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Risk analysis of concrete pouring operation during high dam construction

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Abstract

Due to the close connection of the high dam concrete pouring operation, the frequent risk evolution path of the personnel, construction machinery and the field environment is complex, which leads to high risk cost and frequent accidents. In order to reduce the operation risk and decrease the frequency of accidents, the risk theory needs to be utilized to analyze the risk of high dam concrete pouring operation. In this paper, we put forward the theory of risk interface framework and a fishbone diagram approach to analyze the factors of this operation. The general idea is that find the risk sources, describe risk interface and put forward the mechanism of high dam concrete pouring accident. Secondly, account for energy carriers, after that the personnel, machine and environment are abstracted as the energy carriers or the dangerous energy carriers, the risk factors are identified. Then risk analysis is carried out according to the theory of risk interface. Meanwhile classify the risk factors according to fishbone diagram and their respective categories. The final risk analysis shows that the dangerous energy carriers are frequently interacted with each other and the risk factors are complex, and the possibility of accidents is extremely high in high dam concrete pouring operation.

Keywords: risk analysis, risk interface, fishbone diagram, energy carriers, concrete pouring operation

1. INTRODUCTION

As a most critical component of our energy generating, high dam is playing an increasingly important role in social infrastructures for large water reservoir impounded (Hariri-Ardebili and Saouma, 2016). A series of high dams have been constructed, under-constructed or waiting-constructed and put into operation in all over the world during the past several decades, such as Shuangjiangkou arch dam, Jinping-I arch dam, Nurek Earth core rock fill dam, Daniel Johnson arch dam, Sayano-Shushenskaya arch dam and Xiluodu arch dam (Cheng and Liu et al., 2017). The basic information on some high dam projects in the world is given in Table 1 (Wu and Cao et al., 2016). During long-term service processes, high dams are effected by external loads, such as wind waves hydraulic pressure, temperature load, dam foundation uplift pressure, and hydraulic pressure (Yang and Gu et al., 2016). Furthermore, high dams must sustain extreme loads, for instance there have earthquake, floods, and landslide (Lin and Ma et al., 2014; Ma and Chi, 2016).

Concrete structures can sustain not only static loads but also dynamic loads, it strength and durability (Gu and Qin et al., 2013; Chen and Gu et al., 2016). Therefore, concrete structures has become an essential material in high dam construction (Zhang and Wang...
et al., 2014; Wang and Wang et al., 2015). Through the operation of concrete pouring, the advantage of concrete structures be embodied. Concrete pouring have a rather straitness storehouse surface, complicated construction process, poorer controlling performance and tightly connected operation (Forquin and Safa et al., 2010). Characteristic of concrete pouring operation as follows: firstly, on the preparation pouring storehouse surface, assembling reinforcement, formwork hoisting, embedded parts laying, etc. are usually initiated simultaneously, at the same time, the temporary operation of foundation grouting, consolidation grouting, etc. are often revolving around it; secondly, on the pouring storehouse surface, cooling water tube laying, placement, vibrating and evenness of concrete, quality inspection of storehouse surface, etc have to be finished before initial curdle of concrete; lastly, on the finish pouring storehouse surface, quality inspection of drilling, metal constructions hoisting, etc have to be carried out one after another (Wu and Tao et al., 2013). By the restriction of site arrangement and spatial resource, crane, levelling machine, drilling rig, etc. and artificial can only operate in a limited spatial, resulting in multiple cross activities, which may, in a certain extent, lead the increases of operation risk (Teizer and Allread et al., 2010). Risk analysis is a assessment for economic losses which created by decision mistake, it include risk identification and risk control, risk identification is first step of risk analysis. After make sure the risk factors, risk control will beginning, through risk control will find the way to decrease risk factors, then the operation risk will reduce. Therefore we should analysis the risk of high dam concrete pouring operation to ensure the safty of concrete pouring and reduce operation risk.

<table>
<thead>
<tr>
<th>Project</th>
<th>Year of completion</th>
<th>Type of dam</th>
<th>Installed capacity</th>
<th>Maximum height of dam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shuangjiangkou</td>
<td>2023</td>
<td>Earth core rock fill dam</td>
<td>2000(MW)</td>
<td>312(m)</td>
</tr>
<tr>
<td>Jinping-I</td>
<td>2014</td>
<td>Concrete arch dam</td>
<td>3600(MW)</td>
<td>305(m)</td>
</tr>
<tr>
<td>Nurek</td>
<td>1980</td>
<td>Earth core rock fill dam</td>
<td>2700(MW)</td>
<td>300(m)</td>
</tr>
<tr>
<td>Daniel Johnson</td>
<td>1989</td>
<td>Concrete arch dam</td>
<td>2732(MW)</td>
<td>214(m)</td>
</tr>
<tr>
<td>Sayano-Shushenskaya</td>
<td>1989</td>
<td>Concrete arch dam</td>
<td>6400(MW)</td>
<td>245(m)</td>
</tr>
<tr>
<td>Xiluodu</td>
<td>2014</td>
<td>Concrete arch dam</td>
<td>13860(MW)</td>
<td>285.5(m)</td>
</tr>
</tbody>
</table>

Several study about risk analysis in global as follow: The accident tendency theory was firstly put forward by Greenwood and Woods (Greenwood and Major, 1919), in which considered that people with certain characteristics were more likely to have accidents than others (Farmer and Chambers, 1929). supplemented the accident tendency theory, and clearly put forward the frequent accident tendency theory which entirely blames the industrial accidents to human nature. Lenne (Lenne and Salmon et al., 2012) proposed a "human factor analysis system" and pointed out that primary factor of the accident was human beings in the frequent tendency accidents (Otte and Jänsch et al., 2012). demonstrated that human factors are the key factors in frequent accidents of road traffic accidents. The gradual perfection of the frequent accident tendency theory has driven the increased interest in explore the accident’s root causes in recent years. Heinrich (Heinrich, 1950) put forward the accident causation sequence theory and expound the interrelationships between the various factors and accidents. Bird (1974) believed that the accident causation sequence theory includes five factors: the essential reason (safety management), the basic reason (personal and working conditions), the direct reason (unsafe behavior or unsafe condition), accidents and losses. Li et al., (2010). proposed an accident analysis model for complex workflows and believed that the accident was due to complex processes and the coupling between multiple factors. Benner (1972) proposed the "P accident theory" and considered the accident process with a series of successive events which were initiated by disturbances and ended with
injury or damage. Johnson (1973) viewed dynamic change as a potential cause of accidents by creating a "change-error" model and revealed that accidents were caused when the manager or operator were failed to adapt changes on human or material factors. Zhang (2011) studied the development of the construction accident process and summed up the change law in each stage. He et al., (2011) pointed out that key point of the accident control is to keep the accident evolution below the mutation of the warning point. Helen (1960) and Hadden (1973) confirmed that accident was an abnormal or unwanted releasing of energy and various forms of energy constituted the immediate cause of damage, which formed a theory of energy accidental release.

However, all the papers mentioned above were only considered the accidents to the effect of single factor such as personnel. In fact, the occurrence of an accident was the result of the interaction of the two factors of unsafe behavior and unsafe condition (Bena and Mamo et al., 2006). The accident of concrete pouring operation during high dam construction usually can be caused by common stimulate of different types risk factors (Adbel Montes et al., 2013). There have been lots of study for single type of risk factors, but few for the common effect of variety of risk factors and interaction of the relations between and among operating personnel, construction machinery and field environment. There have lots of study for analysis of the whole process of project, but few for specialize in concrete pouring operation. Whereas, high dam concrete pouring operation will be analysed based on the theory of risk interface. The theory of risk interface is interassociation and support with theory of risk control (Salvador, 2016). In this paper, the main research method as follow: First of all, by analyzing the concrete pouring process, the accident mechanism is put forward to deeply excavate accident causes. Secondly, each risk factors is elaborated after the energy carriers is defined. Then, each kind of risk factors and their relationship between energy carriers are analyzed with the theory of risk interface. Finally, with the applying of fishbone diagram, the relationship among each of the energy carriers and risk factors are clearly categorized.

2. ACCIDENT MECHANISM

The operation of concrete pouring can be resolved into 5 parts, including pouring storehouse surface preparation, unloading, concrete vibrating, concrete evenness and quality inspection. Operation setails are shown in table 2 (Clough, 1999).

<table>
<thead>
<tr>
<th>Operation process</th>
<th>Personal</th>
<th>Operation content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pouring storehouse Surface preparation</td>
<td>Worker</td>
<td>Assembling reinforcement, Formwork hoisting, Embedded parts laying</td>
</tr>
<tr>
<td>Unloading</td>
<td>Driver</td>
<td>Cooling water tube laying, Pouring concrete</td>
</tr>
<tr>
<td>Concrete vibrating</td>
<td>Worker</td>
<td>Use vibrating needle make concrete inspires pounds densely</td>
</tr>
<tr>
<td>Concrete evenness</td>
<td>Worker</td>
<td>According to a certain thickness paving</td>
</tr>
<tr>
<td>Quality inspection</td>
<td>Engineer</td>
<td>Quality inspection of drilling, Metal constructions hoisting</td>
</tr>
</tbody>
</table>

Because of concrete pouring operation need be satisfied with construction scheduled plan and construction organization design, it will operation in a small and crowed interface. Therefore, risk factors mainly come from frequently interface of personal, machinery and environment. The main component of personal, machinery and environment shown in table 3.
Based on above theory, the concept of risk interface be arised. Risk interface is a physical or suppositional contact interface among personal, machinery and environment. On one hand the physical contact interface is actual, such as, the electric shock accident is occurred on the physical contact interface between personal and machinery which leakage as well as damage, this interface is existence. On the other hand the suppositional contact interface is not real existence as a material, for instance, the electrostatic interaction will be caused by starting of machinery in the winter construction, and the suppositional contact interface is the interface between environment and machinery. Risk interface is shown on figure 1.

In figure 1, risk interface is three straight line on the simply pie chart, and every line contact two areas, for example, the line 1 contact the area of personal and the area of machinery.

In the common situation personal, machinery and environment are insulated by risk interface, but when personal with unsafe behavior, machinery in unsafe condition and environment with evil, the insulate will disappear. Then, construction machinery and field environment converted into the dangerous situation because of risk. At this time, the accident will happened.

3. RISK FACTORS

3.1 ENERGY CARRIES

Personnel, machinery and environment be abstracted as energy carriers. Energy carriers, a kind of material or energy, may release energy unexpected by stimulate of risk factors. There have three different energy carriers, every carriers will contact with
another two carriers, in the most situations, because of the constraint around carriers, the contact of two carriers can not lead to energy release. In briefly, contact may doesn’t result in release, but release surely happened in interface between two carriers. Theory of risk interface is put forward considering of frequent interaction of personal, machinery and environment, it include the conception of risk interface and energy carriers.

3.2 RISK FACTORS IDENTIFY

According to theory of risk interface, risk factors are objective existence and always in risk interface. Every risk factors belong to one area of the personal, machinery and environment. From figure 1, in area of personal, part of risk factors in line 1 and 2 own to personal, these factors be divided into two groups, one is in line 1 and another in line 2. Same situation in area of machinery and area of environment. Therefore, there have 6 different risk factors in high dam concrete pouring operation, and the specific risk factors be shown in table 4.

**Table 4 Risk factors of high dam concrete pouring operation**

<table>
<thead>
<tr>
<th>Factors</th>
<th>Variables</th>
<th>Factors</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision</td>
<td>Poor selection on mechanical equipment; Unreasonable schedule; Unreasonable technical</td>
<td>machinery</td>
<td>Incorrectly use of machinery; No protective on machinery; Falling at high altitude; Improper operation; Unregularly maintenance</td>
</tr>
<tr>
<td>Site management</td>
<td>Uncoordinate with personnel; disorderly on site; Poor machinery maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Personnel</td>
<td>lack of experience; Poor professional skills; Poor team awareness; Poor self-protection awareness</td>
<td>Climate</td>
<td>Cold; High temperature; Wind; Fog; Rainfall</td>
</tr>
<tr>
<td>Rules and regulations</td>
<td>Defects; Pool execution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergency</td>
<td>Unreasonable method; Lack of simulation exercises; Inopportune disposal; No existence of contingency scheme</td>
<td></td>
<td>Narrow operating surface; Insufficient safety facilities; Interaction on operating Surface</td>
</tr>
<tr>
<td>Monitoring and supervision</td>
<td>Defective institution; Pool execution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Management organization</td>
<td>Defects on materials; Disorderly on machinery layout</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrostatic field</td>
<td>Static electricity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spark</td>
<td>machinery collision; Leakage of machinery</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. RISK METHOD

The accident of the high dam concrete pouring operation mainly include the following aspects:
1) During the stage of assembling reinforcement, formwork hoisting and embedded parts laying, low efficiency of aloft work may lead to some quality accidents such as binding quality without up to standard or lifting laid not compliance.

2) During the stage of cooling water tube laying, placement, evenness and vibrating of concrete and quality inspection of storehouse surface, may cause leakage, fire and other accidents due to use a large number of pouring machinery and the circuit of power supply is arrangement

3) During the stage of quality inspection of drilling and hoisting of metal constructions, may cause mental tension which can easily lead to congestion, collision and falling accident because of the narrow space of high dam aloft work, the interaction frequently between operating personnel and construction machinery and the complex field environment.

The risk factors of above accidents’ are difficult to identifying and classifying directly, so that can use the fishbone diagram. The fishbone diagram is first raised by Japanese professor Kaoru Ishikawa. It's connects accidents and risk factors with dendritic arrow line which from sparse to dense. Each big fishbones consisted of lots of medium fishbone and it is representative the energy carriers; Each of the medium fishbone is composed of many small fishbone and they behalf of each risk factor; Each small fish bone can be made up of smaller fish bone and so on. By using the fishbone diagram to classifying the risk factors, we can classify the risk factors and decompose it step by step until the corresponding methods of risk control are more easily to be find, as far as possible to ensure every risk factors which possible cause an accident.

Based on the theory of risk interface, can dividing the risk factors of concrete pouring operation into 6 groups risk factors which related to 3 energy carriers: personnel, machinery and environment. Personnel, machinery and environment as the energy carriers, both can be the initiative part of an accident and the passivity part of an accident. When it as initiative part of an accident, it has been the provider of all kinds of risk factors which could cause an accident, causing an accident; When it as passivity part of an accident it has been the heir of all kinds of risk factors, affected by the accident. Such as, If the operating personnel is regarded as the initiative part of an accident, the risk factors which related it are rules and regulations, the poor scene management, operating personnel dereliction of duty, etc. ; When the operating personnel as the passivity part of an accident it may lead to the operating personnel injury and even death. As the same that, when the construction machinery is regarded as the initiative part of an accident, the risk factors associated with them have damage, static electromagnetic field, sparks, etc. ; When the construction machinery as the passivity part of an accident it may cause the damage of construction machinery, electric leakage of equipment, shutdown, etc. When the field environment is regarded as the initiative part of an accident the risk factors related it have evil climate and evil working environment, etc; When the field environment as the passivity part of an accident it may cause environmental pollution, fire, etc. Based on these, we can get the fishbone diagram of the risk identification and classification of high dam concrete pouring operation, it is shown in figure 2.
In figure 2, the "operating personnel → construction machinery" expressed that operating personnel, the body with energy, is stimulated by the risk factors (such as decision-making misplay, operating personnel dereliction of duty, etc.) which related to the personnel, and it transformed into the dangerous energy carriers, then it contact with construction machinery which is the dangerous energy carriers. However, this process possible lead to the accident eventually, and the operating personnel is the initiative part of an accident, construction machinery is the passivity part of an accident. Through the stimulation of multiple risk factors, and the connection between the dangerous energy carriers, all of the dangerous energy packed into the "fish-head"--the breaking point of the accident.

According to the results of risk factors identified could classify the energy carriers and the risk factors by the big fishbone (such as: "operating personnel → construction machinery" or "operating personnel → field environment"), the medium fishbone (such as the decision-making misplay or the poor scene management) and the small fishbone(such as: the error selection of construction machinery plan or the unreasonable progress schedule). Then get the analysis table of risk factors, it is shown in table 4.

**Table 5** Risk factors of concrete pouring operation during high dam construction

<table>
<thead>
<tr>
<th>Energy carries</th>
<th>Factors</th>
<th>Variables</th>
<th>Energy carries</th>
<th>Factors</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>P → M</td>
<td>Decision</td>
<td>Poor selection on mechanical equipment; Unreasonable schedule; Unreasonable technical indicators</td>
<td>M → P</td>
<td>Machinery</td>
<td>Machinery collisions; Incorrectly use of Machinery; No protective on machinery; Falling at high altitude</td>
</tr>
</tbody>
</table>
In table 5 “P” refer to personal, “M” refer to machinery, “E” refer to environment. The results of analysis shows that the risk factors of concrete pouring operation during high dam construction is more, and can be explained based on the theory of risk interface as follows: Each of the operating personnel, construction machinery and field environment can be abstracted as different energy carriers in the process of operation, and they are in a stable state at this point. But when the personnel do unsafe behavior, the construction machinery is damaged and the environment is evil, the risk factors will be arisen, the energy carriers will be converted into the dangerous energy carriers. Concrete pouring operation process is complex, each type of personnel, construction machinery and field environment are frequent interaction, each type of dangerous
energy carries are frequent interaction. The result is leading to higher risk or higher potential of accident.

5. CONCLUSION

According to the risk theory of interface, can come to the conclusion that the accident comes into being due to the interaction between the stimulation of risk factor and the contact of the dangerous energy carriers after illuminating the accident mechanism; identifying and categorizing every risk factor by using fishbone diagram, so that we can draw a conclusion that more risk factors in concrete pouring operation, frequent interaction in the dangerous energy carriers and larger accident rate. By means of the risk theory of interface, the concept of the energy carriers will be lead into illuminate the accident mechanism from view of essence as well as express the abstract process vividly and systematically in order to analyze and discuss the accident. Moreover, identifying comprehensively causes the risk factors of accident to be more reasonable and makes the ownership relationships of risk factors to be more accuracy. On account of the risk theory, be able to analyze the risk of operation more comprehensively, and systematically with the addition of the way of quantitative analysis is led up, which makes analytic result be more comprehensive, rational and persuasion. Meanwhile, the theory can be extended to other process operations of frequent interaction among personnel, machinery and environment.

Concluding from the theory of risk interface, there exists two ways to control risk and prevent accidents. On one hand, the risk can be controlled by reducing the occurrence probability of risk and the frequency of contact between dangerous energy carrying subjects. On the other hand, by transforming the dangerous energy carriers into general energy carriers, the risk factors including unsafe operation of personnel, unsafe state of the equipment and environmental risks can be reduced even eliminated. The risk can be controlled from root cause by

6. ACKNOWLEDGEMENTS

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7. REFERENCES


