Numerical modelling of monorail support requirements in decline development

By

B Besa[1], M Kuruppu[2] and E K Chanda[3]

ABSTRACT

This paper discusses support requirements for the proposed monorail system to be used in decline development. The monorail drilling and loading systems are systems that move on the rail (monorail) installed in the roof of the decline and supported by roof bolts, suspension chains and steel supports. However, due to the weight of the components of the two systems, it is imperative that the force in each roof bolt, suspension chain and steel support capable of suspending the weight of the heaviest component is determined. Numerical models that relate the weight of the monorail drilling and loading components to the required strength in the support system have been developed. Using these developed models, numerical values of the forces in each roof bolt, suspension chain and steel support, required to suspend the weight of the heaviest component of the monorail drilling and loading systems are determined.

Keywords: monorail, roof bolt, suspension chain, steel supports.

INTRODUCTION

The monorail drilling and loading systems are systems that move on the rail (monorail) installed in the roof of the decline and supported by roof bolts, suspension chains and steel supports (Figure 1). The monorail consists of a track of jointed section rails, which can easily be extended to the desired length. Monorails are made of an I-profile rail, which completely prevents any derailment of the train. The monorail train, together with containers or carriages, hangs by its wheels on the bottom flange of the track. The train is powered by electric motors. Depending on the transportation task, the monorail system can be equipped with man-riding cabins, material container and bottom discharge hoppers (Guse and Weibezhn, 1997). With a load carrying capacity of up to 30 tonnes and the ability to negotiate gradients of up to 36^0, the monorail system can make transport in decline development considerably more efficient than conventional truck haulage system. Considering the requirements of typical underground mines, the monorail system is designed to negotiate horizontal and vertical curves with a minimum radius of 4m and 10m respectively. The system also shares many of the advantages of floor mounted rail, but overcomes the bulk of that system's limitations (Scharf, 2007; Chanda and Besa, 2008). Other advantages include:

- Reduction in size of excavations leading to improved stability of underground excavations;
- Small excavations also means reduced ventilation and need for air conditioning;

[1] Research Fellow, Curtin University of Technology, Mining Engineering and Surveying Department, Western Australian School of Mines, Locked Bag 22, Kalgoorlie WA 6433, E-mail: b.besa@curtin.edu.au

[2] MAusIMM, Senior lecturer, Curtin University of Technology, Mining Engineering and Surveying Department, Western Australian School of Mines, Locked Bag 22, Kalgoorlie WA 6433, E-mail: r.kuruppu@curtin.edu.au

[3] MAusIMM, Associate Professor and Program Leader in Mining Engineering, The University of Adelaide, School of Civil & Environmental & Mining Engineering Adelaide SA 5005 AUSTRALIA, Email: echanda@civeng.adelaide.edu.au

- Reduced haulage costs per tonne per kilometer because of less power consumption;
- Less fire hazards compared to truck haulage system;
- Environmentally friendly technology – no diesel fumes;
- Multipurpose haulage system for men, material and rock;
- Small and medium sized ore bodies can be mined with less initial capital investment;
- The system has potential for automation – reduction in personnel; and
- Low system operating costs – a must for narrow vein high grade ore bodies, hence improved profitability for such ore deposits.

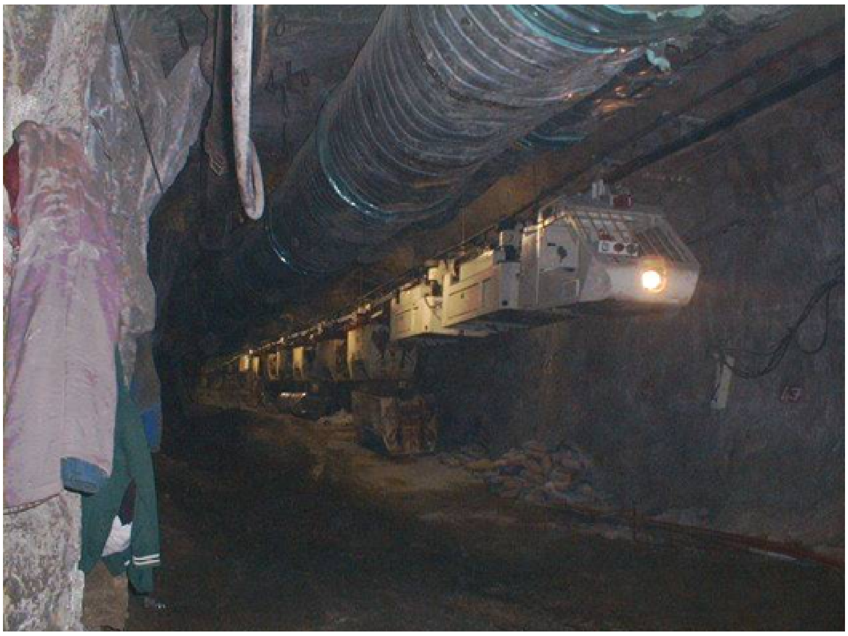


Fig 1 - Monorail train in an underground opening (Scharf, 2007)

Considering the above and many more advantages that the monorail system offers, Chanda et al. (2008a) and Chanda and Besa, (2009) conceptualized the drilling and loading systems based on the monorail technology. The conceptual monorail drilling and loading systems will be used in decline development for face drilling and cleaning, respectively. Figure 2 shows the conceptual monorail drilling and loading systems in a decline.

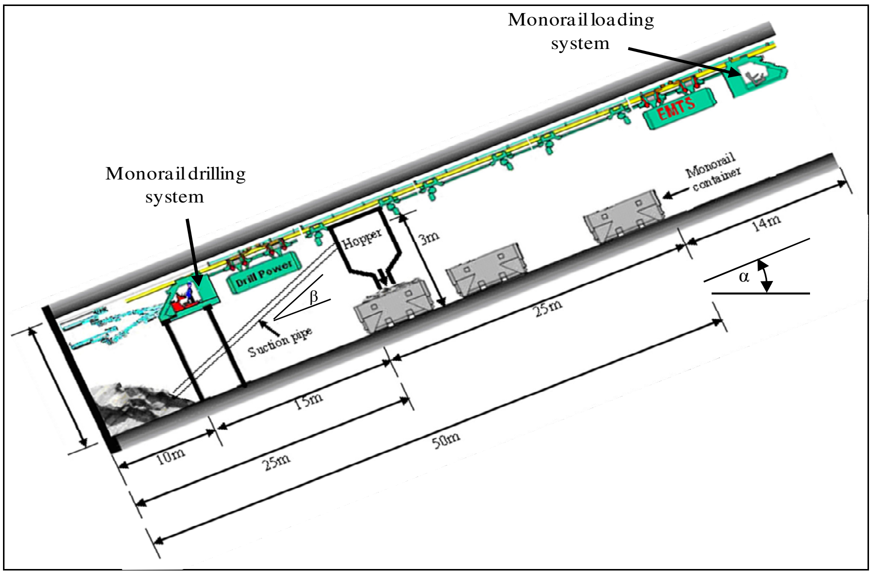


Fig 2 - Conceptual monorail drilling and loading system (Chanda and Besa, 2009)

The monorail train is fitted with two independent drilling booms that are used in decline development. The system has its own power supply attached to it. It has also two horizontal and two vertical hydraulic stabilizers to act as supports during drilling operations. The loading system consists of an incline suction pipe that is connected to the hopper. The high pressure pump / fan connected to a storage hopper creates negative pressure inside the hopper that enables transport of blasted rock fragments from the development face into the hopper to take place (Chanda and Besa, 2009). The monorail loading system will also serve as a means of ore and waste transport system from underground to surface. Men and material will also be transported using the system by, respectively, connecting man riding and material carriers to the system. According to manufacturers of the monorail train, Scharf, the system has a self-weight of 92 tonnes and carries up to 6 containers with total payload up to 30 tonnes including the weight of the container.

The aim of this paper is to determine the minimum required strength of the roof bolt, suspension chain and steel supports for suspending and supporting the monorail drilling and loading systems components during operations. This is in order to avoid failure of the two systems from the support systems as well as to overcome dynamic forces. The methodology employed to achieve this objective is to develop numerical models that relate the weight of the monorail drilling and loading systems components to the required strength in each roof bolt, suspension chain and steel support. Using the developed models, numerical values of the minimum required strength in each roof bolt, suspension chain and steel supports to suspend and support the components of the two systems are determined.

NUMERICAL MODELLING

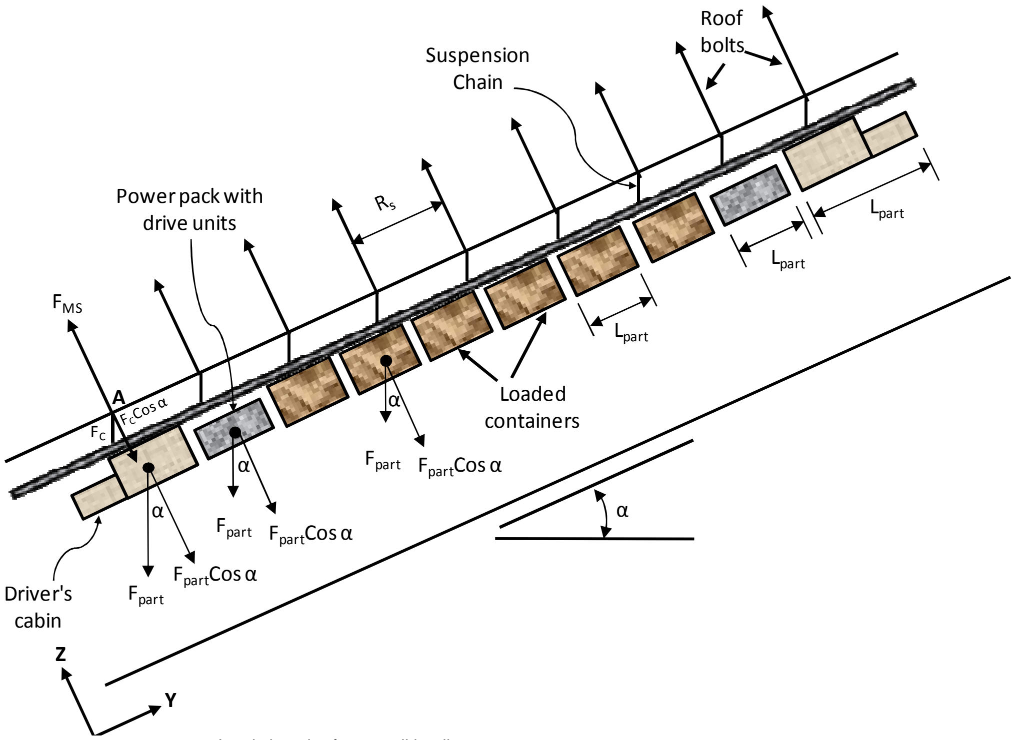
In this Section, numerical models that relate the weight of monorail system components with required support system at various sections of the decline (i.e., in inclines as well as at vertical and horizontal curves) are presented.

Equilibrium of forces in the loading system

The force required in each roof bolt and suspension chain to support and suspend the monorail drilling and loading system components in an incline is significant in ensuring the components of the two systems remain suspended under load. To avoid failure of roof bolts and / or suspension chains due to the weight of monorail system components, high strength roof bolts and suspension chains must be installed. It is, therefore, important that the minimum required force in each support system necessary to suspend the weight of monorail drilling and loading system components is determined. In this section, models that determine the required force in each roof bolt and suspension chain in an incline based on the heaviest monorail drilling and loading system components are established.

Weight of monorail loading system components versus required support system

The relationship between the weight of monorail loading system components and required force in each roof bolt and suspension chain in an incline is shown in Figure 3.



L_{part} is length of monorail loading system component
F_{part} is weight of monorail loading system component
R_s is roof bolt spacing
F_{MS} is force in each roof bolt (forces suspending monorail system)
F_C is force in each suspension chain
α is decline gradient

Fig 3 - Forces in roof bolts and suspension chains for the monorail loading system components in an incline

Taking equilibrium of forces in Z-direction at point A, the following equation that relates the force in each roof bolt and suspension chain is established.

$$F_{MS} = F_C \mathrm{Cos}\alpha \quad (1)$$

However, the monorail loading system component remains in equilibrium (in Z - direction) if the total upward force (i.e., total forces in suspension chains installed within length L_{part} occupying the system component is equal to the total downward force (i.e., weight of the heaviest monorail loading system component). In these calculations, the weight of the rail, chains and bolts is neglected.

Total force in suspension chains within L_{part}

The total force in suspension chains depends on the number of suspension chains installed within the span L_{part} and the force in each chain. Since the roof bolt spacing (R_s) is known (which is also equal to suspension chain spacing), the number of suspension chains installed within L_{part} is determined as follows:

$$\text{Total number of suspension chains within } L_{part} = \left(\frac{L_{part}}{R_s}\right) \quad (2)$$

Thus, the total force in suspension chains within the span L_{part} is the product of the total number of suspension chains installed and the force in each chain (F_C) as indicated below:

$$\text{Total force in suspension chains within } L_{part} = F_C\left(\frac{L_{part}}{R_s}\right) \quad (3)$$

$$\text{Z-component of the total force in suspension chains} = F_C\left(\frac{L_{part}}{R_s}\right)\cos\alpha \quad (4)$$

Weight of monorail loading system component

In determining the weight of the heaviest monorail loading system component (F_{part}) of length L_{part}, the weight of the driver's cabin, loaded containers and the power pack (with drive units) and their respective lengths were considered in this analysis. Figure 4 shows the monorail loading system components with respective lengths and weights.

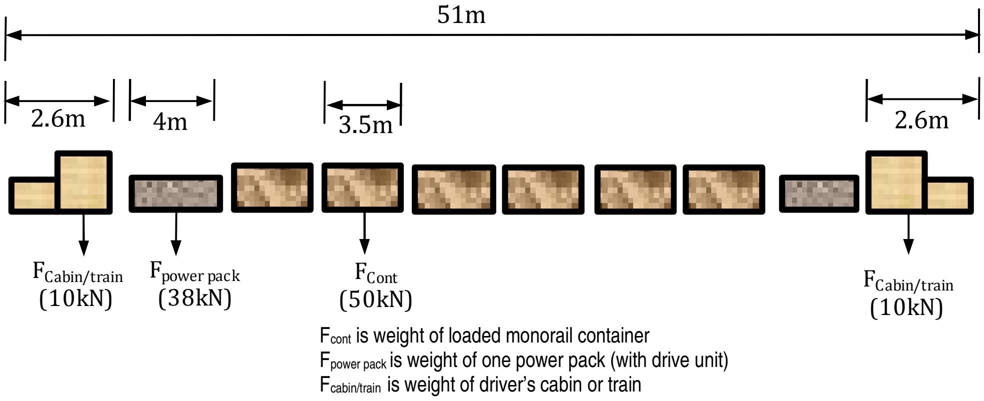


Fig 4 - Schematic diagram showing lengths and weights of monorail loading system components

As shown in Figure 4, the monorail loading system consists of components of different lengths and weights (Scharf, 2007). The heaviest component is the loaded monorail container, which has a total weight of 50kN. Therefore, the length (L_{part}) and weight (F_{part}) of the heaviest component of the monorail loading system used in the analysis is 3.5m and 50kN, respectively. The weight of the heaviest component of the monorail loading system is:

$$\text{Weight of heaviest component of monorail loading system} = F_{part} \quad (5)$$

$$\text{Z-component of the heaviest monorail loading system} = F_{part}\cos\alpha \quad (6)$$

Required strength of suspension chains

As shown in Figures 3 and 4, the heaviest monorail loading system component remains in equilibrium (in Z-direction) if its weight and total force in the suspension chains are equal. Therefore, the relationship between the weight of the heaviest monorail loading system component and the required force in each suspension chain just before failure is determined by equating Equations 4 and 6 to yield:

$$F_C = \frac{R_s}{L_{part}}F_{part} \quad (7)$$

However, for the heaviest monorail loading system component to remain in equilibrium requires that the total force in the suspension chains within L_{part} be equal to the total weight of that component. Since the allowable load in suspension chains just before failure is known (from Equation 7), the strength of the suspension chain should be more than the allowable load. However, the classical approach used in designing engineering structures is to increase the capacity (ultimate load) of the system in comparison with the allowable load. It should also be noted that suspension chain failure occurs if the weight of the heaviest monorail loading system component (allowable load) is more than the capacity (ultimate load) of the chains within L_{part} occupying the heaviest component. Since the allowable force in each suspension chain is the same as the required force just before failure, a factor of safety is applied to increase the loading capacity of the chains. In this study, a factor of safety of 2.0 is assumed. Therefore, applying a factor of safety to Equation 7 yields:

$$F_{C,\,max} = \frac{2R_s}{L_{part}} F_{part} \tag{8}$$

Since R_s and L_{part} are constants, the required strength of suspension chains, therefore, depends on the weight of the loaded monorail containers. Alternatively, R_s can be determined if the strength of the suspension chain is known.

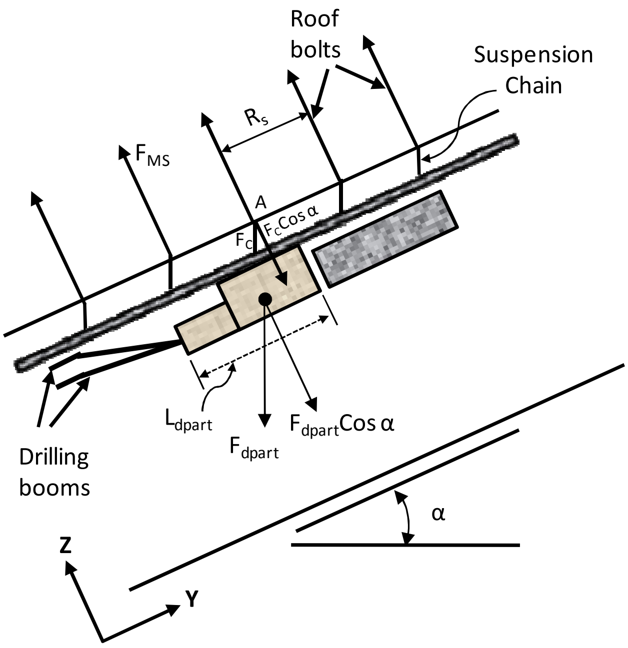
Required strength of roof bolts

The required strength of installed roof bolts within the span occupying the heaviest monorail loading system component L_{part} is determined using the relationship in Equation 1. Therefore, substituting Equation 8 into Equation 1 gives the required strength in each roof bolt as:

$$F_{MS,\,max} = \frac{2R_s}{L_{part}} F_{part} \operatorname{Cos}\alpha \tag{9}$$

Equilibrium of forces for the drilling system

The minimum strength required in each roof bolt and suspension chain to suspend the monorail drilling system components depends on the weight of the drilling system components (i.e., the weight of monorail train together with the two drilling booms and the weight of power pack with drive units). Figure 5 is used to determine the required strength in each roof bolt and suspension chains based on the weight of monorail drilling system components. It should be noted that this analysis is limited to the case of drilling system in transit. The system is further supported when drilling a face.



L_{dpart} is length of monorail drilling system component
F_{dpart} is weight of monorail drilling system component
R_s is roof bolt spacing
F_{MS} is force in each roof bolts (forces suspending monorail system)
F_C is force in each suspension chain
α is decline gradient

Fig 5 - Forces in roof bolts and suspension chains for the monorail drilling system components in an incline

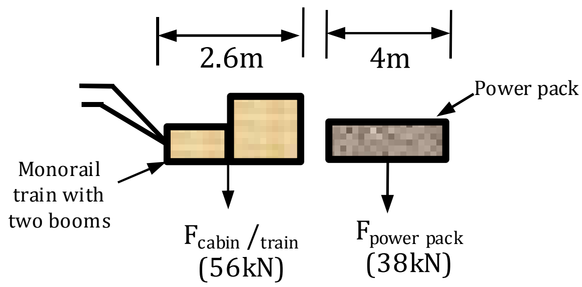
Total forces in suspension chains within L_{dpart}

An analysis similar to that shown in the previous section yields;

$$\text{Z - component of total force in suspension chain} = F_C\left(\frac{L_{dpart}}{R_s}\right)\cos\alpha \qquad (10)$$

Weight of monorail drilling system component

Figure 6, is used to determine the weight of the heaviest component to be used in the analysis.



$F_{power\ pack}$ is weight of power pack with drive unit
$F_{cabin\,/\,train}$ is weight of driver's cabin together with two drilling booms

Fig 6 - Schematic diagram showing lengths and weights of monorail drilling system components

Figure 6 shows the monorail drilling system consisting of two components, i.e., the driver's cabin with two drilling booms and the power pack each with different length and weight. Thus, to determine the strength of the roof bolts and suspension chains the heaviest component of the drilling system is used in the analysis. Figure 6 shows that the heaviest component is the driver's cabin together with the two drilling booms which has a weight of 56kN (i.e., weight of driver's cabin is 10kN and the two drilling booms were assumed to weigh 46kN (Chanda, et al. 2008b)). Therefore, the length (L_{dpart}) and the weight (F_{dpart}) of the heaviest monorail drilling system component used in the analysis are 2.6m (suspended length only) and 56kN, respectively. The heaviest drilling system component in Z-direction is written as:

$$\text{Z - component of the heaviest drilling system component} = F_{dpart} \cos\alpha \tag{11}$$

Required strength of suspension chains

The required strength (with factor of safety of 2.0) in each suspension chain is determined by equating Equations 10 and 11 to yield:

$$F_{C,\,max} = \frac{2R_s}{L_{dpart}} F_{dpart} \tag{12}$$

Required strength of roof bolts

The required strength in each roof bolt is determined by substituting Equation 12 into Equation 1 to yield:

$$F_{MS,\,max} = \frac{2R_s}{L_{dpart}} F_{dpart} \cos\alpha \tag{13}$$

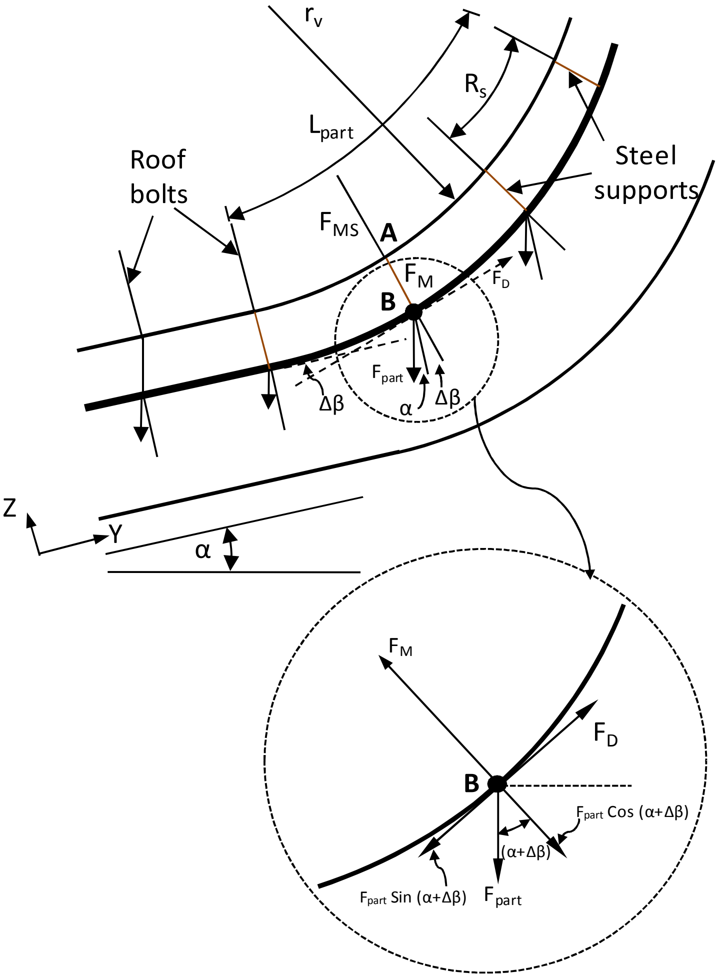
Strength of support system at horizontal and vertical curves

During monorail installation at vertical and horizontal curves, the required support system must be sufficient to overcome the dynamic effects and to avoid system failure. Also, it should be noted that during monorail installation process, the monorail components are rigidly fixed using steel supports at vertical curves while suspension chains are used at horizontal curves. It is, therefore, necessary to determine the strength of the required support systems that are used to suspend the monorail components at vertical and horizontal curves. As highlighted in the introduction, the monorail system can negotiate horizontal and vertical curve radii of 4m and 10m respectively. However, the curve lengths that result from these radii are small to accommodate the whole length of the monorail drilling and loading systems. Therefore, the weight of heaviest monorail drilling and loading systems components passing the vertical and horizontal curve is used. In this section, models that determine the strength of roof bolts, steel supports and suspension chains at vertical and horizontal curves based on the dynamic forces of the heaviest monorail drilling and loading system components are presented.

Strength of steel supports at vertical curves based on weight of monorail loading system components

Taking equilibrium of forces at point A (Figure 7), the following equation that relates the force in each roof bolt and steel support is established:

$$F_{MS} = F_M \tag{14}$$



L_{part} is length of monorail loading system component
R_s is roof bolt spacing
F_{MS} is force required in each roof bolts (forces suspending monorail system)
F_{part} is weight of monorail loading system component
F_M is force in each steel support
F_D is net driving (propulsion) force
α is decline gradient
Δβ is angle change at vertical curve
r_v is vertical curve radius

Fig 7 - Schematic longitudinal-section view of required support system at vertical curve based on the weight of monorail loading system components

During motion of the monorail loading system at a curve a centrifugal force F_S (Equation 15) directed towards the centre of the curve is needed to make the monorail train or any component attached to it undergo motion at a vertical curve (Alan, 2003; Lawrence, 1997):

$$F_S = \frac{m_{part} v^2}{r_v} \qquad (15)$$

where:

F_S is the centrifugal force needed to make the monorail train or its components undergo uniform motion at a curve;
v is velocity of the monorail train or its component as it moves along the curve;
r_v is vertical radius of the curve around which the monorail loading system or its components is moving; and
m_{part} is mass of the monorail loading system component negotiating the curve.

Total force in steel supports at vertical curve

The total force in steel supports at vertical curves depends on the number of steel supports installed within the length, L_{part}, occupying the monorail loading system component and the force in each steel support. Since the roof bolt spacing, R_s, is known, the number of steel supports occupying the monorail loading system component of length L_{part}, at a vertical curve is determined as:

$$\text{Total number of steel supports within } L_{part} = \left(\frac{L_{part}}{R_s}\right) \tag{16}$$

where:

L_{part} is the length of monorail loading system component.

Thus, the total force in steel supports within the length L_{part} at a vertical curve is the product of the total number of steel supports installed within the length L_{part} and the force in each steel support (F_M) as:

$$\text{Total force in steel support within } L_{part} = F_M \left(\frac{L_{part}}{R_s}\right) \tag{17}$$

It is assumed that the support distance L_{part} is small and the variation of angle can be ignored. Using Equation 15 and taking equilibrium of forces in Z-direction at point B (Figure 7), the resultant force of the monorail loading system component at a curve is determined as:

$$F_M \left(\frac{L_{part}}{R_s}\right) - F_{part} \mathrm{Cos}\,(\alpha + \Delta\beta) = \frac{m_{part} v^2}{r_v} \tag{18}$$

where

$$0^0 \le \Delta\beta \le 70^0$$

Similarly, the net propulsion force (F_D) of the monorail train at a curve is determined using Equation 19:

$$F_D = F_{part} \mathrm{Sin}\,(\alpha + \Delta\beta) \tag{19}$$

From Equation 18, the strength in each steel support (with a factor of safety of 2.0) is determined as:

$$F_{M,\,max} = \frac{2R_s}{L_{part}} \times \left(\frac{m_{part} v^2}{r_v} + F_{part} \mathrm{Cos}\,(\alpha + \Delta\beta)\right) \tag{20}$$

The strength of steel supports at vertical curves is determined based on the heaviest component of the monorail loading system as discussed in previous section.

Required strength of steel supports at vertical curves

The required strength of each steel support at a vertical curve is determined using Equations 20. It should be noted that the maximum force in steel supports occurs when $\Delta\beta = 0$. Therefore, with this condition, Equation 20 can be written as:

$$F_{M,\,max} = \frac{2R_s}{L_{part}} \times \left(\frac{m_{part} v^2}{r_v} + F_{part} \mathrm{Cos}\,\alpha\right) \tag{21}$$

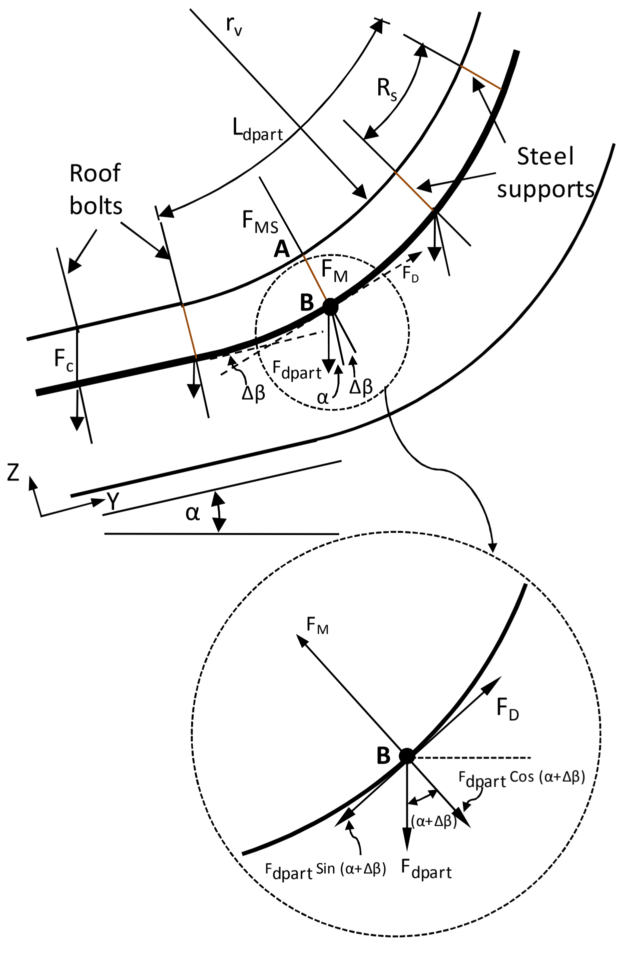
Required strength of roof bolts at vertical curves

According to Equation 14, the force in each roof bolt at vertical curve is equal to the force in each steel support. Therefore, using Equations 14 and 21, the required strength in each roof bolt is determined as:

$$F_{MS,\,max} = \frac{2R_s}{L_{part}} \times \left(\frac{m_{part} v^2}{r_v} + F_{part} \cos\alpha \right) \tag{22}$$

Strength of steel supports at vertical curves based on weight of monorail drilling system component

The strength of required roof bolts and steel supports at vertical curves based on the weight of the monorail drilling system components is determined using Figure 8 (configuration is the same as loading system in Figure 7)



L_{part} is length of monorail drilling system component
R_s is roof bolt spacing
F_{MS} is force required in each roof bolts (forces suspending monorail system)
F_{dpart} is weight of any monorail drilling system component
F_M is force in each steel support
α is decline gradient
$\Delta\beta$ is angle change at vertical curve
r_v is vertical curve radius

Fig 8 - Schematic longitudinal-section view of required support system at vertical curve based on weight of monorail drilling system components.

Total force in steel supports at vertical curves

Using similar analysis as for the monorail loading system yields:

$$\text{Total force in steel supports within curve } L_{dpart} = F_M\left(\frac{L_{dpart}}{R_s}\right) \quad (23)$$

The net pushing force (F_D) of the monorail drilling system at vertical curve is determined as:

$$F_D = F_{dpart}\text{Sin}\,(\alpha + \Delta\beta) \quad (24)$$

The force in each steel support (with a factor of safety of 2.0) is also determined as:

$$F_{M,max} = \frac{2R_s}{L_{dpart}} \times \left(\frac{m_{dpart}v^2}{r_v} + F_{dpart}\text{Cos}\,(\alpha + \Delta\beta)\right) \quad (25)$$

Weight of monorail drilling system component

The weight of the heaviest monorail drilling system component (F_{dpart}) of length L_{dpart}, is determined as outlined in previous section.

Required strength of steel supports at vertical curve

Since the maximum force in steel supports occurs when $\Delta\beta = 0$, the ultimate force in steel supports at a vertical curve is determined as:

$$F_{M,\,max} = \frac{2R_s}{L_{dpart}} \times \left(\frac{m_{dpart}v^2}{r_v} + F_{dpart}\text{Cos}\,\alpha\right) \quad (26)$$

Required strength in roof bolts at vertical curve

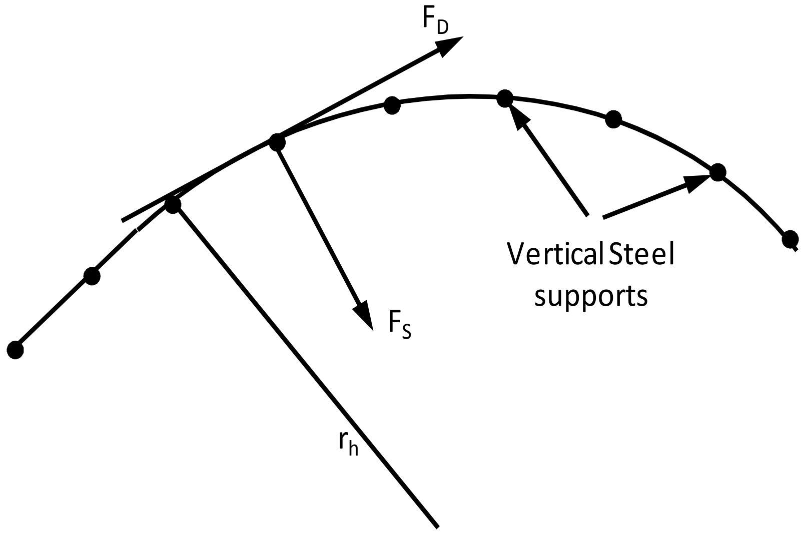
Using Equations 14 and 26, the ultimate force in each roof bolt is determined as:

$$F_{MS,\,max} = \frac{2R_s}{L_{dpart}} \times \left(\frac{m_{dpart}v^2}{r_v} + F_{dpart}\text{Cos}\,\alpha\right) \quad (27)$$

Strength of suspension chains at horizontal curves based on monorail loading system

Force and displacement of suspension chains at horizontal curves

As the monorail loading systems negotiates a horizontal curve, suspension chains are displaced from the vertical position due to dynamic forces resulting from the motion of the systems. Figures 9 and 10 show the forces and displacement of suspension chain at a horizontal curve.



F_S is centrifugal force exerted on moving monorail loading system
F_D is net driving (propulsion) force
r_h is horizontal curve radius

Fig 9 - Plan view of forces at the horizontal curve

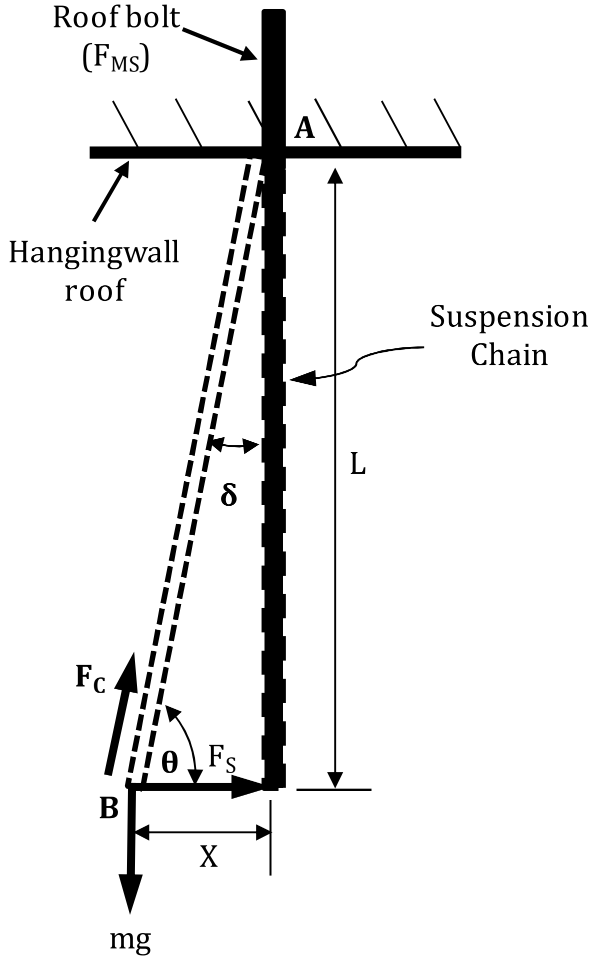


Fig 10 - Displacement of suspension chain from vertical position at horizontal curve

As shown in Figures 9 and 10, centrifugal force, F_S, results as the monorail loading system moves along the curve as given in Equation 28.

$$F_S = \frac{m_{part} v^2}{r_h} \tag{28}$$

where;

r_h is horizontal radius of the curve around which the monorail loading system or its components is moving

As shown in Figure 10, as the monorail drilling and loading systems negotiate the horizontal curve, the suspension chains are displaced from vertical positions by the angle, δ, and horizontal distance, X. It is important to determine these two parameters and the force carried by the suspension chains so as to determine whether the chains will fail or the systems will crash (as the chain is displaced) into the sidewall of the underground opening at a horizontal curve so that control measures are put in place.

Using Figure 10, the following equation that relates the force in each roof bolt and the force in suspension chains at horizontal curve is established.

$$F_{MS} = F_C \mathrm{Sin}\,\theta \tag{29}$$

Angular displacement (δ) of suspension chains due to monorail loading system

The angular displacement of suspension chains from the vertical position is determined by resolving forces at point B to yield:

$$\text{Horizontal force balance:} \quad F_C \mathrm{Cos}\theta = F_S = \frac{m_{part} v^2}{r_h} \tag{30}$$

$$\text{Vertical force balance:} \quad F_C \mathrm{Sin}\theta = m_{part} g \tag{31}$$

Dividing Equation 31 by Equation 30 yields:

$$\mathrm{Tan}\theta = \left(\frac{g \times r_h}{v^2} \right) \tag{32}$$

Therefore, the angular displacement of suspension chains is determined as:

$$\delta = 90 - \mathrm{Tan}^{-1}\left(\frac{g \times r_h}{v^2} \right) \tag{33}$$

Equation 33 indicates that the maximum angular displacement of suspension chains depends on the radius of curvature of the horizontal curve and the velocity of the monorail system component at the curve. Thus, an increase in the radius of the horizontal curve results in smaller angular displacement and vice versa. Equation 33 also reveals that an increase in the velocity of the monorail system component at a curve results in an increase in angular displacement of suspension chains and vice versa.

Horizontal displacement (X) of suspension chains due to monorail loading system

Using trigonometry, the horizontal displacement by which suspension chains are displaced from the vertical position due to dynamic forces is found using Equation 34:

$$X = \frac{L \times v^2}{r_h \times g} \tag{34}$$

Equation 34 shows that horizontal displacement depends on the length of suspension chains, velocity of the monorail loading system components and the radius of curvature of the horizontal curve. The length of suspension chains and square of the velocity of the monorail loading system component varies directly with the horizontal displacement while the radius of curvature is inversely related with X.

Force in suspension chains at horizontal curves

Having found θ as per Equation 32, Equations 30 gives the value of the force (with a factor of safety of 2.0) in suspension chains F_C due to dynamic force of the system as:

$$F_{C,\,max} = \frac{2m_{part}v^2}{r_h} \times \frac{1}{Cos\theta} \tag{35}$$

Using trigonometry;

$$Cos\ \theta = \frac{v^2}{\sqrt{v^4 + g^2 r_h^2}} \tag{36}$$

Replacing Equation 36 into Equation 35 gives:

$$F_{C,\,max} = \frac{2m_{part}}{r_h} \times \sqrt{v^4 + g^2 r_h^2} \tag{37}$$

Force in roof bolts at horizontal curves

The force in roof bolts at horizontal curves is obtained using Equation 32 and 37 to yield:

$$F_{MS,\,max} = 2m_{part}g \tag{38}$$

Strength of suspension chains at horizontal curves based on monorail drilling system

Force and displacement of suspension chains at horizontal curves

Base on similar analysis as in previous section, centrifugal force, F_S, which results as the monorail drilling system moves along the curve is:

$$F_S = \frac{m_{dpart}v^2}{r_h} \tag{39}$$

Using Figure 10, the angular displacement of suspension chains from the vertical position is given as follows:

$$\text{Horizontal force balance:}\quad F_C Cos\theta = F_S = \frac{m_{dpart}v^2}{r_h} \tag{40}$$

$$\text{Vertical force balance:}\quad F_C Sin\theta = m_{dpart}g \tag{41}$$

Required strength of suspension chains at horizontal curves

The required strength of suspension chains (with a factor of safety of 2.0) at horizontal curves for the monorail drilling system is:

$$F_{C,\,max} = \frac{2m_{dpart}}{r_h} \times \sqrt{v^4 + g^2 r_h^2} \tag{42}$$

Force in roof bolts at horizontal curves

The force in roof bolts at horizontal curves is obtained by using Equation 32 and 42 to yield:

$$F_{MS,\,max} = 2m_{dpart} g \tag{43}$$

Variation of support system strength with change in decline gradient

In this section, the variation of support system strength with changes in decline gradient is established. As the decline gradient changes, there is a corresponding change in the required force in each support system. The developed models are used to establish this variation. Table 1 show the data used during the determination. The data is based on information from manufacturers of the monorail train, Scharf, and publications on monorail drilling and loading systems (Chanda and Besa, 2008a; Chanda et al, 2008b; Chanda and Besa, 2009).

Table 1
Parameters of the monorail system

Parameter	Unit	Value	Comment
L_{part}	m	3.5	Manufacturer supplied
L_{dpart}	m	2.6	Manufacturer supplied
m_{part}	kg	5.1	Manufacturer supplied
m_{dpart}	kg	5.7	Manufacturer supplied
F_{part}	kN	50	Manufacturer supplied
F_{dpart}	kN	56	Manufacturer supplied
R_s	m	3	Manufacturer supplied
α	degrees	20	Assumed (Chanda et al, 2008; Chanda and Besa, 2009)
r_v	m	10	Manufacturer supplied
r_h	m	4	Manufacturer supplied
v	m/s	3.5	Manufacturer supplied
L	m	0.6	Manufacturer supplied
g	m/s^2	9.81	Constant

Numerical values of forces required in the support systems

Using the developed models, the strength of the required support system with changes in decline gradient for the monorail drilling and loading systems is determined as of Figures 11 and 12.

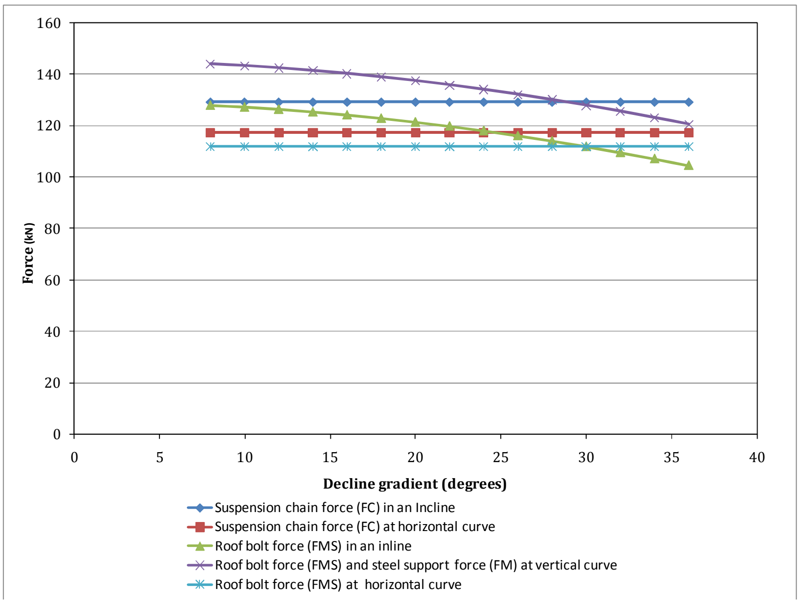


Fig 11 - Variation of force in support system with change in decline gradient for the monorail drilling system

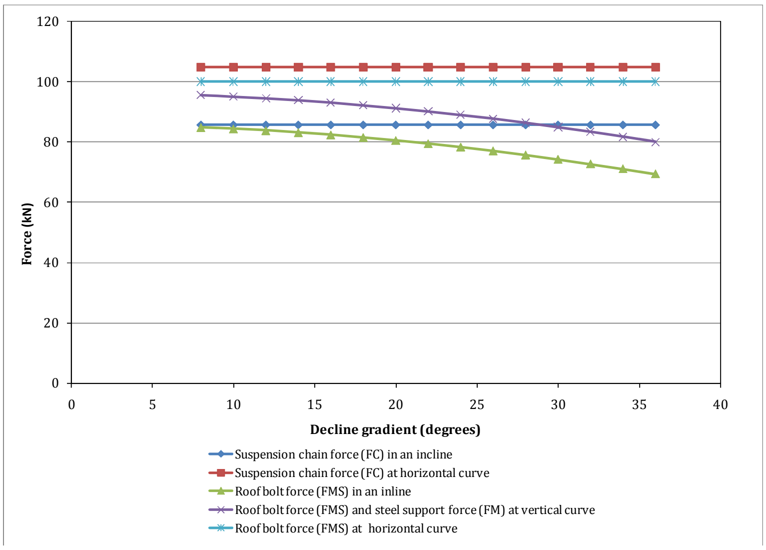


Fig 12 - Variation of force in support system with change in decline gradient for the monorail loading system

Results shown in Figure 11 and Figure 12 indicate that the force required to suspend the monorail drilling system components is higher than that needed to suspend the loading system components. According to the results, the force in suspension chains in an incline, horizontal curves and in roof bolts at horizontal curves remains constant with changes in decline gradient. However, in an incline and at vertical curves, the force in the roof bolts varies inversely with change in decline gradient, i.e., as the decline gradient increases the required force in the roof bolts reduces. Similarly, the force in steel supports at vertical curves varies inversely with decline gradient.

Strength of support system at 20^0 decline gradient

Chanda and Besa, 2008 presented a mine design case study in which a decline gradient of 20^0 was used. Using this case study, numerical values of the required support system strength at that gradient have been determined. Figure 13 shows the numerical values for each system while Table 2 shows the displacements of suspension chains at horizontal curves for 20^0 gradient.

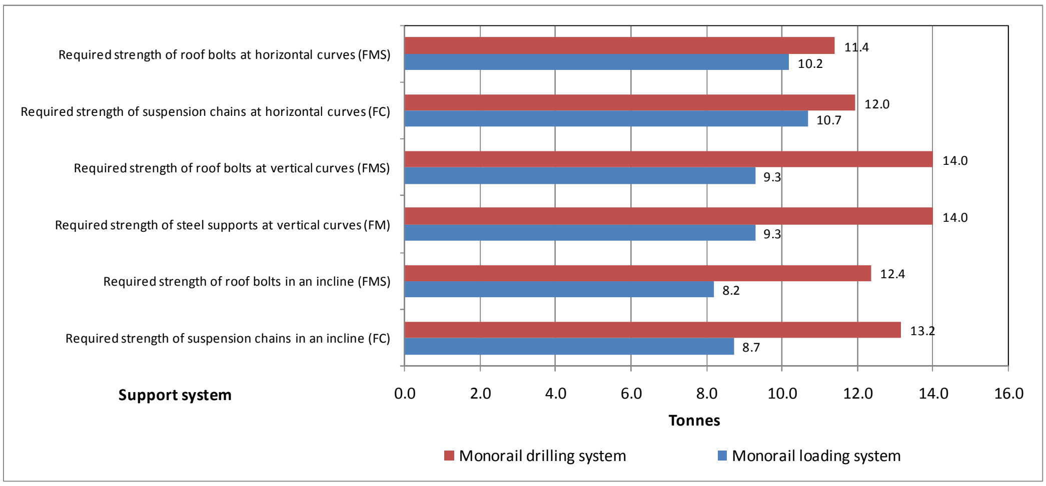


Fig 13 - Strength of support system at 20^0 decline gradient

Table 2
Displacement of suspension chains at horizontal curves

Parameter	Unit	Monorail loading system	Monorail drilling System
Angular displacement (**δ**)	degrees	17.3	17.3
Horizontal displacement (**X**)	cm	18.7	18.7

High strength roof bolts, suspension chains and steel supports are required to suspend and support the monorail drilling system components more than that required for the monorail loading system. In comparison with the roof bolts (namely Hilti OneStep® roof bolts) and suspension chains currently being used which have an ultimate strength of 320kN (32 tonnes) and 250kN (25 tonnes), respectively, it is clear that the roof bolts and suspension chains have adequate strength to suspend and support the components of the two systems. Analysis of variation of decline gradient with strength of support system shows that the higher the decline gradient, the lower is the force in the support system. In terms of suspension chain displacements at horizontal curves, results have shown that both systems would give the same angular and horizontal displacement of 17.3^0 and 18.7cm, respectively. These displacements can be minimized by reducing the velocity of the monorail systems at horizontal curves or increasing the radius of the curve. Since both systems move on the same rail, Table 3 shows minimum numerical values that have been recommended.

Table 3
Required strength of the support system

Strength of parameter	Recommended value	
	kN	Tonnes
Suspension chains in an incline (F_C)	129.2	13.1
Roof bolts in an incline (F_{MS})	121.4	12.3
Steel supports at vertical curves (F_{SS})	137.6	14.0
Roof bolts at vertical curves (F_{MS})	137.6	14.0
Suspension chains at horizontal curves (F_C)	117.3	12.0
Roof bolts at horizontal curves (F_{MS})	112.0	11.4

DISCUSSION AND CONCLUSION

In spite of the advantages of the monorail system, one of the major risks is the potential of failure of the support system due to inadequate strength of roof bolt, suspension chain and steel support. Therefore, to avoid system failure, adequate strength of roof bolt, suspension chain and steel support that can support the proposed monorail system needs to be installed.

This paper has demonstrated that to avoid roof bolt, suspension chain and steel support failure due to additional stresses from weight of the monorail drilling and loading systems, high strength roof bolts, suspension chains and steel supports to support the two systems must be installed. In comparison with the roof bolts currently in use, the models developed have demonstrated that the support system has adequate strength to support and suspend the two systems. It has also been established that the required strength of roof bolts varies inversely with the decline gradient. However, the strength of suspension chains in the decline and at horizontal curves as well as the strength of roof bolts at horizontal curves remains constant. To reduce or minimise displacements of suspension chains, it is recommended that the velocity of the monorail system at horizontal curves be reduced during motion.

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