(r)$ of the load decreases gradually and finally approaches zero with the increase in distance r. Accordingly, the relationship between the correlation coefficient $\rho(r)$ and distance r obeys the exponential distribution.



(a)



(a)

Fig. 3 Correlation coefficient of VMLs. (a) Prior to concrete placement; (b) After concrete placement

The exponential function can be fitted to the calculated correlation coefficient as follows:

$$\rho(r) = a\exp\left(-\frac{r}{b}\right) + c \tag{12}$$

where a, b, and c are constants.

The least squares method was adopted to calculate a, b, and c. The correlation coefficients $\rho_1(r)$ and $\rho_2(r)$ before and after concrete placement can be respectively calculated as

$$\rho_1(r) = 0.746\exp\left(-\frac{r}{0.957}\right) - 0.027 \tag{13}$$

$$\rho_2(r) = 0.632\exp\left(-\frac{r}{0.905}\right) + 0.016 \tag{14}$$

Therefore, according to Eqs. (13) and (14), the corresponding covariance functions $G_{\text{bef}}(r)$ and $G_{\text{aft}}(r)$ of the load random field $\varepsilon(x, y)$ before and after the concrete placement are respectively given by

$$G_{\text{bef}}(r) = \sigma_{v1}^2\rho_1(r) = (1.452)^2 \times \left(0.746\exp\left(-\frac{r}{0.957}\right) - 0.027\right) \tag{15}$$

$$G_{\text{aft}}(r) = \sigma_{v2}^2\rho_2(r) = (1.962)^2 \times \left(0.632\exp\left(-\frac{r}{0.905}\right) - 0.016\right) \tag{16}$$

where σ_{v1} and σ_{v2} are the standard deviations of the random field $\varepsilon(x, y)$ before and after concrete placement, respectively.

By substituting Eqs. (15) and (16) into Eq. (5), the covariance functions $Z_{\text{bef}}(r)$ and $Z_{\text{aft}}(r)$ of the VMLs before and after concrete placement can be respectively described as follows:

$$Z_{\text{bef}}(r) = 0.139 + (1.452)^2 \times \left(0.746\exp\left(-\frac{r}{0.957}\right) - 0.027\right) \tag{17}$$

$$Z_{\text{aft}}(r) = 0.114 + (1.962)^2 \times \left(0.632\exp\left(-\frac{r}{0.905}\right) - 0.016\right) \tag{18}$$

3 Statistical Characteristics of EUDLs

3.1 Characteristics of influence surface

The formwork system is shown in Fig. 4. The VML acting on the form face is transmitted to the shore through the joist, bearer, and U-head, and the shore bears the axial pressure.

The maneuver method was used to draw the influence surface for the shore axial force. The commercial software ANSYS was adopted to study the characteristics of the influence surface. The model featured an 8 × 8 bay with the longitudinal and transverse span and bearer spacing set as 1.2 m. The joist spacing is 0.2 m. Except for

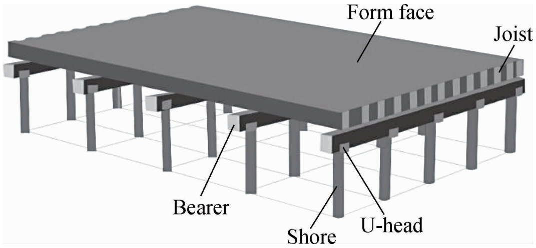


Fig. 4 Schematic diagram of the formwork system

the target shore (constraining the displacement in the X and Y directions), the displacement in the X, Y, and Z directions at the lower nodes of all shores was constrained. More details can be found in Ref. [23]. Fig. 5 shows the influence surface of the target shore obtained by the maneuver method.

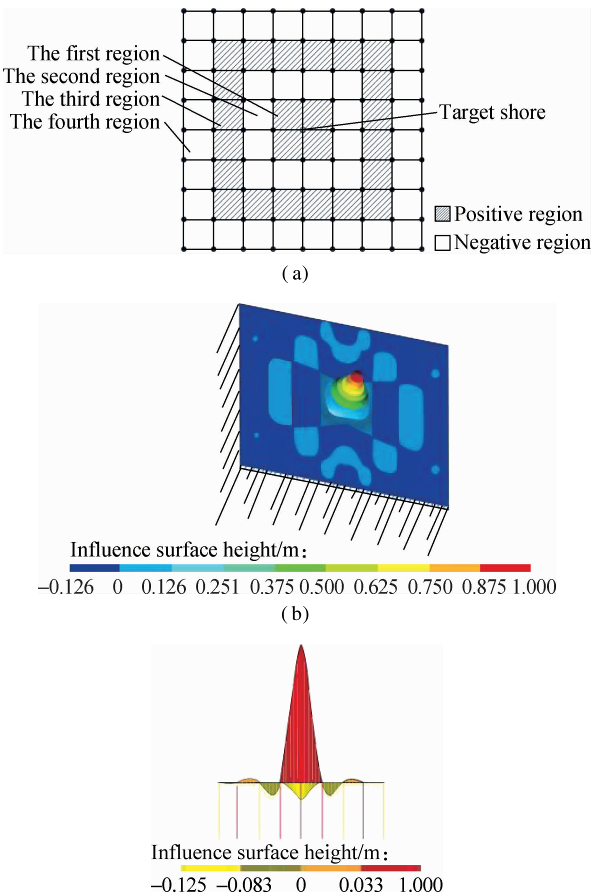


Fig. 5 Influence surface of the shore: (a) Positive and negative regions; (b) Three-dimensional diagram; (c) Sectional diagram

Fig. 5 shows that the adjacent two spans of the target shore have a great impact on the influence surface. The region separated by two or three spans from the target shore has almost no impact on the influence surface, and the influence can be ignored. The influence surface height has strong local effects. According to the characteristics of the influence surface, the load was arranged in the form's surface region of two spans around the target shore to obtain the most unfavorable condition.

3.2 Modeling and loading

The model featured a 6 × 6 bay with the longitudinal and transverse span and bearer spacing set as 1.2 m. The total height used is 3.2 m. Other modeling details are consistent with those presented in Section 3.1. The finite element model is shown in Fig. 6.

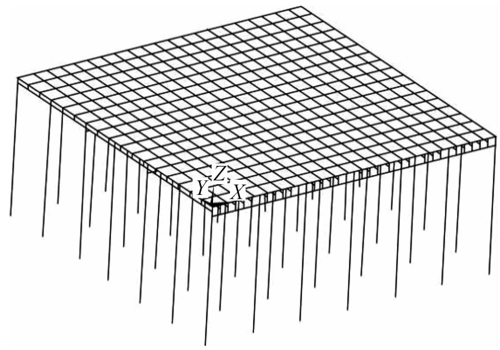


Fig. 6 Finite element model of the formwork

The load was applied to the formwork according to the stockpiling sequence of materials on the form surface prior to concrete placement. The 4 × 4 bay form, including the target shore, was divided into several grids. The grid size was set to 0.6 m × 0.6 m. The multi-load step method was used to solve the axial force of the shore. Fig. 7 shows the direction and boundary of the applied load. The VMLs were generated according to the aforementioned random field model. The random field model mainly includes three parts: constant μ_q, random variable γ_p, and two-dimensional stationary random field $\varepsilon(x, y)$. The process of generating loads is summarized as follows:

1) According to the function obtained by combining the constant μ_w with the random variable γ_p, which obeys an exponential distribution, the random load sample $\boldsymbol{F}_1$ can be outputted by adopting MATLAB software.

2) When the distancer is set, the corresponding value of the correlation coefficient is calculated using Eq. (13). Then, the resulting value is transformed into the matrix $\boldsymbol{D}_1$.

3) Matrix $\boldsymbol{A}$ obtained by the Cholesky decomposition matrix $\boldsymbol{D}_1$ can be expressed as $\boldsymbol{D}_1 = \boldsymbol{A}^{\mathrm{T}}\boldsymbol{A}$. The matrix $\boldsymbol{D}_1$ is transformed into the standard normal distribution correlation coefficient matrix $\boldsymbol{D}_2$ based on the Nataf transformation. Accordingly, the multidimensional standard normal distribution sample $\boldsymbol{B}$ can be obtained.

4) The multidimensional normal distribution sample $\boldsymbol{C}$ corresponding to the correlation matrix $\boldsymbol{D}_2$ can be expressed as $\boldsymbol{C} = \boldsymbol{B}\boldsymbol{A}^{\mathrm{T}}$. The matrix $\boldsymbol{C}$ is used for the Cholesky decomposition to obtain the load sample $\boldsymbol{F}_2$.

5) The results obtained by combining the samples $\boldsymbol{F}_1$ with $\boldsymbol{F}_2$ are used for loading.

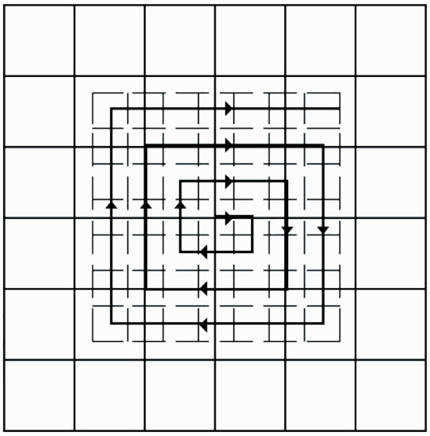


Fig. 7 Load pattern of the model

3.3 Statistical analysis and recommended value

This study mainly examined the EUDL corresponding to the maximum axial force of the shore during the loading process. The bearing area method was used to calculate the EUDL on the form surface. According to the relationship between the shore axial force and bearing area, the EUDLS can be obtained as follows:

$$S = \frac{N_{max}}{A_n} \tag{19}$$

where N_{max} is the maximum shore axial force and A_n is the bearing area of the shore.

To ensure the accuracy of the calculation results and save the calculation time, 500 Monte Carlo simulations were performed for the formwork system under random loads. The spiral loads were performed in the grid according to the distance between the center point of the grid and the central grid. The maximum axial force of the target shore was obtained during the loading process. The EUDLS was calculated using Eq. (19). Fig. 8 shows the frequency histogram for the EUDL. Through simulation calculation, the mean value of the EUDL for the target shore is 2.73 kPa, and the coefficient of variation is 0.30. A goodness-of-fit test, namely, the chi-squared test, was performed. The results show that the maximum EUDL S can be best fitted by a normal distribution.

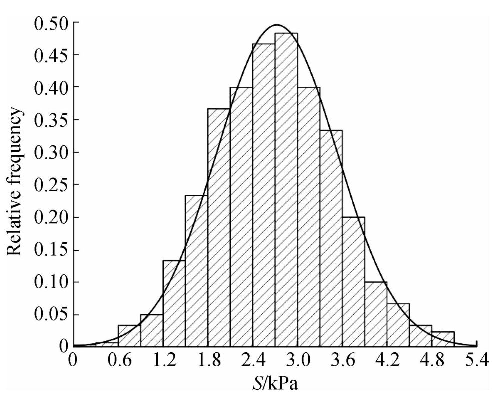


Fig. 8 Histogram for the EUDL (fitted with a normal distribution)

Refer to the method of taking the standard value of load in the normal service stage of the structure; that is, the standard value takes the load value with a 95% guarantee rate. Based on this, the distribution law of the obtained EUDL was used to determine the standard value. Based on the statistical analysis, the 95% quantile value of the EUDL for the target shore is 4.1 kPa. Compared with the standard value specified by the Australian standard AS 3610-1995[20] template design, it is close to the standard value of VMLs, which is 4.0 kPa. To simplify the calculation and consider the technical situation of general construction enterprises, the VML standard value of reinforced concrete structures prior to concrete placement should be 4.1 kPa in the relevant Chinese construction specifications. The in situ survey data show that a large number of materials may well be stacked on the surfaces of the formwork before and after concrete placement. Considering that the Chinese standards neglect the detailed provisions on VMLs, the recommended value can provide a reliable basis for perfecting the standards and improving the safety level of formwork systems. However, due to the limited data sources of the investigation and many factors affecting the load distribution, we will further conduct several in situ investigations and analyses in the future to make the conclusion more universally applicable.

4 Conclusions

1) The statistical characteristics of VMLs were obtained through an in situ investigation prior to and after concrete placement. The statistical results clearly indicate that the VMLs among construction sites vary greatly.

2) A random field model was established to describe the VMLs. With the increase in the distance, the correlation coefficient of the random field zero-mean load decreases gradually and finally approaches zero prior to and after concrete placement. The relationship between the correlation coefficient and distance obeys an exponential distribution.

3) The maneuver method was used to draw the influence surface for the axial force of the shore. The results show that the adjacent two spans of the target shore have a great impact on the influence surface, and the region separated by two or three spans from the target shore has almost no impact on the influence surface.

4) The Monte Carlo simulations of the formwork system under random loads show that the maximum EUDL obeys the normal distribution. The recommended value of VMLs prior to concrete placement for concrete structures is 4.1 kPa. The research results can be used for reference to perfect the standards and improve the safety level of formwork systems.

5) Many factors affect the distribution of VMLs. In the future, we will further perform several in situ investiga-

tions and analyses to make the conclusions more universally applicable.

References

[1] Carper K L. Structural failures during construction[J]. *Journal of performance of constructed facilities*, 1987, **1**(3): 132 − 144. DOI: 10. 1061/(ASCE) 0887-3828(1987)1:3(132).

[2] Hadipriono F C, Wang H K. Causes of falsework collapses during construction[J]. *Structural Safety*, 1987, **4**(3): 179 − 195. DOI: 10. 1016/0167-4730(87)90012-9.

[3] Cimellaro G P, Domaneschi M. Stability analysis of different types of steel scaffolds[J]. *Engineering Structures*, 2017, **152**: 535 − 548. DOI: 10. 1016/j. engstruct. 2017. 07. 091.

[4] Buitrago M, Moragues J J, Calderón P A, et al. Structural failures in cast-in-place reinforced concrete building structures under construction[J]. *Handbook of Materials Failure Analysis*, 2018, **6**: 153 − 170. DOI: 10. 1016/B978-0-08-101928-3. 00008-2.

[5] Structural Engineering Institute. Design loads on structure during construction: SEI/ASCE 37-02 [S]. Reston, VA, USA: American Society of Civil Engineers, 2002.

[6] Zhang C M, Fang D P, Geng C D, et al. In situ investigation and statistical analysis of live loads of reinforced concrete buildings during construction[J]. *Engineering mechanics*, 2002, **19**(5): 62 − 66. DOI: CNKI: SUN: GCLX. 0. 2002-05-011. (in Chinese)

[7] Hu X P, Peng G, Zhang C Z, et al. Investigation and statistical analysis of variable loads of concrete building during construction[J]. *Journal of Hohai University (Natural Sciences)*, 2019, **47**(02): 131 − 137. DOI: 10. 3876/j. issn. 1000-1980. 2019. 02. 007. (in Chinese)

[8] Jian C J, Hu C M, Ye Z W, et al. In situ investigation and statistical analysis of live loads of large span frame structure during construction[J]. *Construction Technology*, 2015, **44**(15): 32 − 34. DOI: CNKI: SUN: SGJS. 0. 2015-15-011. (in Chin- ese)

[9] Xie N, Zhang J, Zhang L, et al. Surveys and statistical analyses of construction loads during concrete placement based on influence surface[J]. *Engineering Mechanics*, 2015, **32**(2): 90 − 96. DOI: 10. 6052/j. issn. 1000-4750. 2013. 08. 0 729. (in Chinese)

[10] Karshenas S, Ayoub H. Construction live loads on slab formworks before concrete placement[J]. *Structural Safety*, 1994, **14**(3): 155 − 172. DOI: 10. 1016/0167-4730(94)90082-5.

[11] Ayoub H, Karshenas S. Survey results for concrete construction live loads on newly poured slabs[J]. *Journal of Structural Engineering*, 1994, **120**(5): 1543 − 1562. DOI: 10. 1061/(asce)0733-9445(1994)120:5(1543).

[12] Rosowsky D V, Philbrick T W, Huston D R. Observations from shore load measurements during concrete construction[J]. *Journal of Performance of Constructed Facilities*, 1997, **11**(1): 18 − 23. DOI: 10. 1061/(ASCE) 0887-3828(1997)11: 1(18).

[13] Ikäheimonen J. *Construction loads on shores and stability of horizontal formworks*[D]. Stockholm, Sweden: Royal Institute of Technology, 1997.

[14] Puente I, Azkune M, Insausti A. Shore-slab interaction in multistory reinforced concrete buildings during construction: An experimental approach[J]. *Engineering Structures*, 2007, **29**(5): 731 − 741. DOI: 10. 1016/j. engstruct. 2006. 06. 018.

[15] Zhang H, Reynolds J, Rasmussen K J R, et al. Reliability-based load requirements for formwork shores during concrete placement[J]. *Journal of Structural Engineering*, 2016, **142**(1): 04015094. DOI: 10. 1061/(ASCE) ST. 1943-541X. 0001 362.

[16] Jin W L, Yuan X X, Liu X, et al. Grey relational comprehensive evaluation based on fuzzy numbers and its application in risk analysis for fastener-style tubular steel formwork-support[J]. *Journal of Southeast University (Natural Science Edition)*, 2006, **36**(4): 621 − 624. DOI: 1001-0505(2006)04-0621-04. (in Chinese)

[17] Yuan X X, Jin W L, Chen T M. Structural reliability of reinforced-concrete building under construction[J]. *Industrial Construction*, 2011, **41**(5): 60 − 65. DOI: 10. 13204/j. gyjz2011. 05. 017. (in Chinese)

[18] Rosowsky D V, Stewart M G. Probabilistic construction load model for multistory reinforced-concrete buildings [J]. *Journal of Performance of Constructed Facilities*, 2001, **15**(4): 145 − 152. DOI: 10. 1061/(ASCE)0887-3828(2001)15:4(145).

[19] Standards Policy and Strategy Committee. Falsework—Performance requirements and general design: BS EN 12812:2008 [S]. London, UK: British Standards Institution, 2011.

[20] Standards Australia. Formwork for concrete: AS 3610-1995 [S]. Sydney, Australia: Standards Australia, 1995.

[21] Karshenas S, Ayoub H. Analysis of concrete construction live loads on newly poured slabs[J]. *Journal of Structural Engineering*, 1994, **120**(5): 1525 − 1542. DOI: 10. 10 61/(ASCE) 0733-9445(1994)120:5(1525).

[22] Peir J C, Cornell C A. Spatial and temporal variability of live loads[J]. *Journal of the Structural Division*, 1973, **99**(5): 903 − 922. DOI: 10. 1061/JSDEAG. 0003512.

[23] Du T, Xie N, Liu Z T, et al. Probabilistic limit state design of falsework considering joint lap defects during concrete pouring period[J]. *Journal of Southeast University (Natural Science Edition)*, 2021, **51**(4): 575 − 580. (in Chinese)

施工期模板支架体系可变材料荷载的调查与统计分析

杜　涛[1]　谢　楠[1]　贾松松[2]

([1]北京交通大学土木工程学院，北京 100044)
([2]唐山建投房地产开发有限公司，唐山 063000)

摘要：为了准确预测施工期间混凝土结构的可变材料荷载(VML)，在立杆中产生与实际 VML 相同荷载效应的等效均布荷载(EUDL). 对混凝土浇筑前后钢筋混凝土结构的 VML 进行现场调查和统计分析，得到其统计特征，并进行随机建模，推导出其空间相关性，建立了模板系统的有限元模型. 利用机动法分析立杆轴力影响面的特点，对模板面施加随机荷载，计算出与实际 VML 具有相同荷载效应的 EUDL. 基于一般情况下荷载标准值的取值方法，得到混凝土浇筑前 VML 的建议取值. 结果表明：在不同施工现场所调研的 VML 差异较大；随着距离的增加，随机场零均值荷载的相关系数逐渐减小；VML 的推荐值可为模板支架体系的设计和安全控制提供可靠依据.

关键词：模板支架体系；可变材料荷载；随机场；影响面；等效均布荷载

中图分类号：TU755.2；TU312