Research on emergency rescue technology and equipment for train operation accidents on a heavy-haul railway network

Xianping Zhou*, Xiang Wei, Lin Ma, Fuwei Bai and Hongwei Huang

Institute of Science and Technology, Daqin Railway Company, No. 328, Jianshe North Road, Taiyuan, Shanxi, 030013, China.

*Corresponding author. E-mail: tristzxp@126.com

Abstract

Bridges, tunnels, cuttings and high subgrade account for a relatively large proportion in China’s heavy-haul railway system, where 10 000 t of unit trains and 20 000 t of combined trains are in operation. When a train operation accident occurs, it can easily cause vehicle intrusions, slant-span lines, tipping and stacking. Based on the viewpoint of system engineering, rescue methods such as hoisting, lifting, pulling and overturning are integrated, according to the characteristics of heavy-haul transport and the construction practice of train accident rescue system. A scheme of technical research and equipment configuration relating to heavy-haul railway rescue in China is put forward based on the situation—embankment, bridge, tunnel (including cuttings), ramp and curve rescue, and so on—and three-dimensional finite-element modelling and calculation checks on the key components are carried out.

Keywords: heavy-haul railway; train operation accident; rescue technology; rescue equipment

1. Introduction

Heavy-haul railway transport has the advantages of large capacity, high efficiency, low cost, and environmental protection and low carbon emission; it is clean and energy-saving, and is the backbone of railway transport organization in China. From the 1980s onwards, heavy-haul railway transport has been vigorously developed in China. On 21 December 1992, the first double-line heavy-haul electrified coal transport line—the Daqin Railway [1]—was opened. In recent years, the Wari Railway, Tanghu Railway, Haoji Railway and other national heavy-haul lines have...
been opened; in addition, the Shuohuang Railway and other joint-venture railways have also been an important part of China’s heavy-haul railway transport system.

Through continuous development in recent years, China has built a relatively well-equipped emergency rescue system for its heavy-haul railway network. There are rescue trains along the heavy-haul railway lines, which are equipped with domestic-made or imported 160 t telescopic boom track cranes; a number of special rescue trains are equipped with 200 t imported track cranes. Rescue teams are based in stations of second-class and above, the relatively large intermediate stations at the junctions of bureaus, and the operation workshops of vehicle depots. As a consequence of the optimization and integration of railway stations and depots, as well as the popularization and application of CTC technology [1], some stations have been changed to unattended, and the organization of rescue teams has also been adjusted accordingly.

Tunnels and bridges account for a large proportion of the heavy-haul railway network, with most being continuous lines of bridges and tunnels in mountainous areas, which have always been a difficult task in rescue work. Bridges, tunnels and cuttings account for 25.3% of the whole line on the Daqin Railway, while the proportion of bridges and tunnels on the Haoji Railway is as high as 46.9%. Secondy, 20 000 t of combined trains [1] and 10 000 t of unit trains are generally operated on heavy-haul lines. When a train operation accident occurs, it can easily derail a dozen or even dozens of vehicles, leading to a serious large-scale accident and making rescue highly difficult. Furthermore, heavy-haul lines have a high operation density: the Daqin Railway runs nearly 100 heavy-haul combined trains per day. In the event of an accident, the line will be severely congested, and rescue trains and cranes will not be able to reach the scene quickly. At the same time, there are many types of heavy-haul locomotives and vehicles. In terms of locomotives, 25 t axleload HXD1 and HXD2 locomotives are commonly used on heavy-haul railways; application assessment and technical review of the 30 t axle-load HXD1F and HXD2F electric locomotives have been completed. In terms of vehicles, the Daqin Railway mainly includes C76 and C80 dedicated coal wagons with 25 t axle load [1]; C80E general-purpose freight wagons with 27 t axle load have also been operating on the Daqin Railway for five years, and the C96H dedicated wagon with 30 t axle load is currently being evaluated on the Wari Railway [2]. The bogies of the rolling stocks are not uniform; some models are in groups of three connected vehicles with non-coupler connecting rods. Therefore, the existing rescue equipment is not completely suitable for the rolling stock and cannot function effectively.

For foreign railway rescue, on one hand, research has focused on railway transport and the loading and unloading of large-scale emergency rescue machinery. For example, Germany, the United States and France have developed large-scale freight trains to solve the problem of transporting rescue machinery with loads of around 400 t. In order to solve the loading and unloading problem of rescue machinery in conditions of station or line damage, the United States, Germany and Russia have also developed assembled mobile platforms with different structures. The technology and equipment involved in line repair and reconstruction have also been studied. In order to guarantee rail transport in the event of war, Germany has developed a dual-use bridge for both road and railway transport, which has its own lifting equipment and can be quickly assembled to facilitate emergency railway transport. Russia has developed a professional recovery train that can be used for quick repair of railway subgrade, bridges, lines and turnouts [3].

Based on the above analysis of the difficulties involved in and the current situation of heavy-haul railway rescue, it is clear that existing rescue technology and equipment cannot fully adapt to rescue operations on heavy-haul railway networks. The relevant rescue methods should be supplemented and refined based on the characteristics of heavy-haul railway lines and rolling stock, and the relevant rescue equipment should be upgraded.

2. Rescue principles and methods of heavy-haul railway rescue operations

The opening of heavy-haul railway lines and increases in their transportation capacity bring new difficulties and challenges to rescue operations in the event of heavy-haul railway accidents. After an accident on a heavy-haul railway line, the rescue department should carry out the rescue work in accordance with the rescue principle of ‘people-orientedness, hierarchical responsibility, emergency preparedness and efficient disposal’ and the rescue idea of ‘opening first, restoring later’ [4]. The rescue commander should first
determine the circumstances of the accident by analysing accident information, and then make a reasonable rescue plan according to the rescue machinery and equipment available at the rescue site and in the surrounding area, and the labour force that can be mobilized.

Heavy-haul railway rescue mainly uses hoisting, lifting, pulling, overturning and other rescue methods. The hoisting method is a rescue method that uses a track crane or other hoisting equipment to hoist the derailed rolling stock and return it to the rail, and is suitable for accidents involving serious damage to the line, train stacking, rollover and other large-scale accidents. The lifting method is a rescue method in which the rolling stock, together with its bogie, is lifted transversely (horizontally), then placed onto the track using hydraulic lifting equipment or an air-powered lifting bag. It is suitable for derailment accidents in which the bogie of the rolling stock is in good condition and the line is easy to recover. The pulling method is a rescue method that uses the rescue locomotive or hydraulic traction equipment to pull or drag the derailed rolling stock along a rerailer onto the track; this method is suitable for accidents in which the derailment distance is less than 500 mm [5]. Overturning is a rescue method that uses high-power equipment to pull the derailed vehicle or uses a crane to lift the vehicle out of the railway clearance. It is suitable for accidents in which the vehicle is overturned or the line is damaged, without the conditions necessary for hoisting, lifting or pulling [6].

Based on the characteristics of heavy-haul railway transport, combined with the types of railway accidents and rescue practices of heavy-haul railways in recent years, as well as the comprehensive application of different rescue methods, such as hoisting, lifting, pulling and overturning, feasible rescue plans for train operation accidents involving embankments, bridges, tunnels (including cuttings), ramps, curves and other line sections are proposed in the following section. No matter which rescue method is adopted, ensuring the safety of the operation is always the most important factor; at the same time, reducing the rescue time, protecting the derailed rolling stock and line equipment, and minimizing the direct and indirect losses of the accident as far as possible should be also considered.

3. Rescue technology and equipment at different line sections

3.1 Accidents on embankments

When train derailment occurs on an embankment section of high subgrade and with a high slope, the hoisting, lifting, pulling and overturning methods can be used to quickly open the line, due to the unlimited operation space.

3.1.1 The hoisting method.

a) Confirmation of the hoisting method. Track cranes of 160 t can be used to hoist all kinds of existing rolling stock at one end or to hoist 100 t heavy-haul freight vehicles as a whole on the same line; they can also hoist a single locomotive as a whole if an adjacent line is available. However, when the rail shoulder width is not sufficient to enable the track crane to expand the leg, it is difficult to use the hoisting method, as shown in Fig. 1.

Using social rescue machinery such as a truck crane to hoist vehicles involved in stacking, crossing and overturning accidents can speed up the rescue process. At the same time, the operation
For vehicles whose couplers are interlocked and cannot be separated, or for a group of three-carriage hard-connected C80 vehicles (as shown in Fig. 2), it is necessary to remove or cut off the coupler or connecting rod first, and then carry out the hoisting operation on each individual carriage of the vehicle.

b) 3D modelling and finite-element strength validation of the hoisting beam. After selecting the rescue method, it is necessary to model and calculate the strength of the key component—the hoisting beam—based on its stress condition, so as to optimize the structure of the hoisting beam and validate the safety of the operation. The structure should be reasonably simplified when modelling to clarify the load-boundary conditions [7], as shown in Fig. 3. First, the stress and deformation of the linear elasticity are calculated in terms of the linear elastic material performance. The linear elastic result is credible if the maximum stress is within the yield stress of the material (735 MPa). When the linear elastic result exceeds the material yield stress, a true stress–strain curve (true) is required for checking the calculation. The stress–strain curves of the material of the hoisting beam are shown in Fig. 4, and the main parameters are shown in Table 1.

Table 1: Main parameters of the hoisting-beam material

| Density (kg/m³) | Elasticity modulus (GPa) | Poisson ratio | Yield stress (MPa) | Tensile strength (true stress; MPa) |
|----------------|--------------------------|---------------|-------------------|-----------------------------------|
| 7800           | 200                      | 0.29          | 735               | 882.3                             |

Based on the three-dimensional model, the hexahedral mesh is used to build the high-precision finite-element mesh using finite-element analysis software (ALGOR). The resulting finite-element model of the hoisting beam has 75 452 elements and 74 613 nodes, as shown in Fig. 5.

The distribution of global and local equivalent stress and the distribution of total displacement of hoisting beams obtained by linear elastic calculation show that:

1. The maximum displacement of the hoisting beam is 5.3 mm, which is located at the end of the hoisting beam and is dominated by Z-shape deformation. The deformation is magnified about 40 times to clearly show the deformation trend of the hoisting beam, as shown in Fig. 6; and
2. The maximum stress is about 503 MPa, which is located at the transition corner of the top surface of the hoisting beam. This is the stress-concentration site, but the maximum stress...
does not exceed the 735 MPa yield limit of the material, therefore the linear elastic results are accurate and do not require further non-linear calculations. The equivalent stress distribution of the hoisting beam is shown in Figs 7 and 8.

3.1.2 The lifting method. When the line is damaged to a lesser extent and can be repaired easily, hydraulic lifting equipment can be used to restore the rolling stock with integrity of the bogie to the track. After the rolling stock with the damaged bogie is lifted, the damaged bogie is replaced by the rescue trolleys.

At present, all rescue trains (teams) generally use a single multistage cylinder to lift the derailed rolling stock vertically, and then use the transverse moving cylinder to move to the centre of the line; furthermore, the wheels are felled to the rail, as shown in Fig. 9. The main technical parameters of the hydraulic lifting equipment are shown in Table 2.

The single-point lifting operation is suitable for most rolling stock and line conditions. Its advantages include the fact that the multistage cylinder can lift all the rolling stock at once, little equipment is required, the preparation time is short and...
Table 2: Main technical parameters of the hydraulic lifting equipment

| Parameter                          | Value         |
|-----------------------------------|---------------|
| Pump station power                | 4.0 kW        |
| Working pressure                  | 63 MPa        |
| Lift cylinder capacity            | 3090/1980/1110/500 kN |
| Lift cylinder quality             | 75 kg         |
| Transverse moving cylinder capacity| 200/100 kN    |
| Transverse moving cylinder stroke | 300 mm        |

The operation is simple and convenient. However, for rolling stock that has derailed on a curve of small radius, it is difficult to carry out single-point lifting because of the influence of the superelevation of the outer rail. In such cases, a two-point lifting operation method is needed. The two-point lifting rescue equipment developed and designed by German company LUKAS can meet site rescue requirements [8]. The two-point lifting method requires high synchronous control of the oil cylinders, for which the synchronous control valve produced by German company HAWE can be used [9].

Compared with the hoisting method, the hydraulic lifting equipment works under the carriage—which eliminates many tedious and time-consuming auxiliary operations, such as power cut-off and pulling or dismantling of the OCS—and can therefore play an important role on heavy-haul electrified lines with extremely busy transportation tasks.

3.1.3 The pulling method

a) Confirmation of the pulling method. In the case of minor damage to the line or small tilt of the rolling stock, and if the bogie is in good condition, the pulling method is adopted and a rerailer is used for rerailing. When the distance between the wheel set of the derailed rolling stock and the rail exceeds the range of rerailing, a rail compeller can be used to guide rerailing, as shown in Fig. 10.

Data shows that the starting traction forces of the main locomotives on heavy-haul lines are: HXD1 [1] and HXD2 [1]: ≥700 kN (23t axle load) or ≥760 kN (25 t axle load); SS4 [1]: 628 kN. Taking into account the three-carriage connection in one group of heavy-haul vehicles, without removing the connecting rod, the pulling method for double- or multi-locotive reconnection can be used, if the single-locotive traction is not sufficient. High-strength traction hooks and traction ropes (as shown in Fig. 11) for connecting derailed rolling stock and traction locomotives should be designed based on the starting traction force of the two locomotives, which is 1500 kN.

b) Strength validation of heavy-haul rescue rerailers. The axle load of heavy-haul rolling stock in China has increased from 25 t to 30 t in recent years, so it is necessary to strengthen the structure of the traditional rerailer to meet the requirements of heavy-haul rescue.

The rerailer material is the same as the hoisting beam material. Three-dimensional modelling of the rerailer is carried out, and the actual stress condition of the rerailer is simulated using finite-element software to realize the overload load validation. The vertical loading force of the rerailer is set to 15 t (half of the 30 t axle load) and the transverse loading force is set to 10 t. The rerailer loading points are determined according to the position where the rolling stock wheels may be in contact with the rerailer surface [10], as shown in Fig. 12. Stress distribution diagrams of each loading point are shown in Fig. 13. The operating stress and displacement of each loading point is shown in Table 3.

From the stress-distribution diagram, it can be seen that the stress value in the loading area enters the yield stage and plastic deformation.
occurs, but has only local displacement. Outside the loading area, the stress and displacement change of the rerailer is not obvious. It was also found in the subsequent type tests that the surface will have plastic deformation after the rerailer is used because of the concentrated wheel force, but the overall structure is not deformed and does not affect reuse. The calculation and test results show that the reinforced rerailer structure is safe and can meet the requirements of actual use.

3.1.4 The overturning method. The overturning method involves using the traction power of machines such as loaders, bulldozers and tractors to pull the derailed vehicle over or out of the railway clearance. This method has been successfully applied in many rescue operations on the Daqin Railway, and is shown in Fig. 14.

Normally, the derailed vehicle needs to be turned 180° or pulled more than 4 m to turn over the railway clearance, so it is necessary to make full use of the fact that the line is higher than the ground plane to choose the turning-out direction. The impact of OCS masts, vehicle reconnection and stacking should also be considered in the operation. In cases in which the derailed vehicle cannot be turned over, the vehicle can be pulled out by traction. If the derailed vehicles are connected together, the obstacles should be gradually removed to reduce the traction force.

3.2 Accidents on bridges

When the derailed rolling stock is close to the bridgehead, the gaps between the sleepers can first be filled with stone ballast, and the rolling stock can then be pulled away from the bridgehead. The appropriate rescue method can then be adopted according to the circumstances of the accident. Heavy-loaded vehicles should be unloaded to prevent threats to bridge safety due to unbalanced loads or other uncontrollable factors.

a) Pulling method: in order to overcome the influence of the check rail on the bridge, a split-type rerailer can be used in pulling operations. The locomotive should be avoided when carrying out traction operations on bridges; in addition, pulling operations should be avoided on curved bridge;
b) Lifting method: when the lifting method is used, the bottom of the transverse bridge of the hydraulic lifting equipment should be levelled with stone ballast, and then covered with sleepers to reduce the concentrated force;
c) Hoisting method: generally, hoisting operations are not used on bridges to prevent the track crane from overturning. If hoisting is the only option, the railway maintenance department should confirm whether the bearing capacity of the bridge meets the hoisting load requirements before beginning the operation. When necessary, the bridge should be strengthened; legs cannot be set up on the bridge, and safety measures for operations without legs should be strictly implemented.

3.3 Accidents in tunnels (including cuttings)

At present, the main problems faced during rescue operations following train operation accidents in tunnels include: restricted space, the obstacles posed by scattered goods, the limitations of traditional rescue methods and the need to ensure the safety of rescue workers. Accident conditions usually include: inclined vehicles close to the tunnel wall, damaged bogies, deformed rails and damaged lines, as well as tumbled, sideways-leaning or stacked vehicles overlapping adjacent lines in multi-track tunnels.

3.3.1 Rescue in cases of general tunnel derailment. A general derailment accident is one in which the line in the tunnel is basically undamaged, the distance of the derailment of the rolling stock is less
Fig. 13: Stress-distribution of each rerailer loading point

Table 3: Operating stress and displacement of each rerailer loading point

|    | 1    | 2    | 3    | 4    | A    | B    | C    | D    |
|----|------|------|------|------|------|------|------|------|
| Stress (GPa) | 0.8295 | 0.7748 | 0.8093 | 0.8610 | 0.7795 | 0.7730 | 0.8823 | 0.8129 |
| Displacement (mm) | 1.156 | 0.4534 | 0.2701 | 1.427 | 0.8263 | 0.6667 | 1.630 | 0.9339 |

than 500 mm, and the bogie is basically intact and can resume operation. The pulling or lifting methods can be used to carry out rescue operations.

a) Pulling method: the locomotive or other power source is used to pull the derailed rolling stock up the track along the rail compeller or rerailer. For general derailment accidents in tunnels, the pulling method is more efficient;
b) Lifting method: the derailed rolling stock is lifted together with the bogie and moved transversely, and then replaced on the track. Lifting equipment includes hydraulic lifting equipment and special rigging and ropes for the rolling stock.

3.3.2 Rescue in cases of serious tunnel derailment.
Serious derailment accidents in tunnels are those in which the rolling stock is derailed to different degrees, with some vehicles pushed against the wall of the tunnel, the centre plates detached from
the bogies and/or the lines slightly damaged. The hoisting or lifting methods can be used to carry out rescue operations.

a) Hoisting method: telescopic-boom track cranes and ram-hook hoisting devices are used to hoist empty vehicles on the same line (heavy vehicles should be unloaded), and pull them out of the tunnel quickly after installing a bogie or rescue trolley, as shown in Fig. 15. During the hoisting in the tunnel, the swing amplitude of the boom is limited, generally to 0–4°, and it is best to hoist the coupler head of the rolling stock [11].

b) Lifting method: an air-powered lifting bag is used to right rolling stock that is tilted against the tunnel wall, to separate vehicles that are interlocked after a collision, and to carry out the lifting operation in situations where space is limited and the lifting cylinder cannot easily be installed. After the vehicle body is lifted, the damaged bogie is removed and the rescue trolley is assembled, the derailed vehicle can be quickly pulled away from the area. This method is shown in Figs 16 and 17.

3.3.3 Rescue in cases of major tunnel derailment. A major derailment accident in a tunnel is one in which the entire line is damaged or the bogies of various rolling-stock vehicles are scattered, or an

Fig. 14: Overturning method

Fig. 15: Ram-hook hoisting device

Fig. 16: Air-powered lifting bag

Fig. 17: Rescue trolley
accident involving serious tilting, rolling or stacking. The following rescue methods can be used:

a) Pull-out by locomotive: with the help of a rescue locomotive, the derailed rolling stock is pulled out of the tunnel. Because of the narrow space in the tunnel, the goods cannot easily be unloaded completely, so the traction locomotive and traction equipment should be equipped with the required traction force, according to the strength of the coupler and the vehicle. Traction equipment includes: traction hooks, traction ropes and vehicle traction beam-connection devices (used when the coupler is damaged). In order to reduce traction resistance and avoid damaging the line, old track can be attached on both sides of the basic rail to form 4–6 track panels. After the panels are filled with ballast, the derailed rolling stock can be drawn out of the tunnel safely; and

b) Rapid obstacle clearing: a small multi-purpose caterpillar excavator with digging, grasping and hoisting functionality is used to load and reload the cargo and decompose the vehicle body structure in single- and multi-track tunnels with narrow working space. The functionality of the general excavator is relatively flexible, and can be expanded by the manufacturer according to the actual needs of rescue operations.

3.4 Accidents on ramps

When a rescue operation is carried out on a ramp, the hoisting, lifting, pulling and overturning methods are all applicable, but the following problems should be noted:

a) Anti-slip measures must be taken for track cranes and rolling stock. Track cranes should be linked to a locomotive when working on a ramp with a gradient above 6‰;

b) When wire rope is used to pull the rolling stock, the vehicle cannot be pulled downhill; and

c) Since the spacing between the front wheels of a rail-mounted crane and the steel rails is not identical to that of the rear wheels, it should be adjusted per the technical requirements of the levelling instrument during operation of the vertical leg cylinder. During operation, the conditions of the crane legs must be constantly monitored.

3.5 Accidents on curves

Rescue operations on curves are similar to those on ramps, and various rescue methods can also be adopted according to the equipment situation, but it should be noted that:

a) In rescue operations in which the pulling method is used, the rolling stock should be pulled in the direction opposite to that of the derailment, and more than 2 m of check rails should be installed in front of the rerailer inside the outer rail. The rolling stock should be pulled slowly, so as to prevent another derailment of the rerailed wheels affected by the curve line; and

b) When the track crane sets up the leg, it must be ensured that the outer wheel of the curve has a gap. If the outer rail is too high and the crane cannot be levelled, the load should be reduced by no less than 20% when hoisting on the inside of the curve line or turning to the inside of the curve.

The various rescue methods and equipment mentioned above should be selected according to the specific circumstances of the railway accident. In the actual rescue work, various methods and equipments can be utilized alternatively and simultaneously, and the overriding aim should be to ensure the safety of personnel and to reopen the line as soon as possible.

4. Conclusions

With the development of railway construction in China, the proportion of heavy-haul lines is increasing. Based on the current situation of heavy-haul railway transport in China, especially the practical experience of the construction of the rescue system on the Daqin Railway over the past 30 years, this paper has put forward a scheme of heavy-haul rescue technology and equipment configuration in China, combining rescue methods such as hoisting, lifting, pulling and overturning. Three-dimensional modelling and finite-element strength validation of the hoisting beam and rerailer were also carried out using the ALGOR finite-element analysis tool to further verify the safety of the key rescue components. This paper provides a useful reference for the design, construction and operation of a train accident rescue system on a heavy-haul railway.

Conflict of interest statement. None declared.
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