Analysis on the Anti-Seismic Dynamic Response of Steel Structure Derrick in Mines under Seismic Excitation

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Abstract: This electronic document is a "live" template. The various components of your paper [title, text, heads, etc.] are already defined on the style sheet, as illustrated by the portions given in this document. (Abstract) Taking the steel derrick of a coal mine as the research object, the tensile stiffness and vibration damping force of each wire rope are calculated by analyzing the elastic body theory and equivalent principle, and the structural model of the mine steel structure Derrick is constructed according to the calculation results. Through the simulation experiment, the seismic dynamic response of the mine steel structure Derrick under seismic excitation is analyzed. Firstly, the multi-mass point spatial bar system model is used to draw the seismic influence coefficient curve, and the low-order mode is taken to analyze and improve the calculation accuracy. Secondly, the vibration mode decomposition response spectrum method is used to calculate the hoisting inclined steel Derrick, and the seismic influence coefficient curve is drawn according to the simulated seismic fortification intensity and characteristic period data by time history analysis. In order to analyze the natural vibration period and vibration mode participation quality, the solution is carried out according to MIDAS Civil finite element software. And finally, according to the transient dynamics, the structural strength under the worst working condition in the results is calculated, and the stress time-history curve at the maximum stress is obtained. The results show that, in case of earthquake, the stress intensity requirement is met by the method of this paper.

Keywords: Seismic excitation; Steel structure derrick; Anti-seismic dynamic response

1. Introduction

With the continuous improvement of design and production capacity of large-scale mines, steel derrick has become the main structure of mines to advance production. The lifting of minerals and the transportation of materials are accomplished by lifting the steel derrick, which has been widely used in mines at home and abroad, especially in the coal industry. As a special structure, derrick is faced with the threat of being damaged by sudden earthquakes. In order to improve the safety and reliability of seismic design of steel derrick structure as well as to ensure the seismic fortification quality of steel derrick, we conduct an in-depth study on the anti-seismic performance of steel derrick structure to clarify the anti-seismic safety of steel derrick under the earthquake action, and reduce the loss caused by the earthquake disaster [1].

2. Dynamic Model of Mine Steel Structure Derrick

2.1. Theory of elastomer and principle of equivalence

2.1.1. Theory of elastomer

Elastomer is a system with distributed physical parameters, such as mass, stiffness and damping. It is a continuous system composed of numerous particles by elastic connection. It is necessary to use partial differential equation to study the vibration of elastic body. Similarly, in the present stage, we must rely on the hypothesis theory and the principle of equivalence of the ideal elastomer.

2.1.2. Principle of equivalence

(1) Equivalent stiffness

When establishing the dynamic model, each elastic element needs to be represented by a spring with equivalent stiffness in terms of bending stiffness, torsion stiffness and tension compression stiffness [2]. In the derrick system, each unit is a load-bearing element. If the potential energy of elastic deformation is conserved, its equivalent stiffness is the converted composite stiffness. The tensile stiffness is the main measurement index of steel wire rope in the traveling system. The tensile stiffness of each rope is expressed as:

$$k_0 = \frac{EA}{L} \tag{1}$$

In the above equation, E is the elastic modulus of the material, A is the equivalent section radius of the wire rope, and L is the effective length of the rope.

Set the effective rope number of the traveling system as n. According to the characteristics of "equivalent spring" parallel system, the "equivalent stiffness" can be obtained. The calculation formula is as follows:

$$k_i = nk_0 \tag{2}$$

(2) Equivalent damping

In the vibration system, the response of the component to the external force is expressed as a certain moving speed from the angle of damping. The steel wire rope and derrick are mainly characterized by viscous damping, while the friction damping caused by system friction, material damping generated inside the material and relative sliding damping between components are ignored [3]. The so-called equivalent damping here should be the combination of the viscous damping of each part.

If the expression of steady-state response of forced vibration is:

$$y_i = A\sin(wt - f) \tag{3}$$

And the viscous damping force is directly proportional to the speed, thus:

$$f(x) = cx \tag{4}$$

In this equation,

$$c = 2xw_i \tag{5}$$

In the above equation, $w_i = \sqrt{k/m}$ is the period of vibration. In a certain period, the energy consumed by the vibration of the steel structure derrick of the mine is as follows:

$$W_f = f(x)cpwR^2 \tag{6}$$

According to equation (6), the viscous damping force of the steel structure derrick of mine under vibration condition is directly proportional to the energy consumed. In summary, the vibration damping force can be obtained:

$$Z(n) = f(x)\sqrt{A^2 + W_f^2} \tag{7}$$

2.2. Structural model of mine steel structure derrick

The steel derrick of a coal mine shaft is analyzed. Both vertical frame and diagonal brace are space truss system, which are important parts of derrick [4]. The total height of the steel derrick is 18 m, and the height from the wellhead to the bottom of the derrick is 14 m; four vertical frames are standard H-shaped steel 250 × 250 × 9, the lower end is connected with reinforced concrete foundation, the diagonal brace is standard double angle steel 75 × 75 × 8 back connection, and the cross beam is standard double channel steel 140 × 58 × 6 back connection. All steel is Q235 steel. The elevation layout of steel derrick is shown in Figure 1.

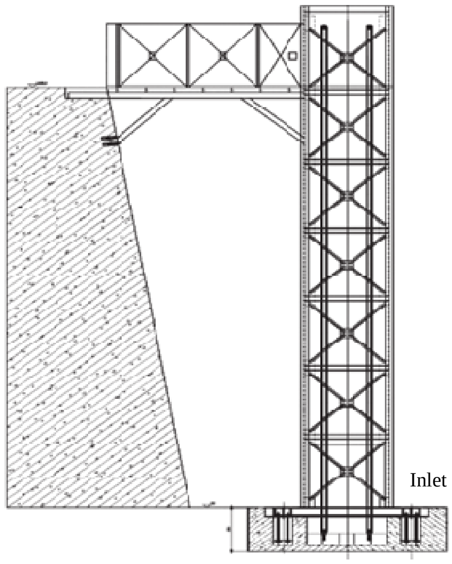

Figure 1. Structural model of mine steel structure derrick

2.3. Transient dynamic calculation model

Solve the transient response under the vibration period w_i. Firstly, it is necessary to analyze the pulse input response of the mine steel structure derrick, and combined with superposition algorithm calculate the pulse input response of the mine steel structure derrick under w_i. The calculation results are as follows:

$$X(y) = Z(n)e + \frac{1}{mv} y_i \tag{8}$$

The transient dynamic equilibrium equation of linear structure is as follows:

$$D_s = (M_u + F)K_t \tag{9}$$

In this equation, M_u represents the quality of the steel structure derrick of the mine; F represents the damping matrix under the earthquake excitation; K_t represents the time load under the earthquake excitation [5]. In a certain time interval Δt, the finite difference method is used to analyze the acceleration a, velocity v_a and displacement vector x_a of derrick structure, and the relationship analysis results are as follows:

$$a = \frac{v_a}{\Delta t[(1-d)x_a]} g_i \tag{10}$$

In th e above equation, g_i is the time integration step.

3. Seismic Horizontal Shear Analysis

Based on the above analysis, the boundary load of derrick structure is calculated. The gravity of monkey board and crown block can be simulated by Mass 21 lumped mass unit, and the vertical components of the self weight of traveling system, rated hook load and working rope force can be applied to the top of derrick on average.

The rated hook load is also called the maximum drill string gravity, and the calculation equation is:

$$Q_i = jp \tag{11}$$

In the above equation, j represents the average gravity of derrick foot; j represents well depth.

In addition, the seismic horizontal force should be considered. In this paper, the bottom shear method is used to analyze the mine derrick. According to its structural characteristics, the structure is divided into three layers: Y-shaped substructure, lower section and upper section, and the seismic shear force is applied to each layer. The calculation formula of seismic horizontal shear force F_i of layer i is:

$$F_i = a\frac{Qh}{D_s} \tag{12}$$

In this equation, h represents the derrick height. Through the above relationship analysis, the dynamic response of the derrick under the earthquake excitation can be obtained. In order to verify the effectiveness and feasibility of the method, simulation experiments are carried out.

4. Analysis of Calculation Results

According to article 11.2.4 of Code for Seismic Design of Structures, anti-seismic calculation of inclined steel derrick should adopt multi-point space bar system model. When the mode decomposition response spectrum method is adopted, more than 3 modes shall be taken for the single rope hoisting diagonal steel derrick, and more than 5 modes for the multi rope hoisting diagonal steel derrick. For 8 degree soft site and 9 degree soft site, time history analysis method should be used for supplementary calculation. In this paper, the seismic fortification intensity is 7 degrees (0.15 g), and the characteristic period is 0.45 s. The seismic group is designed as group 3 and site II to draw the seismic influence coefficient curve, as shown in Figure 2.

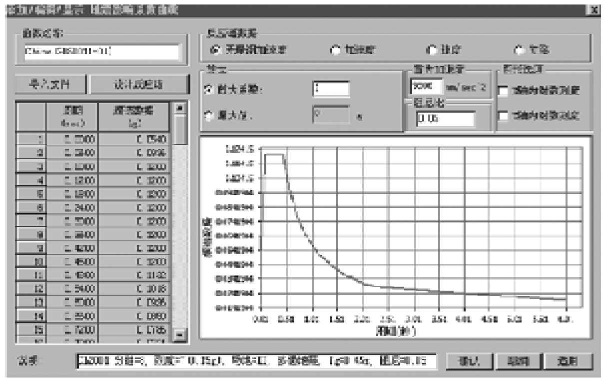

Figure 2. Seismic influence coefficient curve

The vibration of derrick is dominated by the low-order vibration mode, while the high-order vibration mode has little influence on the vibration of derrick, so several low-order vibration modes should be taken for analysis. To sum up, MIDAS Civil finite element software will be used to solve the first 15 modes, and the natural vibration period and mode participating mass of the first 3 modes of the structure will be taken for analysis, as shown in Table 1 and Table 2 respectively.

Table 1. Vibration period and frequency of the first three modes of the structure

Eigen-value Analysis			
Modal number	Frequency		cycle /s
	Rad/s	Cycle/s	
1	10.62	1.52	0.36
2	13.98	2.62	0.51
3	25.64	4.03	0.19
4	20.65	3.88	0.41
5	16.84	3.15	0.32

Table 2. Mass participation coefficient of structural vibration mode

	Mode 1		Mode 2		Mode 3	
Modal number	Participating Mass Ratios	Total	Participating Mass Ratios	Total	Participating Mass Ratios	Total
1	92.36	92.36	0.00	0.00	0.00	94.21
2	0.00	92.36	96.65	96.65	86.32	91.23
3	96.56	96.56	0.00	0.00	0.00	98.36
4	91.62	91.62	93.16	93.16	97.36	0.00
5	96.25	96.25	0.00	0.00	0.00	0.00

4.1. Analysis of derrick displacement under earthquake excitation

When the same seismic shear force acts on the derrick from different directions, the maximum equivalent stress and the maximum total displacement of the structure can be obtained by using the linear elastic static calculation model and the results are shown in Table 3.

Table 3. Maximum stress and total displacement of derrick under different working conditions

Seismic condition	x+	x-	Y +	y-	z+	z-
Maximum Stress /MPa	135	134	146	127	121	136
Total Maximum Displacement /mm	36.44	36.64	42.92	30.30	35.81	36.98

According to Table 3, when the seismic shear force acts along the y+ direction (front opening direction), the maximum stress of derrick structure reaches 146 MPa, and the maximum total displacement is about 0.043 m, among which the maximum stress occurs at the main support of Y-shaped substructure.

4.2. Maximum transient stress analysis of derrick

Taking the worst working condition above for analysis, the structural strength of the derrick of the workover rig is calculated by using the transient dynamic calculation model. Firstly, the optimal time step $\Delta t \approx 0.004$ s is calculated by modal analysis. The mass damping and stiffness damping are 0.778 and 6.363 × 10-3 respectively. In addition, the calculation accuracy is improved again by setting the maximum number of sub steps (NSUBST) of automatic optimization time integration. Assuming that the initial displacement, initial velocity and initial acceleration of the derrick are all 0, the stress time history curve at the maximum stress is shown in Figure 3.

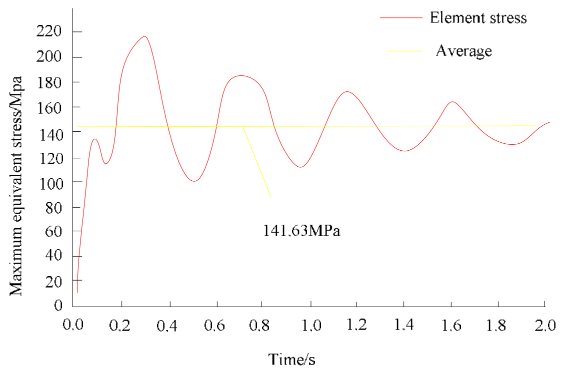

Figure 3. Stress Time History Curve at Maximum Stress

From Figure 3, it can be seen that when t = 0.29 s, the maximum structural stress is 214 MPa, and then it gradually tends to be stable with the average stress after stabilization being about 141 MPa. According to API Spec 4F standard, if the safety factor of stress is 1.33, then the allowable stress σ = σ s / N = 259.4mpa, which indicates that the derrick body still meets the stress intensity requirements when the seismic intensity is 7 with a frequent earthquake situation.

5. Conclusion

In the existing research stage, people do not know the seismic structure of steel derrick, and the existing steel derrick has poor ability to deal with sudden earthquake. Based on the theory of elastic body and the principle of equivalence, this paper calculates the equivalent damping and the equivalent rigid body, and constructs the dynamic model of steel structure derrick. Combined with the superposition algorithm, the instantaneous response is analyzed. With considering the whole situation of the transient response and excluding the transient response with large difference, the data is effective and reasonable, which is conducive to the analysis of the seismic structure of the steel structure derrick. The stable instantaneous response results play an important role in the analysis of anti-seismic performance. Setting low-order vibration mode as the dominant factor of derrick vibration and excluding the non main influence of high-order vibration mode have eliminated the difference for the analysis of main anti-seismic structures.

The method in this paper defines the anti-seismic structure of steel structure derrick, which plays a key role in strengthening the seismic performance of steel structure derrick, improving the safety of mine operation, and playing a very important role in the global anti-seismic.

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