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# Design and Reliability Research of Supporting Structure for Deep Mine Vertical Drainage System

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ABSTRACT: The deep mine vertical drainage system is characterized with large running loads and high requirements for the rigidity and stability of supporting structure, so the three-dimensional solid model of supporting structure is built on the basis of designing the supporting structure and the essential sizes. Take the 800-metre deep mine as an example. Based on static load analysis, Water hammer stress under different working conditions are analyzed by the transient analysis software of water hammer, Obtain the load of supporting structure under conditions of water hammer. The assessment of its reliability and the prediction of fatigue life are made according to the reliability evaluation of the supporting structure model made by ansys workbench software of finite element analysis. The reliability and safety of the supporting structure are verified by its application in projects, which provides guidance for the design of similar supporting beams.

KEY WORDS: Deep mine; Vertical drainage system; Design of supporting structure; Load analysis; Reliability research.

## INTRODUCTION

In recent years, with the large scale mining of coal resources, the coal resources in shallow formation has been gradually exhausted, leading to the coal resource mining practice gradually shifting from shallow formation to deep formation [1-3]. Despite the existence of over 800 meter mining depths for some mines, the mining depths continue to increase by 100~250 m per decade, thus the probability for sudden-onset water disasters in mines is exhibiting rising tendency accordingly [4]. Once water disasters occur in such deep mines, the vertical drainage system is the most common rescue facility. This drainage system is vertically lifted. Through the seat tube connected with drain line, the system's total weight, dynamically stored water weight during operation, and water hammer force during pump failure are all sustained by the wellhead supporting beam [5], therefore, the design of supporting beam is the vital section of the whole system design, which directly determines whether the whole drainage system can be safely operated or not. Conventional support structures are a type, K type or tower model derrick. Due to the disadvantages such as complex design and inconvenience for installation, these support structures can neither meet the manoeuv reability requirement of emergency rescue drainage in mine, nor meet the big load, high intensity, and stability of vertical rescue drainage system operation in deep mines. Most existing papers researched the reliability of support structure of mine drainage system the by static load force analysis and modal analysis [6, 7], while less analyzed the reliability of support structure under pump failure condition. As a result, there is a necessity to redesign the support structure of vertical rescue drainage system by considering the influence of pump failure working condition, so as to guarantee the reliability and stable operation of support structure under various working conditions.

In this paper, firstly the installation form of support structure was designed according to requirement of specific engineering project, and then the critical sizes of support structure were determined based on the design formula; Secondly, by taking the 800 m deep mine as example, the load applied on the support structure under normal working condition was analyzed, in addition, the loads applied on support structure under various working condition were calculated using the HARMMER water hammer transient analysis software, so as to obtain the load value applied on support structure under pump failure condition. Moreover, after establishing 3D support structure model, the ansys workbench software of finite element analysis was adopted to perform the simulation analysis and modal analysis on the bearing reliability of the model under various working conditions and fatigue life prediction under pump failure condition, thus the evaluation was given on the reliability of supporting beam design [9, 10]; Finally, the reliability

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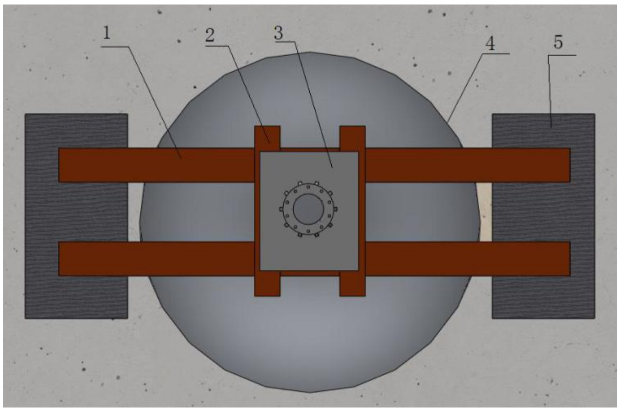
safe operation of the support structure were verified by a successful application of the support structure in a deep mine rescue drainage engineering in China.

## DESIGN OF SUPPORT STRUCTURE

### Whole Design of Support Structure

The vertical rescue drainage system is installed in the way of "heavy load suspension, dive to the bottom", and the whole design of the support structure is shown in Figure 1. During the installation process, the drainage system is installed in sections by the combined method of winch, hold card, and supporting beam. It is necessary to constantly adjust the distance between two supporting beams, so as to guarantee all parts passing through smoothly and the temporary stay of drainage system. However, the crossbeam cannot be moved easily due to the heavy weight, and to meet the demanding for constantly moving the derrick, we employed a method that a pair of crossbeams was on the foundation while a pair of joists was fixed on the crossbeams, forming a structure looking like Chinese character "井", therefore, when the drainage system is put down in sections for installation, it is only needed to adjust the locations of joists on crossbeams to guarantee the smooth installation of drainage system. When the system is lowered to a proper depth, the seat tube will be installed, via which the whole drainage system weight can be sustained on the support structure. The whole design of support structure is shown in Figure 1.




1- crossbeam, 2- joist, 3- seat tube, 4- wellbore, 5- foundation

**Figure 1.**The whole design of support structure.

### Determination of Support Beam Size

According to the requirements on wellhead diameter and installation size, the length *l* of beam is determined. To guarantee the universal usage of the support structure, normally the crossbeam length is set as 12000 mm, joist length is set as 1900 mm. Then based on the design formula, the beam height *h,* beam breadth *b,* thickness of up and down cover plates $a_{ud}$ , thickness of left and right cover plates $a_{lr}$ , and the clapboard thickness $a_g$ , and distance between clapboards $d_j$ are successively determined.

*(1) Determination of beam height h and breadth b*

To guarantee the convenience for installation, the beam height should meet:

$$h = k \bullet l \tag{1}$$

Beam breadth should meet:

$$\frac{h}{6} \le b \le \frac{3h}{5} \tag{2}$$

In the equation, *l*-beam length (mm); *h*-beam height (mm);

*b*- beam breadth (mm); *k*-value range 1/12~1/3.

*(2) Determining the thickness of up and down cover plates*

The thickness of up and down cover plates $a_{ud}$ and the breadth of crossbeam *b* should meet:

$$a_{ud} \geq \frac{b}{13\sqrt{\frac{235}{\sigma}}} \tag{3}$$

In this equation: $a_{ud}$ - the thickness of up and down cover plates (mm);

*b*- beam breadth (mm);

$\sigma$ -material yield strength (*Mpa*).

*(3) Determining the thickness of left and right cover plates* $a_{lr}$

$$a_{lr} \geq \frac{\sqrt{h_{lr}}}{3.5} \tag{4}$$

$$h_{lr} = h - 2a_{ud} \tag{5}$$

In this equation: $a_{lr}$ - the thickness of left and right cover plates (mm);

$h_{lr}$ - The height of left and right cover plates (mm).

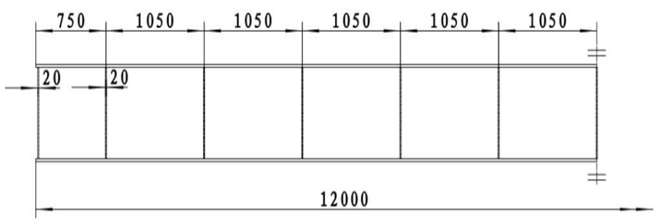
*(4) Determination of clapboard thickness* $a_g$ *and clapboard distance* $d_j$

Normally the clapboard thickness $a_\sigma$ equals to the thickness of left and right cover plates, and the clapboard distance is around 0.5 $h_{lr}$ ～2 $h_{lr}$ , varying from big value when bending moment is big to small value when the bending moment is small. (i.e. Intensive distribution of clapboard at big bending moment while sparse distribution of clapboards at small bending moment)

With yield strength $\sigma$ =345 MPa, steel plate Q345 is selected for supporting beam. According to above design formula, and considering the factors in material selection, the size of supporting beam can be determined as follow:

For crossbeam: *l* = 12000 mm, *h* = 1350 mm, *b* = 400 mm, $a_{ud}$ = 40 mm, $a_{lr}$ = 20 mm, $h_{lr}$ = 1270 mm, $a_\sigma$ = 20 mm, $d_j$ = 1050 mm, the structure size is shown as Figure 2.

For joist: *l* = 1900 mm, *h* = 600 mm, *b* = 350 mm, $a_{ud}$ = 25 mm, $a_{lr}$ = 25 mm, $h_{lr}$ = 550 mm, $a_\sigma$ = 25 mm, $d_i$ = 380 mm, the structure size is shown as Figure 3.



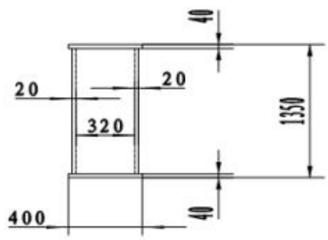



**Figure 2.** Dimensional drawing of crossbeam structure.

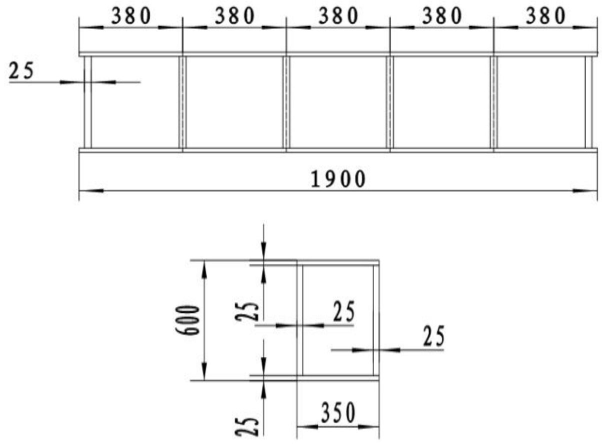



**Figure 3.** Dimensional drawing of joist structure.

## LOAD ANALYSIS OF SUPPORT STRUCTURE

### Static Load Analysis of System Operation

In the case of emergency rescue drainage in 800 m deep mine, it adopted the submersible electric pump with 3200 KV output power, 801 m head, 1000 $m^3$/h flow, 6 KV nominal voltage, 34 T total weight (including wet motor, water pump, water suction cover, motor with full water, and other accessories); The pipeline is made of Q345 seamless steel tube with diameter of 235 m, tube wall of 14 mm. The specification of steel tube is 10m per piece, and the 800m long pipeline totally weighs 91.8 T (including flanges and high-strength bolts); The water retained in pipeline weight totally 55.4 T (0.14852 800 = 55.4); Other accessories weigh 12.4 T (including booster pump and cable).

Total weight of drainage system during the running time = electric pump weight + pipeline weight + weight of water in pipeline + accessory weight = 193.6 T

Loading force sustained by supporting beam = 193600 × 9.8 = 1897280 N.

The contact area between seat tube and joist is 0.777 $m^2$, thus the pressure load on supporting beam can be obtained as 1897280/0.777 = 2441801.8 Pa.

### Load Analysis under the Effect of Pump Failure Water Hammer

In the process of pump failure of drainage system in deep mine, to prevent reverse turning of water pump which is caused by the flowing down of retained water in pipeline, normally a check valve is installed at the outlet end of water pump. Under the effect of check valve, water velocity will be declined to zero in a certain period of time, as we know that flowing water has inertia effect, in the same period of time a water flow shock wave called water hammer will be formed. The water hammer force will be eventually converted to stress which will be periodically acted on support structure [12]. Therefore, during pump failure period, the total load sustained by support structure includes the static load and load caused by water hammer.

In engineering projects, common check valves include fast closing check valve, and slow closing check valve. Theoretically, the slow closing check valve is more effective for declining the water hammer force as compared with the fast closing check valve [13]. Regarding the drainage system working under 800m deep mine, HARMMER water hammer transient analysis software was adopted to respectively simulate the working condition where fast closing check valve was installed at the outlet end of submersible electric pump and the working condition where slow closing check valve (30 s) was installed at the outlet end of submersible electric pump. The simulation results are shown in Figures 4-7.

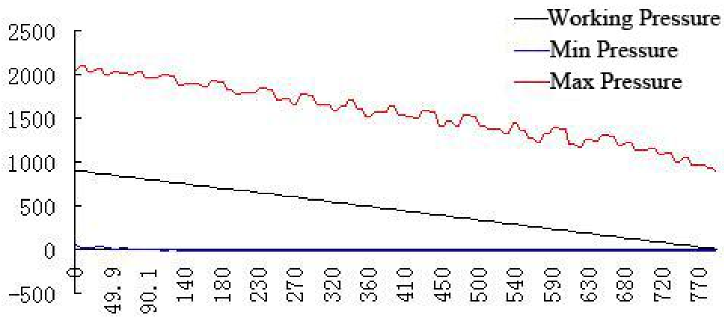



**Figure 4.** Water head envelope curve after installing fast closing check valve at outlet end of pump.

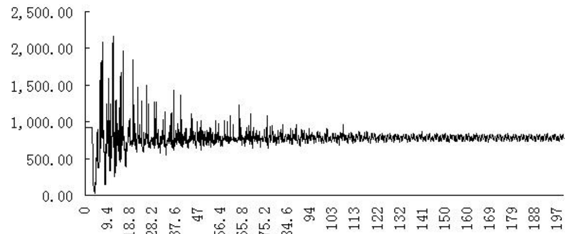



**Figure 5.** Water hammer pressure change after installing fast closing check valve at outlet end of pump.

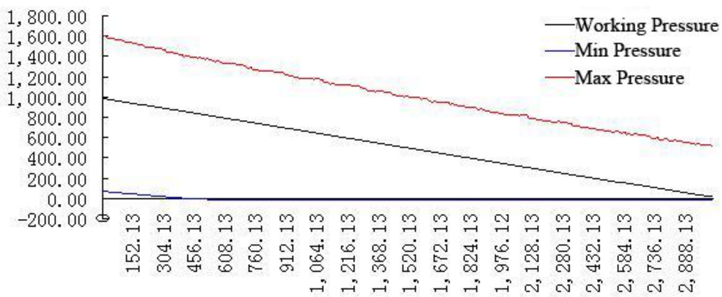



**Figure 6.** Envelope curve after installing slow closing check valve (30 s) at outlet end of pump.

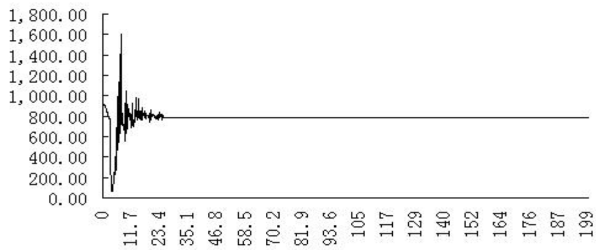



**Figure 7.** Water hammer pressure change after installing slow closing check valve (30 s) at outlet end of pump.

It can be seen from the simulation results in Figures 4-7, when fast closing check valve is installed at the outlet end of submersible electric pump, the max head pressure is 2089.6 m, the action time of water hammer is approximately 100 s, the action cycle of water hammer is about 1000; When slow closing check valve (30 s) is installed at the outlet end of submersible electric pump, the max head pressure is 1607.2 m, the action time of water hammer is approximately 20 s, the action cycle of water hammer is about 200; Obviously, the application of slow closing check valve (30 s) can greatly reduce the head pressure, shorten the action time of water hammer (i.e. water hammer force is smaller) and decrease the action cycle of water hammer, therefore, it is suggested to stop pump by installing slow closing check valve (30 s) at the outlet end of pump in deep mine drainage engineering project.

Total weight of drainage system during pump failure period = electric pump weight + pipeline weight + weight of water in pipeline + accessory weight + 55.4 × (1607.2/800) = 138.2 +111.3 = 249.5 T

Loading force sustained by supporting beam during pump failure period = 249500 × 9.8 = 2445100N.

The contact area between seat tube and joist is 0.777 $m^2$, thus the pressure load on supporting beam can be obtained as 2445100/0.777 = 3146846.8 Pa.

## RELIABILITY ANALYSIS OF SUPPORT STRUCTURE

### Specifications of Supporting Beam

**Table 1.** Specifications of supporting beam.

| Supporting beam | Item | Parameter |
|---|---|---|
| Crossbeam | dimension | L*W*H=12000 mm×400 mm×1350mm, (including 11 ribbed plates) |
| | Material | Q345 |
| | Density | 7850 $kg/m^3$ |
| | Elasticity modulus | $2.06\times10^{11}$ $Pa$ |
| | Poisson's ratio | $\mu$=0.28 |
| | Yield strength | $\sigma_s$=345 $MPa$ |
| Joist | Dimension | L*W*H=1900mm×350mm×560mm, (including 6 ribbed plates) |

### Establishment and Mesh Generation of Support Beam Model

According to the design dimension of support beam, the 3D assembly real model of support beam was constructed using solidworks software, which was then introduced into the software of finite element analysis Ansys workbench for giving material properties. In addition, model segmentation and mesh generation were conducted based on the case of 6 m wellhead, and the results are shown in Figure 8.

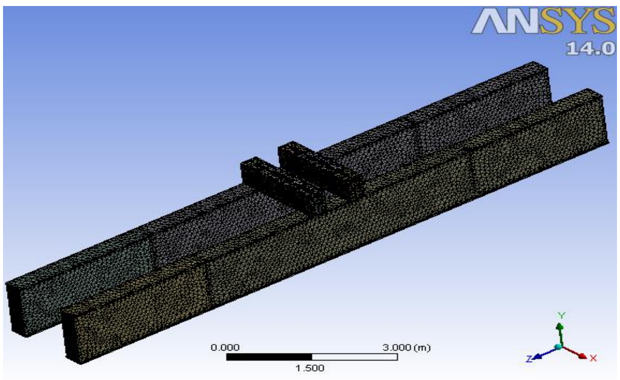



**Figure 8.** Mess generation effect of 3D support beam model.

### Implementation of Boundary Constraint

In the process of simulation analysis using ansys workbench software, according to the loading features of support beam, the crossbeam and joist were added with boundary constraint, respectively.

(1) Displacement constraint was set at the end of crossbeam, wherein displacement was 0 at Y direction, and freedom constraint was set in X and Z direction.

(2) According to the load analysis result of support beam, it was only needed to analyze the working condition under water hammer loading when pump was stopped. Therefore, at the contact area between joist and seat tube, pressure constraint of 3146846.8 Pa in vertically downward direction was implemented.

Results of Reliability Simulation Analysis

*(1) Simulation Analysis of Static Load Bearing*

Using ansys workbench software, it performed the simulation calculation of static load bearing for support structure of drainage system. Results can be observed in terms of Total deformation, Equivalent Stress, and Safety Factor of support beam.

It can be seen from total deformation distribution of support beam in Figure 9, the max total deformation (1.2815 mm) lies in the middle part of joist, which is a relatively small deformation in allowed range. According to the stress distribution and safety factor distribution of support beam in Figure 10, the stress concentrate in the contact area between crossbeam and well base edge with concentration stress value of 86.314 MPa, which is far below the allowable stress of 345 MPa. In addition, the contact area between crossbeam and well base edge is also where the minimum safe factor lies, according to Figure 11, the minimum safe factor is 3.997, which meets the requirement on safe strength.

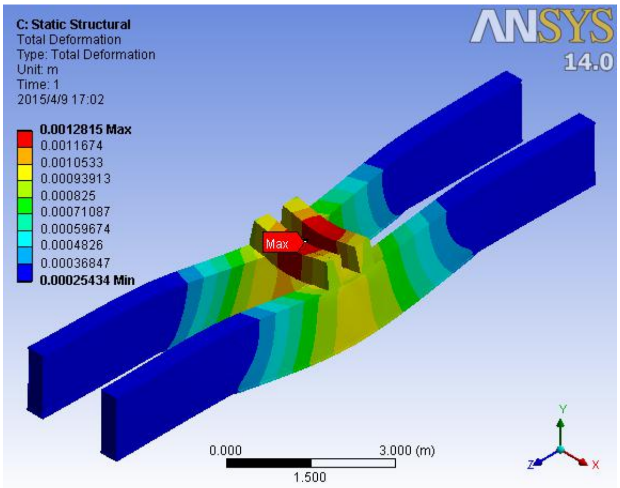



**Figure 9.** Total deformation distribution of support beam.

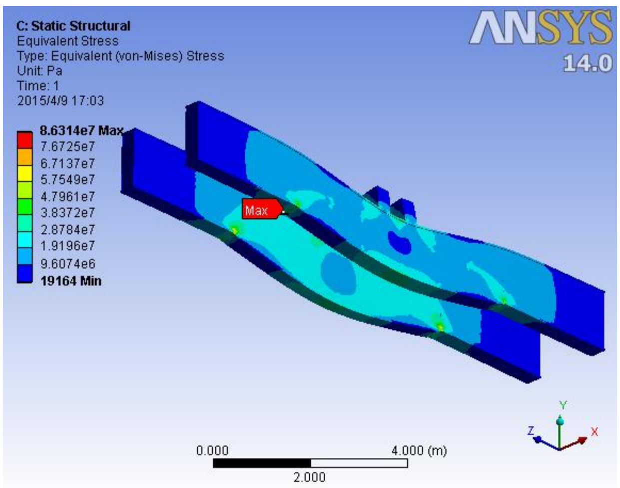


**Figure 10.** Stress distribution of support beam.

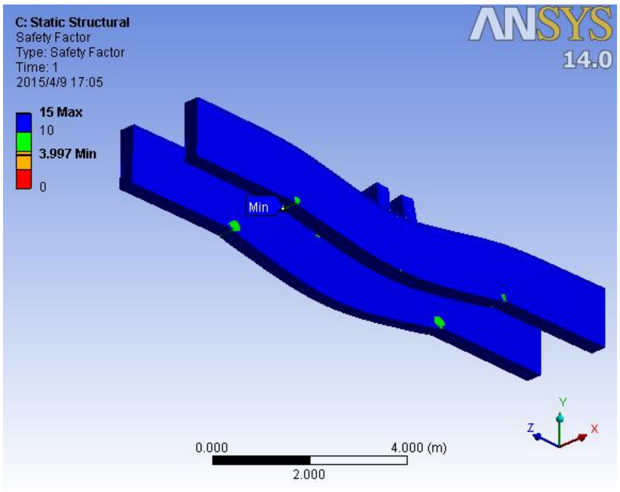



**Figure 11.** Safe factor distribution of support beam.

*(2) Modal Analysis*

To learn the vibration feature of support beam and void the occurrence of sympathetic vibration when drainage system is working, modal analyses were performed for the cross beam and joist, respectively, thus the first six order natural frequencies of crossbeam and joist can be obtained, which are shown in Table 1 and Table 2, respectively.

In normal operation of drainage system, the external excitation source is submersible motor with rotation rate of 1450 r/min, which produces Periodic disturbance frequency of 24.1667 Hz. From Table 1 and Table 2, it can be seen that the natural frequencies of crossbeam and joist in all orders are larger than the disturbance frequency of excitation source. Therefore, in normal drainage process, the support structure ran steadily and smoothly without sympathetic vibration.

**Table 1.** The first 6 order natural frequency of crossbeam.

| Modal order | Frequency (Hz) |
|---|---|
| 1. | 43.633 |
| 2. | 88.55 |
| 3. | 90.292 |
| 4. | 99.1 |
| 5. | 102.07 |
| 6. | 104.67 |

**Table 2.** The first 6 order natural frequency of joist.

| Modal order | Frequency (Hz) |
|---|---|
| 1. | 299.49 |
| 2. | 355.68 |
| 3. | 364.17 |
| 4. | 400.95 |
| 5. | 459.94 |
| 6. | 473.74 |

*(3) Fatigue Life Analysis*

Fatigue is a development process toward non-reversible deformation, cracks or complete break-out under external circulatory force. Fatigue life refers to cycle number and action time of external force before fatigue failure of parts.

In the use process of support structure of deep mine drainage system, it not only bears the external cyclical force, but also bears the continuous water hammer force during pump failure. Therefore, on the basis of static load analysis, the fatigue life analysis was conducted, which can predict the service life of support structure and plays a significant guiding role in using support structure.

The fatigue life of support structure was predicted using Ansys workbench software of finite element analysis. Through inputting the S-N curve of steel material Q345, selecting Goodman correction theory, and setting fatigue factor as 0.85, the analysis results are shown in Figures 12-13.

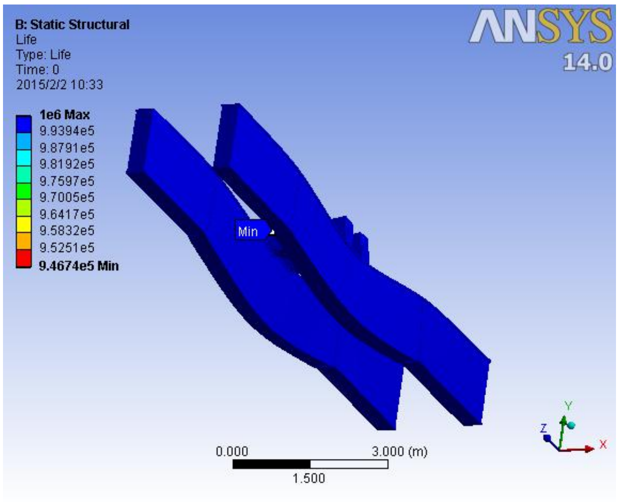



**Figure 12.** Fatigue life distribution of support structure.

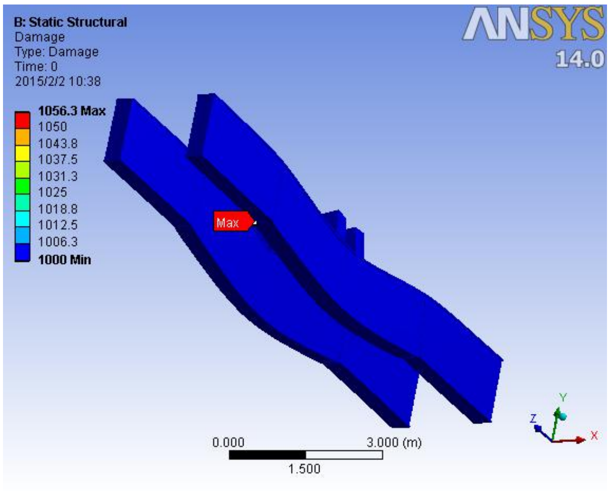



**Figure 13.** Fatigue damage distribution of support structure.

According to analysis results, it can be known that the max fatigue life of support structure is over $10^6$ (infinite fatigue life). Occurred at joist end, the minimum fatigue life is $9.4674\times10^5$, while occurred at the contact area between crossbeam and foundation, the max fatigue life is $9.4674\times10^5$. The occurrence position of fatigue is where minimum fatigue life lies.

In Figure 7, under working condition where slow closing check valve (30 s) is installed at the outlet end of submerged pump, the action cycle of water hammer force is about 200 s. Therefore ,it can predict that the support structure can bear roughly 4733 times of water hammer force during pump failure under working condition where slow closing check valve (30 s) is installed at the outlet end of submerged pump. There data are of vital guiding significance to the safe operation and maintenance of support structure.

ENGINEERING APPLICATION

Taking the emergency rescue drainage in a certain domestic mine as example, where the well hole diameter of auxiliary well is 6.5 m, the elevation of well mouth is 25 m, the elevation of well bottom is -800 m, normal surge water amount is 800 $m^3/h$, the max surge water amount during water inrush is 29,000 $m^3/h$, the net water storage capacity is 3,250,000 $m^3$.

In this mine, a vertical rescue drainage system was adopted, two pairs of 3200 KW power drainage systems were set at the well mouth of auxiliary well, the support beam designed in the method proposed in this paper was adopted as the support structure, and pump was stopped by the slow closing check valve (30 s) installed at the outlet end of pump. In the whole 3 months of drainage, several pump failure processed occurred, however the support structure was always in sound operation, which guaranteed the normal operation of the whole drainage system. After finishing the rescue drainage, flaw detection was conducted on major bearing parts such as support beam, it showed all parameters were in sound state, which verified the reliability and use security of support beam designed in proposed method.

**Figure 14.** Site operation.

CONCLUSIONS

(1) Considering the installation requirement of deep mine vertical rescue drainage system, the support structure of the drainage system was designed with the outer appearance looking like Chinese character "井". The specific sizes of crossbeam and joist were determined based on its design formula.

(2) In the case of using vertical rescue drainage system in 800 m deep mine, it analyzed the load borne on support structure under normal working condition. The total load was analyzed under pump failure condition using HARMMER water hammer transient analysis software. The results showed that compared with fast closing check valve, the slow closing check valve (30 s) was installed at the outlet end of submersible electric pump can effectively reduce the water hammer force to support structure during pump failure as well as reduce the action time and action cycle of water hammer force, so as to improve the operational reliability of support structure.

(3) According to the result of reliability simulation analysis of support structure based on Ansys workbench software of finite element analysis, the max value of support beam stress concentration is 86.314 MPa, forming a safe factor of 3.997 as compared with selected material yield strength of 345 MPa, which meets the demand for safety. According to the modal analysis result of support structure, it showed that the natural frequencies of crossbeam and joist in all orders are larger than the disturbance frequency of excitation source, therefore no sympathetic vibration will occur when support structure is serving. It can be seen from the fatigue life analysis of support structure that the support structure can bear 4733 times of pump failure under the condition when slow closing check valve (30 s) is installed at the outlet end of pump. All these data are of vital guiding significance to the safe use and maintenance of support structure.

(4) In the drainage for resuming mining activity engineering project, the support structure of a drainage system steadily served in a certain domestic 825 m deep mine for 3 months without failure. In this process, several pump failures were encountered, while all safety indexes were in sound state, which proved the reliability of support structure design and indicated the reasonability of simulation method and the correctness of simulation results.

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