Control of Harmful Effects in Blasting Demolition of Multi-span Aqueduct

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Abstract: Taking the demolition blasting of complex structure of continuous multi-span aqueduct as the research object and combining with the importance analysis of safety factors in safety evaluation, the blasting scheme, reliability of electric blasting network, pretreatment quality, protection of buildings around the blasting area and safety protection are emphatically studied. The numerical model of aqueduct is established by LS-DYNA. Through the simulation analysis of the whole process of aqueduct blasting demolition and collapse, the blasting breakpoint and the design of pretreatment notch are reasonably determined. Carry out the equivalent electric blasting network test and field blasting test to check the reliability of the blasting network and determine the single hole charge. By the analysis and verification of safety parameters such as blasting shock wave, collapse vibration and safety distance, the active protective measures are taken to protect the important structures and public facilities within the blasting area. The blasting effect and monitoring data show that the safety technical measures can effectively control the safety risk of aqueduct blasting demolition.

1. Introduction

In recent years, with the acceleration of infrastructure construction in China, the blasting industry has also obtained development opportunities. Blasting safety technology has been widely used in tunnel engineering, mining, petroleum, port and shipping engineering and many other fields [1, 2]. A number of new safety assessment analysis methods and system analysis theories have emerged, which have promoted the safety management of site construction [3]. Especially in the aspect of controlled blasting, the construction safety requirements are close to harsh, and the safety conditions of blasting operation are subject to the complex and changeable environment [4]. Therefore, it is of great significance to study the evaluation and control of blasting hazard factors.

Most of these achievements focus on the basic theory of site safety identification and safety risk analysis [5, 6], and pay less attention to the control measures of construction hazards. Especially in demolition blasting, the construction safety requirements are very strict [7], and the operation safety conditions are subject to the complex and changeable environment on site. Therefore, the safety of blasting construction is the primary task of all blasting projects, and how to effectively control the hazardous factors in engineering blasting process has become a current research hotspot [8, 9]. Song
Z. P et al. [10] reduced the disturbance of tunnel surrounding rock and supporting structure by studying the blasting vibration law of tunnel. Koji et al. [11] used finite difference method to simulate the control process of blasting demolition of pier. Li Xianglong et al. [12] solved the collapse control of black and white water hotel building by blasting demolition through finite element analysis. Tang Xiaojun et al. [13] realized the blasting demolition of nearby high-rise buildings by using zoning controlled blasting, effectively controlling the influence of blasting flying stones, blasting vibration and other hazardous factors. Most of the above achievements are concentrated in the aspects of tunnel blasting vibration reduction and building demolition, and there are few reports on the blasting demolition of aqueduct structure.

In this paper, combined with the importance of hazard factors in safety evaluation of blasting demolition of continuous multi span aqueduct, LS-DYNA numerical simulation technology is used to optimize the blasting scheme. The research on the hazard factors of blasting scheme optimization, reliability of blasting network design, drilling construction quality, pretreatment quality, protection of buildings around blasting area and safety protection are carried out, so as to adopt targeted safety technology and management control measures.

2. Safety risk identification and evaluation

2.1. Project overview
The Yingchun aqueduct in Chenzhou City has been idle for a long time, its functional components are well protected and the bearing structure is stable, so it needs to be demolished due to the project construction. The aqueduct to be demolished is about 1500 m away from the intersection of Chenziguì S322 high-grade highway and X090 County Road in the west, and the main body of aqueduct is about 8 m away from Tobacco Monopoly Bureau Warehouse. The three warehouses in the factory are single-layer red brick workshops with asbestos tile roof, all of which are located under the main structure of aqueduct and are close to the horizontal distance from the demolished main body. Now, these are warehouses for normal use. In the middle of the aqueduct, there is a telecom optical cable passing through the middle of the aqueduct arch column. There are important national defense optical cables buried under the X090 highway in the south, and the national defense optical cable junction box is set under the aqueduct. The detailed distribution of the surrounding environment of the main body to be blasted is shown in Figure 1.

![Figure 1. Surrounding environment of aqueduct](image)

The Yingchun aqueduct is north-south trending, with a total length of 152m, a height of 10m, a span of arch rib of 21m, a height of 6.50m from the top of arch rib to the pavement, and a width of 1.73m on the upper deck. The aqueduct is a double rib arch U-shaped thin shell tube structure. The main body of the aqueduct is designed to be 5 continuous spans, and its rise span ratio is 1/6. The inner width of the
two arch ribs is 1 m and the outer width is 1.60 m. The cross section of the arch rib is a rectangular section with a specification of 0.30 m × 0.50 m. A series of reinforced concrete circular column bent frames with a diameter of 0.30 m are used to support the U-shaped channel body of the main body of the water passage. The load is transferred to the double rib arch through the double circular column bent frame and the transverse tie beam, and then acts on the pier and abutment of the aqueduct bridge.

2.2. Safety assessment model
Taking the blasting demolition project of Yingchun aqueduct as the safety evaluation object, 17 impact factors are selected according to the analogy analysis of blasting demolition engineering experience [14, 15]. The system is divided into four levels: target layer, criterion layer, index layer and scheme layer, and the hierarchical structure chart of aqueduct blasting demolition evaluation is established, as shown in Figure 2.

2.3. Determination of the weight

2.3.1. Construction of fuzzy function. Let \( M \) be a fuzzy set over the universe \( R \), if the membership function of \( M \) \( \mu_A(x): R \rightarrow [0,1] \) is expressed as:

\[
\mu(x) = \begin{cases} 
\frac{x-l}{m-l} & \text{if } x \in [l, m] \\
\frac{x-u}{m-u} & \text{if } x \in [m, u] \\
0 & \text{otherwise}
\end{cases}
\]  

(1)

Where: \( l \) and \( u \) are the degree of fuzziness, \( l \) and \( u \) are the lower and upper bounds of \( M \), \( l \leq m \leq u \), the greater the \( u-l \), the stronger the degree of fuzziness. \( m \) is the value when the membership degree of \( M \) of fuzzy set is 1. The triangular fuzzy set \( M \) is used to characterize and compare the fuzzy judgment scale [16].

On the existence of any two fuzzy numbers \( \bar{M}_1=(l_1, m_1, u_1) \) and \( \bar{M}_2=(l_2, m_2, u_2) \), where \( \lambda \geq 0, \lambda \in R \), then the operation rules are satisfied:

\[
\bar{M}_1 \oplus \bar{M}_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2)
\]  

(2)

\[
\bar{M}_1 \circ \bar{M}_2 = (l_1 l_2, m_1 m_2, u_1 u_2)
\]  

(3)

\[
\lambda \odot \bar{M}_1 = (\lambda l_1, \lambda m_1, \lambda u_1)
\]  

(4)

\[
\bar{M}_1^{-1} = (1/u_1, 1/m_1, 1/l_1)
\]  

(5)

2.3.2. Analysis program. For the decision-making of complex problems, the research object system is usually divided into several levels, and then the method of Fuzzy Analytic Hierarchy Process is used to construct the fuzzy judgment matrix. Through the past fuzziness, consistency judgment and
normalization processing, the group experts can make collective and scientific decisions to obtain the evaluation weight. The process can be summarized as the following steps.

Step 1. As shown in Figure 3, a k-level hierarchical structure model is established, and the project K takes 4 layers.

Step 2. Using triangular fuzzy set $M$ to construct fuzzy comparison matrix $\tilde{A}=[\tilde{a}_{ij}]$.

Step 3. Use the following equation to calculate the geometric mean value of the $K$ layer index row vector $\tilde{r}_i^k$.

$$\tilde{r}_i^k = \left( \prod_{j=1}^{n} \tilde{a}_{ij}^k \right)^{1/n}$$  \hspace{1cm} (6)

Where equation(6) is as follows.

$$\prod_{j=1}^{n} \tilde{a}_{ij}^k = \left( \prod_{j=1}^{n} m_{ij}^k \cdot \prod_{j=1}^{n} u_{ij}^k \right)^{-1}$$  \hspace{1cm} (7)

Step 4. The initial weight is obtained by the following formula.

$$\tilde{w}_i = \tilde{r}_i^k \odot \left( \sum_{l=1}^{n} \tilde{r}_i^l \right)^{-1}$$  \hspace{1cm} (8)

$$W' = [\tilde{w}_1, \tilde{w}_2, \ldots, \tilde{w}_n]^T$$  \hspace{1cm} (9)

Step 5. The center of area method (COA) [17] was used to remove the fuzzy weight.

$$\tilde{w}_i = \frac{l_i + w_i + u_i}{3}$$  \hspace{1cm} (10)

Step 6. The right to carry out the re unification.

$$W = [d(\tilde{A}_1), d(\tilde{A}_2), \ldots, d(\tilde{A}_n)]^T$$  \hspace{1cm} (11)

$$d(\tilde{A}_i) = \tilde{w}_i \odot \left( \sum_{l=1}^{n} \tilde{w}_l \right)^{-1}$$  \hspace{1cm} (12)

Step 7. Calculate the total weight. Repeat steps 3-6 to determine the weight of each index at other levels, and obtain the total weight $W_i^T$ of the target level by the following equation(13).

$$W_i^T = d(\tilde{A}_i) \odot W_i$$  \hspace{1cm} (13)

Step 8. According to the evaluation object’s comment set, an evaluation set $V$ is constructed.

$$V = (V_1, V_2, \ldots, V_m)$$  \hspace{1cm} (14)

Step 9. The single factor evaluation matrix can be obtained by single factor fuzzy evaluation.

$$R_i = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}, \quad 0 \leq r_{ij} \leq 1$$  \hspace{1cm} (15)

Step 10. The comprehensive evaluation vector of each sub-objective is calculated.

$$B_i = W_i R_i \quad (i = 1, 2, \ldots, k)$$  \hspace{1cm} (16)

$$B = (B_1, B_2, \ldots, B_k)^T$$  \hspace{1cm} (17)

Step 11. The following formula is used to calculate the evaluation vector $C$ of the total objective to obtain the maximum membership degree and the safety evaluation level.

$$C = AB$$  \hspace{1cm} (18)

2.4. Safety risk identification

According to the safety evaluation requirements of blasting demolition of aqueduct, combined with the survey data of aqueduct to be demolished, a blasting safety evaluation set composed of 4 first level
evaluation sets and 17 second level single factor evaluation sets is constructed. The weight of impact factors is obtained by fuzzy analytic hierarchy process (FAHP). The evaluation results are shown in Table 1.

| Criterion layer | Weight | Index layer | Weight | Total weight |
|-----------------|--------|-------------|--------|--------------|
| Blasting parameters $B_1$ | 0.501 | Scheme and parameter design $C_{11}$ | 0.454 | 0.227 |
| | | Breakpoint location design $C_{12}$ | 0.169 | 0.085 |
| | | Design of blasting collapse $C_{13}$ | 0.116 | 0.058 |
| | | Network and reliability $C_{14}$ | 0.261 | 0.131 |
| Surrounding environment $B_2$ | 0.141 | Pipeline within blasting area $C_{21}$ | 0.092 | 0.013 |
| | | Buildings around blasting area $C_{22}$ | 0.475 | 0.067 |
| | | Impact on traffic $C_{23}$ | 0.228 | 0.032 |
| | | Stray current on site $C_{24}$ | 0.147 | 0.021 |
| | | Weather conditions and visibility $C_{25}$ | 0.058 | 0.008 |
| Construction quality $B_3$ | 0.252 | Quality of blast hole drilling $C_{31}$ | 0.465 | 0.117 |
| | | Pretreatment quality $C_{32}$ | 0.279 | 0.070 |
| | | Charge quality of blast hole $C_{33}$ | 0.164 | 0.041 |
| | | Length and quality of stemming $C_{34}$ | 0.092 | 0.023 |
| Security management $B_4$ | 0.106 | Security check $C_{41}$ | 0.102 | 0.011 |
| | | Safety education and technical disclosure $C_{42}$ | 0.390 | 0.041 |
| | | Security alert $C_{43}$ | 0.311 | 0.033 |
| | | Active and passive safety protection $C_{44}$ | 0.197 | 0.021 |

3. Risk control measures

Risk control measures according to the safety evaluation report and the expert group's suggestions, it is proposed to strengthen the safety risk control of blasting scheme parameter design optimization, blasting network design reliability, drilling construction quality, pretreatment quality, construction protection and safety protection around the blasting area. Combined with the experts' opinions, the blasting process numerical simulation, field blasting test, equivalent blasting network test, active protection measures and safety parameter verification were studied.

3.1. Numerical simulation analysis

In order to evaluate the one-time collapse effect of aqueduct blasting and the reliability of blasting breakpoints, the finite element software ANSYS / LS-DYNA is used to establish the numerical calculation model of aqueduct, and the large-scale display dynamic analysis software LS-DYNA is used to solve the problem. Considering that the bending capacity of reinforcement in the collapse process is small after the instability at the arch axis is removed by blasting [18] The reinforcement and concrete integrated model is used for analysis. The numerical simulation calculation of aqueduct collapse process is completed in LS-DYNA environment, and the whole process simulation deduction of stress, disintegration, overall instability, collapse and accumulation form of explosive slag of aqueduct crossing highway line after explosive explosion is obtained. The numerical simulation process is shown in Figure 3. According to the design of blasting scheme, the bridge deck, guardrail and U-shaped Aqueduct were pre demolished before blasting. At the time of $t=0.01$s, the relevant units were deleted to simulate the pre demolition. When $t=0.29$s, the arch axis blasting is released; at $t=0.70$s, the column and vault are demolished simultaneously; at $t=1.40$s, it is completely collapsed and disintegrated under the action of gravity.
3.2. Design of blasting breakpoint and cut

The A1-A5 points of the aqueduct barrel are manually pretreated, and the detailed location points are shown in Figure 4; the double arch ribs are divided into East and West ribs, and the layout position, blasting parameters, charge quantity, blocking and initiating mode of the blasting points of the East and West ribs are the same, points B1-B5 are the blasting breakpoints on the top of the rib arch, and C1-C10 are the blasting breakpoints at the bottom of the rib arch.

3.3. Pretreatment

In order to reduce the charge and improve the reliability of aqueduct base collapse, it is necessary to pre-cut the U-shaped Aqueduct barrel, aqueduct sidewalk and other facilities, and design manual pretreatment parts, such as A1 ~ A5 points as shown in Figure 4, and the transverse coupling beam of pedestrian cover plate.

Figure 4-a, three rows of blasting breakpoints are designed at the arch rib and vault to form reliable cut-off to destroy the supporting effect of arch span.

Figure 4-b, in the middle of each span, a hand-held electric impact hammer is used to cut an opening through the section of the tube body, with a window width of about 20-30 cm. The constraint of auxiliary facilities on the rib arch of the main bearing member of the U-shaped Aqueduct is relieved, so as to improve the reliability and demolition effect of the overall one-time blasting collapse process of the aqueduct.

Figure 4-c, the reinforced concrete beam connecting the aqueduct barrel is set every 3 m interval, which forms an integral part with the pedestrian cover plate on both sides. According to the numerical analysis of the model, it is considered that the series of beams are not conducive to the disintegration of the aqueduct cylinder by segmented blasting and restrict the rib arch to break down and collapse after blasting. Therefore, the blasting scheme design adopts manual breaking the middle beam and cutting the internal connecting reinforcement of the beam.

3.4. Blasting parameters and network

Before blasting, in order to determine the reasonable single hole charge, two test holes were designed in the transverse tie beam of arch rib, and 50 g and 75 g of No.2 Rock Emulsion Explosive with the specifications of $\Phi$ 32 mm (200 g) were respectively loaded into the holes, and the holes were blocked
with blasting mud without any cover. The two blast holes can completely cut off the beam. According to the measurement of flying objects left on the ground, the distance of flying stone in 75 g charge hole is far, the farthest distance is 8 m, and 50 g is selected as the design basis of single hole loose blasting charge. According to the test of transverse tie beam of arch rib, a single row of blast holes are arranged on the longitudinal central plane and column of arch rib, and the explosive quantity of blasting part of aqueduct is adjusted according to the specification of construction section. See Table 2 for detailed parameters.

Table 2. Blasting parameters of column and arch rib of aqueduct

| Items            | Blasthole | Single hole charge /g | Total number /PCS | Total charge /g |
|------------------|-----------|------------------------|-------------------|-----------------|
| Location         | Direction | Distance /m            | Depth /m          | Number /PCS     |                 |
| Column Root      | Horizontal| 0.20                   | 0.20              | 2               | 66              | 98              | 6468            |
| Arch rib Top     | Normal    | 0.30                   | 0.40              | 3               | 66              | 30              | 1980            |
| Arch rib Foot    | Normal    | 0.20                   | 0.30              | 3               | 40              | 60              | 2400            |

The blasting network adopts electric detonator initiation network. Two parallel instantaneous detonators are installed in a single hole to start the explosive, and then they are connected in series. Before blasting, the equivalent resistance was used to simulate the initiation network in the field, and the CHA-500 high-energy pulse initiator was used to detonate the equivalent electric blasting network, and the air explosion test was carried out to test the reliability of the network.

3.5. Verification and protection of blasting vibration

The current safety regulations in China use the empirical equation (19) of Саовски to verify blasting vibration.

\[ v = KK' \left( \frac{\sqrt{Q}}{R} \right)^\alpha \]  

Where: \( v \) is the allowable vibration velocity of particle blasting, cm/s. \( K' \) is the correction coefficient of urban controlled blasting, the value range is 0.25 ~ 1.00, and the single hole less charge is adopted. Take 0.25; \( K \) and \( \alpha \) are the geological and formation coefficients related to blasting conditions, \( k = 50 \) and \( \alpha = 2.0 \) according to the medium hard rock. \( Q \) is the maximum charge quantity at one time, and the total instantaneous charge is 10.85kg. \( R \) is the distance from the blasting source center, and the relevant data can be substituted into the above formula to obtain Table 3.

Table 3. Theoretical calculation value of blasting vibration

| Protection target                          | Distance from explosion source center \( R \) (m) | Calculated vibration velocity \( v \) (cm/s) | Safety allowable value \([V]\) (cm/s) | Safety judgment |
|--------------------------------------------|-----------------------------------------------|---------------------------------------------|-------------------------------------|-----------------|
| Tobacco factory warehouse                   | 8                                             | 0.96                                        | 2.0 ~ 2.5                           | Security        |
| Brick and concrete house                    | 45                                            | 0.03                                        | 2.0 ~ 2.5                           | Security        |
| Flue curing barn                            | 80                                            | 0.01                                        | 3.5 ~ 4.5                           | Security        |
| Factory wall                               | 7                                             | 1.25                                        | 3.5 ~ 4.5                           | Security        |
| Factory gate                               | 25                                            | 0.10                                        | 3.5 ~ 4.5                           | Security        |

The collapse vibration velocity of building blasting demolition is larger than that of particle vibration caused by blasting seismic wave. The dimensionless similar parameter analysis method is usually used to analyze the collapse vibration velocity caused by concentrated mass or collapse on the ground.

\[ v_t = K_t \left( \frac{R_1}{\sqrt{M_{0H}}} \right)^{\beta} \]  

(20)
8

Where: $v_1$ is the vibration velocity of the blasting object falling to the ground, cm/s. $K_e$ is the attenuation coefficient, generally taken as 3.37. $\sigma$ is the failure strength of the ground medium, MPa; the highway pavement in the collapsed area is hardened by cement, taking $\sigma = 10$ MPa. $\beta$ is the attenuation coefficient, $\beta = 1.66$. $R_i$ is the distance from the observation point to the impact center, taking 30 m. $M$ is the mass of the collapsed part of the blasting target, $M = 400$ t. $H$ is the height of center of gravity of blasting object, $H = 5$ m. $v_c = 0.79$ cm/s, within the safe range. Considering that the junction box of national defense optical cable is close to each other, loess and thatch are covered to reduce the impact of grounding. The actual measurement is shown in Table 4.

### Table 4. Vibration monitoring data

| Protection target       | Monitored blasting vibration velocity $V$ (cm/s) | Monitored collapse vibration $v_1$ (cm/s) | Safety allowable value $[V]$ (cm/s) | Safety judgment |
|-------------------------|-----------------------------------------------|------------------------------------------|------------------------------------|-----------------|
| Tobacco factory warehouse | 1.71                                          | 0.73                                     | 2.0~2.5                            | Security        |
| Brick and concrete house | 0.33                                          | 0.21                                     | 2.0~2.5                            | Security        |
| Flue curing barn        | 0.26                                          | 0.19                                     | 3.5~4.5                            | Security        |
| Factory wall            | 1.85                                          | 0.89                                     | 3.5~4.5                            | Security        |
| Factory gate            | 0.54                                          | 0.36                                     | 3.5~4.5                            | Security        |

3.6. Control of flying rock in blasting

In the top hole of the arch rib of the aqueduct, which is the highest point of the blasting, the loose blasting parameters are adopted. The top of the blast hole is fully blocked, and the resistance line is thick at the top and thin at the bottom, so as to prevent the flying rock from rushing upward during the blasting. The calculation is made by using the trajectory formula of the horizontal throwing of objects.

\[
R_f = v_0 \sqrt{\frac{2H}{g}}
\]

Where: $v_0$ is the initial velocity of blasting flying objects, m/s. $H$ is the height of blasting site from the ground, m; $g$ is the acceleration of gravity, 9.8 m/s². According to the calculation of blasting flying rock velocity, the velocity $v_0$ is not more than 50 m/s, the top height $H$ of arch rib is 6.5 m, and the calculation $R_f$ is 70 m according to (3), then the blasting safety warning radius of personnel is taken as 100 m, and all personnel in the blasting area must clear the site and evacuate to the safety point to hide the gun. As shown in Figure 5, the explosive charge in the direction close to Tobacco Monopoly Bureau Warehouse should be appropriately reduced. The single hole should be taken as 50 g, and all the blast holes in the blasting area should be protected by stemming with blasting mud and covering with multi-layer woven bags.

4. Blasting effect and conclusion

4.1. Blasting effect

The successful blasting of Yingchun aqueduct in Chenzhou City has realized one-time collapse control blasting of a 150 m long cross-line aqueduct. After blasting, the debris falling on the road surface of the aqueduct was cleaned up and the traffic was quickly restored in 20 minutes. The optimization of blasting
design scheme comprehensively considers the safety evaluation suggestions. Before blasting, numerical technology is used to analyze the decomposition of the cylinder and the inverted direction of the column. The cylinder part of the aqueduct across the highway is pre-cut. The dumping direction of the circular column bent on both sides of the road is designed. Precise technical control measures and safety protection are adopted. At the site, the vibration of the aqueduct falling to the ground is small, the flying stone distance is controlled within 15 m, the window glass and asbestos tile of the nearby warehouse are not damaged, the telecom optical cable and national defense optical cable are in good condition, only the window glass of the warehouse guard duty room (abandoned, to be removed, no protection) attached to the aqueduct is broken through two holes. There are 188 effective charge holes in the blasting, and the single hole double shot instantaneous electric detonator is connected in parallel. The holes are connected in series with 48 wires of copper core rubber soft wire (the resistance is 7 $\Omega$/100 m). The CHA-500 high-energy pulse initiator is used to initiate the blasting without misfire. The total blasting charge is 10.85 kg.

4.2. Conclusion

(1) In the process of aqueduct demolition blasting management, standardize the blasting operation process of enterprises, incorporate scheme design, safety evaluation and blasting construction into project management, realize the whole process management and control, give full play to the role of safety evaluation expert think tank, and fully integrate hazard identification and effective control.

(2) Through the numerical model of blasting demolition of continuous multi-span aqueduct, the dynamic process of its stress → disintegration → instability → collapse → blasting debris accumulation was simulated, and the sequence of aqueduct base collapse in the blasting demolition process was optimized, and the technical prevention and control in the design stage was realized.

(3) By the test hole to verify the reasonable charge distribution, simulate the equivalent resistance electric explosion network, covering and blocking protection measures, effectively reduce the hazards of risk factors, and realize the effective protection of blasting flying rocks, surrounding structures, telecom and national defense optical cable.

Acknowledgements

This research was financially supported by Guangxi Young and middle-aged teachers' basic ability improvement project (Grant No. 2020KY10027).

References

[1] Jiang K. C. (2019) Research on the underwater medium-deep hole blasting safety technology for Mingyuexia Yantze River Bridge. Journal of Railway Engineering Society, 36(7):44-47,91.
[2] Wu B., Lan Y.B., Yang J.X., et al. (2019) Influence of new tunnel blasting on vibration characteristics of adjacent existing tunnel. China Safety Science Journal, 29(11):89-95.
[3] Yu W.G. (2010) Current situation of safety assessment work in China and its countermeasures. China Safety Science Journal, 20(1):56-60,181.
[4] Wang X.G., Yu Y.L., LIU D.Z. (2010) Enforceable handbook of safety regulations for blasting. Communications Press, Beijing: China. Pp. 5-15.
[5] Han L., Mei Q., Lu Y.M, et al. (2004) Analysis and study on AHP-Fuzzy comprehensive evaluation. China Safety Science Journal, 07:89-92,3.
[6] Zhang L.M., Ci E.A., Zhao M.S., et al. (2015) Application of fuzzy comprehensive evaluation in rock-soil blasting safety assessment. Engineering Blasting, 21(2):13-17.
[7] Wang D.D., Zhang G., Gao G.M., et al. (2017) Safety evaluation of the high-rise building demolition blasting based on fuzzy-AHP. Engineering Blasting, 23(4):48-53.
[8] Lu Z.J., Lin D.Z. (2000) New task faced by safe blast engineering in China. Journal of Safety Science and Technology, 02:24-28,1.
[9] Fu S.G., Wang Y.H., Xu K.L. (2008) Study on the evaluation of blasting effect and measure of reducing vibration. Journal of Safety Science and Technology, 4(06):25-28.
[10] Tian X.X., Song Z.P., Wang J.B. (2019) Study on the propagation law of tunnel blasting vibration in stratum and blasting vibration reduction technology. Soil dynamics and earthquake engineering, 126:1-12.

[11] Koji U., Hiroshi T., Hiroshi Y., et al. (2010) PC-based simulations of blasting demolition of RC structures. Construction and building materials, 24:2401-2410.

[12] Li X.L., Yang Y., Luan L.F. (2013) Numerical simulation of reinforced concrete structure directional collapse by blasting demolition based on integral model. Transactions of Beijing Institute of Technology, 33(12):1220-1223.

[13] Tang X.J., Cheng S. (2018) Control technology of site leveling blasting near the high-rise building. Engineering blasting, 24(04):77-81.

[14] Chang D.Y. (1996) Applications of the extent analysis method on fuzzy AHP. European Journal of Operational Research, 95(3):649-655.

[15] VEERABTHIRAN R, SRINATH.K.A. (2012) Application of the extent analysis method on fuzzy AHP. International Journal of Engineering Science and Technology, 7,4(7):3472-3480.

[16] SHIKHA V, SHARAD C. (2014) Integration of fuzzy reasoning approach (FRA) and fuzzy analytic hierarchy process (FAHP) for risk assessment in mining industry. Journal of Industrial Engineering and Management, 7(5):1347-1367.

[17] BUCKLEY J.J. Fuzzy hierarchical analysis. Fuzzy Sets and Systems, 1985, 17(3):233-247.

[18] Xu P.F., Gai S.H., Zhang Y.C. (2014) Demolition blasting of flyover over the running highway. Engineering Blasting, 20(03):16-19.