Effects of Thickness of Roof Layers on Optimum Design of Truss Bolt System Using Finite Element Modeling Techniques

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ABSTRACT

In underground excavations, optimum design of reinforcement systems is largely based on geological features of the surrounding rock such as in-situ stress distribution, rock strength properties, thickness of the layers, etc. In current design of truss bolt systems these parameters are yet to be considered. In this study, effects of changing thickness of roof layers on optimum design of truss bolt have been investigated using three stability indicators, namely reduction in the loosened area above the roof, number of plastic points and horizontal movement on the first bedding plane. Total of 7 different bedding configurations have been generated and 100 different truss bolt designs have been tested on each bedding configuration. Results showed that by changing the thickness of the roof layers, the optimum design of truss bolt changes drastically. In highly laminated formations, it has been demonstrated that a gently inclined bolt angle is more effective, while by increasing the thickness of roof layers, truss bolt systems with a higher bolt angle and longer bolts, i.e. similar to systematic rock bolt systems, responds better.

KEYWORDS: Truss bolt; ground reinforcement; FEM; optimum design

INTRODUCTION

Truss bolt is a ground reinforcement system which is used specially in severe roof conditions and coal mining industry (Gambrell and Crane, 1986; Liu et al., 2005). This system is consisted of two inclined bolts and a tie-rod, connecting the inclined bolts on the roof. The inclined bolts are anchored outside of the disturbed zone around the excavation and a horizontal tension is applied at the middle of tie-rod using a turnbuckle (Figure 1). This tension produces a compressive stress in areas around and between inclined bolts which reinforces the ground (Gambrell and Haynes, 1970; Gambrell and Crane, 1986). Since invention of truss bolt system in

1960s, many efforts have been made to investigate the reinforcing mechanism of truss bolt using techniques such as photoelastic modeling, experimental, and empirical studies (Neall et al., 1977; Cox and Cox, 1978; Neall et al., 1978; Wahab Khair, 1984). Several design schemes have been proposed in the literature for truss bolt system based on semi empirical, numerical, and analytical solutions (Sheorey et al., 1973; Cox and Cox, 1978; Zhu and Young, 1999; Liu et al., 2001; Liu et al., 2005). However, none of the design procedures considers the changes in geology and properties of the coherent rock material.

Variable rock mass quality around underground excavations is always a problem in finding the optimum design pattern for rock mass reinforcement. An optimum reinforcement design can vary with respect to changes in the geological features such as thickness of the rock layers, joint directions, strength parameters of rocks and changing the overburden load. To have a better understanding of the effects of the factors and finding the optimum design patterns, these variables should be changed alongside with the design parameters of the truss bolt. This only can be realistically achieved by using numerical simulation which is able to consider different variables at the same time.

In this paper three stability indicators have been introduced to monitor the response of the reinforcement on the surrounding rock. Truss bolt system on a rectangular tunnel in layered rock formation has been modeled using finite element package ABAQUS (2010). Truss bolt design

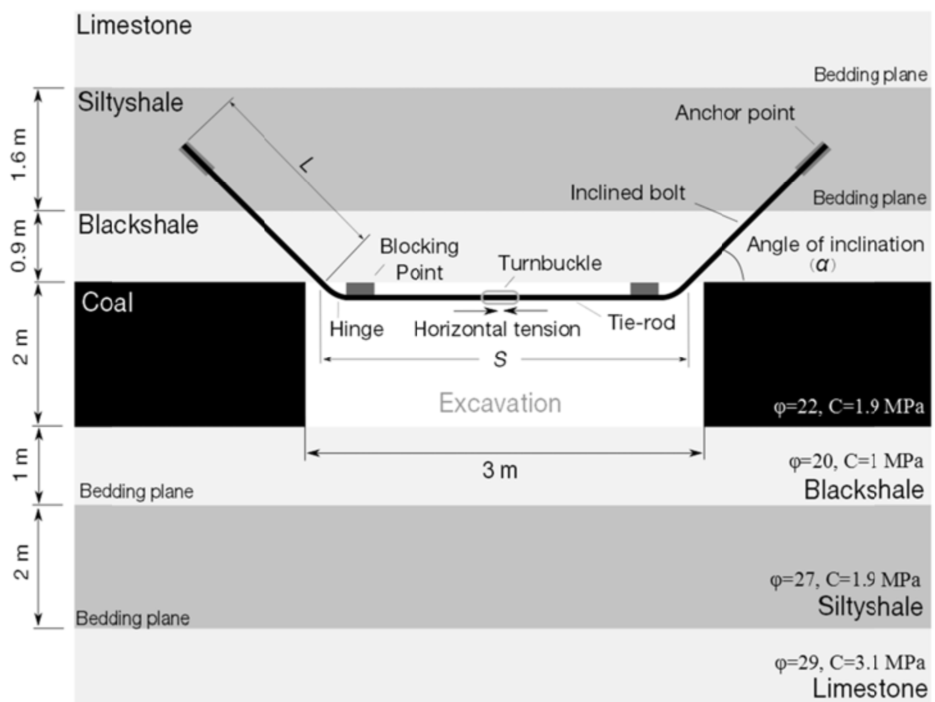

Figure 1: Schematic view of truss bolt, dimensions of the model, and material properties

parameters (length and angle of inclined bolts and length of tie-rod) together with thickness of the roof layers have been studied to find the optimum design pattern of truss bolt for each bedding configuration.

NUMERICAL MODEL

An underground excavation in laminated rock formation has been modeled. The model has 4 bedding planes. In-situ stress has been considered as hydrostatic stress equal to 1.9 MPa. The dimensions of the tunnel, thickness of bedding planes and material properties are shown in Figure 1. Mohr-Coulomb failure criterion has been adopted to model the rock mass material in plain strain condition. Rock has been modeled as elastic-perfectly plastic material and verified using analytical solution proposed by (Hoek et al., 1998).

Bedding planes have been modeled according to Coulomb friction model as

$$\tau = \mu p \tag{1}$$

where τ is shear stress, μ is coefficient of friction on the plane of weakness ($\mu = \tan\varphi$, φ is friction angle) and p is contact pressure. In this model, no penetration is allowed between layers and sticking or slipping behavior of bedding planes governs by the forces mobilized between two contact surfaces when they are in contact. The finite element model has been verified using the analytical equations proposed by (Brady and Brown, 2005).

Inclined bolts have been modeled using one dimensional *truss elements* in ABAQUS. Two ends of these elements have been anchored to the rock where no separation is allowed, representing end-anchored rock bolts. After excavating an underground excavation displacement happens in the surrounding rock. This displacement induces some amount of stress in rock bolts which may exceed the capacity of the bolts and cause failure (Hoek and Brown, 1980). To prevent failure of the rock bolt elements, the amount of pre-tension stress has been chosen as 60% of the ultimate tensile stress. Physical properties of rock bolts are shown in Table 1.

Table 1: Bolt properties in numerical model

Cross-sectional area	313 mm^2
Modulus of Elasticity	200 GPa
Ultimate tensile strength	1671 MPa
Elongation on 660 mm length	6-7%
Mass of perimeter-cable	2.782 kg/m

Seven bedding configurations have been modeled which are shown in Table 2. Here we call each model by two numbers where the first number is the distance of the first bedding plane from the roof and the second number is the distance of the second bedding plane from the roof. For example, 30-150 is a model with thickness of the first layer equal to 30 cm and the second layer equal to 150 - 30 = 120 cm (Table 2).

Table 2: Different bedding configurations

Name of the model	Thickness of the first layer (cm)	Thickness of the second layer (cm)
30-90	30	60
30-150	30	120
30-250	30	220
90-150	90	60
90-250	90	160
120-250	120	130
150-250	150	100

Three design parameters of truss bolt patterns have been chosen to be changed: angle (α) and length (*L*) of inclined bolts and length of tie-rod (*S*). These variables and their values are shown in Table 3. As a result, a total number of 5×5×4 = 100 models is generated for each bedding configuration. Considering seven types of bedding configuration, a total number of 7×100 = 700 models has been simulated.

Table 3: Truss bolt design parameters

Design parameter					
α(°)	15	30	45	60	75
L (m)	1.0	1.5	2.0	2.5	3.0
S (m)	1.6	2.0	2.4	2.8	

Stability Indicators

To evaluate and compare the effects of different truss bolt patterns three stability indicators have been introduced. The three indicators are number of plastic points; reduction in the loosen area above the roof and horizontal movement of rock layers. As explained below, these indicators monitor the plastic behavior of rock, horizontal movement of the bedding planes and the reinforcing effect of truss bolt system on roof rock.

Number of Plastic Points

After excavating an underground excavation, depending on the size and geometry of the excavation, physical properties of rock, and in-situ stress distribution, rock undergoes elastic-plastic deformation. This deformation induces an amount of pressure on the reinforcement system which in response increases the tension force in the system. Hence, more loads are transferred to rock by truss bolt. This increase in load continues to reach an equilibrium in which the stress in rock is equal to the applied stress by reinforcement system. This effect of reinforcement system prevents some areas of rock from yielding and plastic deformation. Figure 2a shows an example of this indicator in a sample model. The reduction in the number of yielded points can be used to compare the response of different truss bolt patterns.

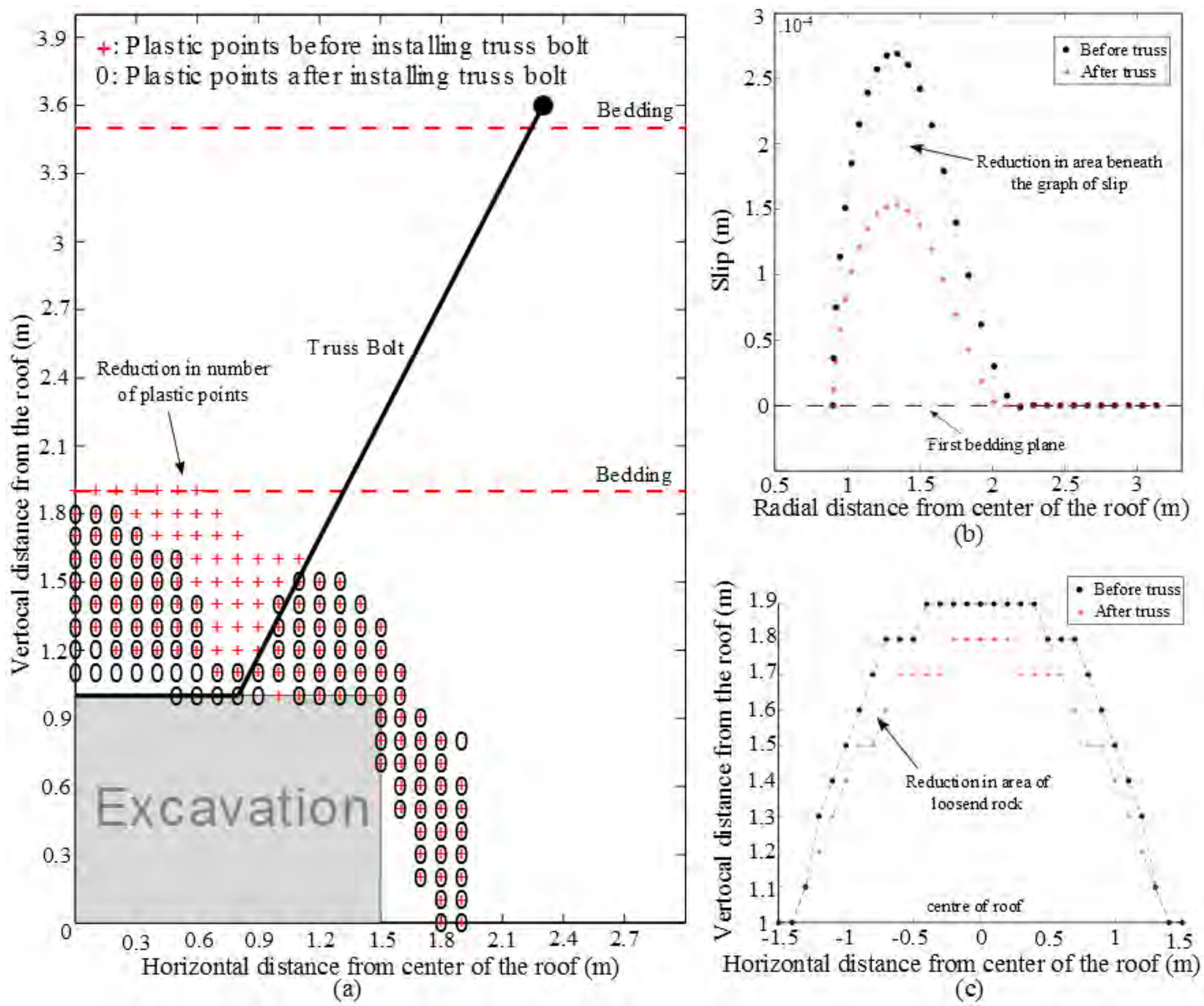

Figure 2: (a) plastic points distribution, (b) slip on the first bedding plane and (c) reinforced arch before and after installing truss bolt pattern (L=3m, α=60, S=1.6) on model 90250

Slip on the First Bedding Plane

Truss bolt system has proven to be more effective in controlling cutter roof failures than regular systematic rock bolt (Stankus et al., 1996). Horizontal movement of rock layers is one of the key parameters causing cutter roof failure (Altounyan and Taljaard, 2001). Truss bolt system by having two inclined bolts reduces the amount of slip on the bedding planes. The induced tension in inclined bolts has a horizontal component opposite to the direction of the movement which reduces the horizontal movement of the roof layer. Also, the vertical component of this tension increases the normal stress component on the bedding plane which, according to Coulomb friction model (Equation 1), increases the resistance against slip. Figure 2b shows an example of how truss bolt reduces the horizontal movement of the first roof layer.

To compare the effect of different truss bolt patterns on the slip on the first bedding plane, the reduction in the area beneath the graph of slip versus radial distance from center of the roof, has been calculated.

Slip on the First Bedding Plane

The in-situ stress around an excavation forms an arch-shaped reinforced structure above the roof (Bergman and Bjurstrom, 1984; Huang et al., 2002; Li, 2006). This arch is stable but the area beneath it should be stabilized. Depending on the geological features of rock domain, in-situ stress distribution, dimensions and shape of the tunnel, the location of this arch varies. In addition to reinforcing the loosened area beneath the arch, truss bolt system can change the location of the reinforced arch and reduce the area of the loosened rock (Ghabraie et al., 2012). Comparing reduction in the area of the loosened rock (beneath the reinforced arch) before and after installing truss bolt for different truss bolt patterns illustrates one of the main differences of various truss bolt patterns.

Location of the reinforced arch can be determined by using a displacement based criterion. The amount of displacement above the roof defines the stable-unstable area. In this model points with less than 50% of maximum vertical displacement can be considered as stable. Hence, the reinforced arch is a line with displacements closest to 50% of the maximum vertical displacement and can be expressed as

$$|d_i - (n \times d_{max})| = Minimum \qquad (2)$$

where d_i is vertical displacement at each point and d_{max} is the maximum vertical displacement in the model. Figure 2c shows the reinforced arch before and after installing a sample truss bolt system, resulting from Equation 2.

PERFORMING NUMERICAL ANALYSIS

To compare the response of each truss bolt design, a normalized function of all the indicators has been calculated in which the effect of all stability indicators has been considered equally. This function can be expressed as

$$a_{in} = a_i \times \frac{100}{\max(a_i)} \qquad (3)$$

where a_{in} is the normalized value and a_i is the initial value resulting from each indicator. In this calculation the maximum value for each indicator will be 100. The optimum design is a truss bolt which scores the highest, i.e. closer to 300.

According to several reports, inclined bolts should be anchored far enough from the loosened area, above the ribs of the tunnel to provide a safe anchorage (Cox and Cox, 1978; O'Grady and Fuller, 1992; Liu et al., 2005). This factor should be controlled during the model generation, while the design parameters of the truss bolt are being changed. A rejection criterion has been developed to reject the models with less than 0.6 m length of inclined bolts behind the walls of the tunnel, i.e. not anchored in the safe area (Cox and Cox, 1978). This criterion is simply based on the length and angle of inclined bolts and the position of the drill-hole which is defined by the length of the tie-rod.

RESULTS AND DISCUSSION

After running the models and performing calculations to measure the normalized stability indicators, the top 15 models (out of 100) have been considered as optimum design patterns for each bedding configuration. Figure 3 shows these optimum design patterns and Table 4 shows the values of each stability indicator. These 15 patterns have been split in three groups shown by different colors: upper 5% as red, 5% to 10% as blue and between 10% and 15% as green. The rejected models have been specified by cross (×) in Figure 3 and gray color in Table 4.

Optimum designs for model 30-90 (Figure 3a), which represents a highly laminated rock formation, show that the optimum angle of inclination changes between 30° and 60° while the optimum tie-rod length changes between 1.6 and 2 m. Considering the change in the length of inclined bolts for a specific angle of inclination and tie-rod length (e.g. 45° and 1.6 m tie-rod), it can be concluded that the longer inclined bolts are not necessarily favorable as by increasing the length of inclined bolts the overall score of the pattern decrease (changing color from red to blue or blue to green by increasing length of inclined bolts in Figure 3a).

For model 30-150, optimum designs mostly have 45° angled inclined bolts (Figure 3b). 4 out of 5 most optimum patterns (red points) lie under 2 m tie-rod. Long length, 30° inclined bolts and a number of models with 45° inclined bolts are also ranked as green and blue while the optimum tie-rod length varies from 1.6 to 2.4 m.

Comparing the results of increasing the thickness of the second layer from 60 cm to 220 cm, while the thickness of the first layer is constant (models 30-90 to 30-250, see Figures 3a to c), reveals that patterns with 30° inclined bolts are no longer the optimum designs for models with thick second layer. Instead, truss bolt systems with 45° inclined bolts, 1.6 and 2 m tie-rods and various lengths of inclined bolts show better responses. Also, in all of these three bedding configurations (Figures 3a to c), 60° with 2 to 3 m inclined bolts and 1.6 and 2 m tie-rods show fairly good response, by having a number of blue and green ranked designs.

Figures 3d and 3e are mostly the same, showing the negligible effect of changing the thickness of the second bedding plane while the first bedding plane is relatively thick. Most of the optimum designs in these two bedding configurations are patterns with long inclined bolts, angle of inclination of 45° and 60° and short tie-rod length (1.6 m). Also, from Figure 3e, most of the patterns with 75° inclined bolts and short length tie-rod are rejected. However, using longer inclined bolts, if possible, would result in anchoring the inclined bolts out of the rib area and good response of truss bolt system as two of these patterns are in upper 5% of the optimum designs in 90-250 model. The same result can be seen in Figures 3f and 3g for 120-250 and 150-250 models.

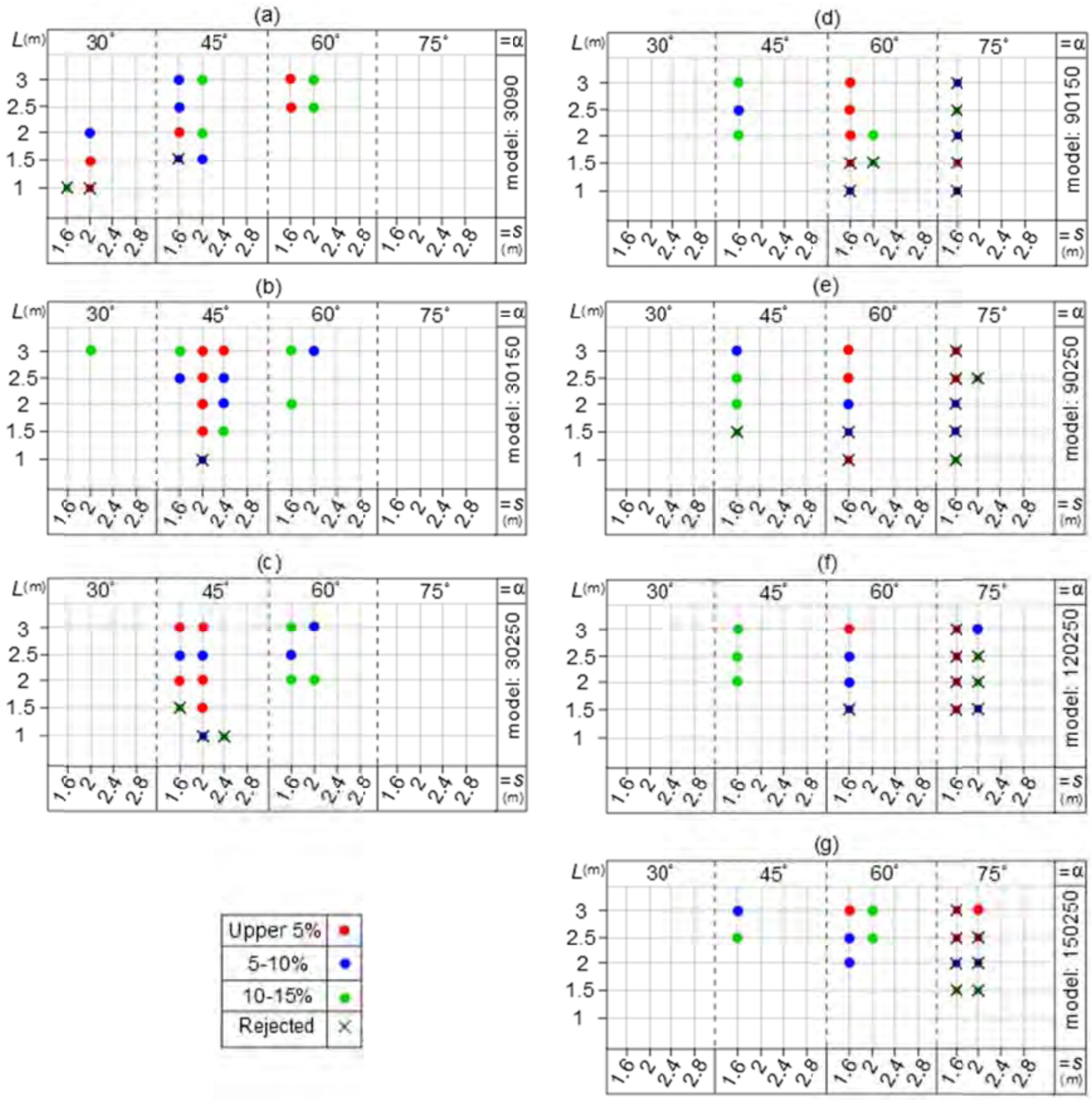

Figure 3: Optimum truss bolt designs for different bedding configurations

By increasing the thickness of the first layer, while the second layer remains constant (comparing Figures 3c, e, f and g), the optimum angle of inclined bolts increases from 45° to 60° and 75° and the longer inclined bolts show better response. This change is probably because of the change in the nature of the models: a model with thick rock layers tends to behave like a continuum material model. Furthermore, changing the optimum angle of inclination from 45° to 75° shows that higher angle of inclination is more favorable in models with thick layers (or continuum material). High angled inclined bolts (ultimately 90°) represent a pattern similar to systematic rock bolt. It can be concluded that, in continuum material or thick roof layers, systematic rock bolt would response better in comparison with truss bolt pattern. It should be noted that considering the effect of horizontal tension on 90° inclined bolts is vital and should be compared with vertically tensioned systematic rock bolt to have a better understanding in this content.

CONCLUSION

The effects of changing thickness of the roof layers on the optimum design of truss bolt system have been investigated in this study. For this purpose, FEM has been used to model different bedding configurations and truss bolt patterns. Three different stability indicators have been introduced to examine the effects of truss bolt systems on each model. After the numerical analysis being conducted, optimum designs of truss bolt system for each bedding configuration have been presented. The main observations and conclusions can be outlined as follows:

- Changing thickness of the roof layers significantly affects the optimum design parameters of truss bolt system.
- Longer inclined bolts do not necessarily result in better response. For example when the roof layers are relatively thin, 2 m inclined bolts response better than 2.5 or 3 m inclined bolts.
- By increasing the thickness of the immediate roof layer while the second roof layer is constant, the optimum angle of inclined bolts increases from 45° to 75° (from horizon) and longer inclined bolts response better.
- By increasing the thickness of the second layer while the thickness of the immediate layer is constant, optimum angle of inclined bolts increases from 30° to 60° (from horizon).
- When the rock layers are thick, the surrounding rock tends to behave in a similar way to continuum material. In this case, highly angled inclined bolts, which make a truss bolt pattern similar to systematic rock bolt, represent the best design.

Table 4: Detailed values of stability indicators

Model	L	a	S	Plastic	Arch	Slip	Total
model 3090	3	60	2	90.9	87.2	30.6	208.7
	2.5	60	2	90.9	87.2	32.1	210.2
	3	45	2	81.8	71.8	57.4	211.0
	2	45	2	81.8	66.7	63.7	212.2
	1	30	1.6	63.6	51.3	100.0	214.9
	1.5	45	1.6	81.8	66.7	68.3	216.8
	3	45	1.6	81.8	74.4	61.7	217.9
	2	30	2	100.0	51.3	66.8	218.1
	1.5	45	1.6	72.7	74.4	71.2	218.3
	2.5	45	1.6	81.8	74.4	63.9	220.0
	1.5	30	2	100.0	46.2	74.6	220.7
	2	45	1.6	81.8	74.4	67.7	223.9
	1	30	2	90.9	46.2	87.5	224.6
	2.5	60	1.6	90.9	94.9	38.9	224.7
	3	60	1.6	90.9	100.0	37.9	228.8
model 30150	3	60	1.6	76.9	87.2	48.7	212.9
	1.5	45	2.4	76.9	74.5	62.7	214.1
	3	30	2	92.3	61.7	60.8	214.8
	3	45	1.6	76.9	74.5	66.5	217.9
	2	60	1.6	76.9	91.5	50.2	218.6
	1	45	2	61.5	70.2	87.0	218.8
	2.5	45	1.6	76.9	74.5	68.5	219.9
	3	60	2	84.6	95.7	40.1	220.5
	2.5	45	2.4	92.3	78.7	51.6	222.7
	2	45	2.4	92.3	78.7	55.4	226.4
	3	45	2.4	100.0	78.7	49.7	228.5
	2	45	2	84.6	78.7	67.1	230.5
	2.5	45	2	92.3	78.7	62.0	233.0
	1.5	45	2	84.6	74.5	74.9	234.0
	3	45	2	100.0	83.0	60.1	243.0
model 30250	2	60	2	83.3	89.3	45.8	218.5
	3	60	1.6	83.3	89.3	50.4	223.0
	2	60	1.6	91.7	78.6	53.4	223.7
	1.5	45	1.6	75.0	67.9	82.4	225.2
	1	45	2.4	75.0	73.2	79.0	227.2
	3	60	2	91.7	96.4	41.2	229.3
	1	45	2	75.0	67.9	87.7	230.6
	2.5	60	1.6	91.7	89.3	52.7	233.6
	2.5	45	1.6	91.7	71.4	70.7	233.8
	2.5	45	2	100.0	75.0	63.4	238.4
	2	45	1.6	91.7	71.4	77.0	240.1
	3	45	1.6	91.7	82.1	67.3	241.1
	3	45	2	100.0	82.1	60.2	242.3
	2	45	2	100.0	75.0	70.2	245.2
	1.5	45	2	100.0	75.0	77.3	252.3
model 90150	2	60	2	57.6	100.0	67.4	225.0
	2.5	75	1.6	75.8	78.4	77.5	231.7
	1.5	60	2	57.6	94.6	80.1	232.2
	3	45	1.6	100.0	67.6	64.9	232.5
	2	45	1.6	97.0	67.6	68.9	233.4
	2.5	45	1.6	100.0	67.6	66.3	233.9
	1	75	1.6	81.8	56.8	97.3	235.9
	3	75	1.6	75.8	83.8	76.5	236.1

Model	L	a	S	Plastic	Arch	Slip	Total
model 90150	2	75	1.6	84.8	78.4	79.4	242.6
	1	60	1.6	93.9	51.4	100.0	245.3
	1.5	75	1.6	84.8	78.4	82.6	245.8
	2	60	1.6	90.9	83.8	81.0	255.7
	3	60	1.6	97.0	83.8	75.6	256.3
	1.5	60	1.6	90.9	73.0	95.0	258.9
	2.5	60	1.6	97.0	83.8	78.3	259.0
model 90250	2.5	75	2	43.5	94.9	61.2	199.6
	2	45	1.6	78.3	59.0	67.3	204.5
	1.5	45	1.6	82.6	53.8	72.1	208.6
	2.5	45	1.6	91.3	59.0	62.6	212.8
	1	75	1.6	69.6	53.8	92.0	215.4
	3	45	1.6	95.7	69.2	60.2	225.1
	2	60	1.6	82.6	64.1	80.5	227.2
	1.5	75	1.6	91.3	64.1	81.9	237.3
	1.5	60	1.6	82.6	64.1	93.7	240.4
	2	75	1.6	87.0	79.5	76.5	243.0
	2.5	60	1.6	100.0	74.4	74.9	249.3
	1	60	1.6	100.0	53.8	100.0	253.8
	3	60	1.6	100.0	84.6	69.8	254.4
	3	75	1.6	95.7	94.9	72.6	263.1
	2.5	75	1.6	95.7	94.9	73.4	263.9
model 120250	2	45	1.6	92.9	59.2	61.6	213.6
	2.5	75	2	59.5	87.8	70.9	218.2
	2.5	45	1.6	92.9	63.3	62.6	218.8
	2	75	2	57.1	83.7	79.0	219.8
	3	45	1.6	100.0	63.3	61.9	225.2
	3	75	2	61.9	93.9	69.5	225.3
	1.5	60	1.6	85.7	69.4	87.9	243.0
	1.5	75	2	54.8	100.0	91.4	246.1
	2.5	60	1.6	95.2	77.6	80.1	252.9
	2	60	1.6	90.5	77.6	85.4	253.5
	3	60	1.6	100.0	85.7	75.1	260.8
	2	75	1.6	85.7	85.7	89.5	260.9
	3	75	1.6	90.5	89.8	81.7	261.9
	2.5	75	1.6	90.5	89.8	82.9	263.2
	1.5	75	1.6	88.1	77.6	100.0	265.6
model 150250	1.5	75	2	55.8	68.6	95.2	219.6
	2.5	60	2	58.1	68.6	95.1	221.9
	3	60	2	55.8	76.5	94.4	226.7
	2.5	45	1.6	79.1	60.8	90.8	230.6
	1.5	75	1.6	79.1	60.8	93.3	233.1
	3	45	1.6	88.4	60.8	91.7	240.9
	2	60	1.6	90.7	60.8	100.0	251.5
	2	75	1.6	90.7	64.7	100.0	255.4
	2.5	60	1.6	90.7	64.7	100.0	255.4
	2	75	2	65.1	96.1	100.0	261.2
	3	75	2	62.8	100.0	99.6	262.4
	2.5	75	2	65.1	100.0	99.9	265.0
	3	60	1.6	100.0	68.6	100.0	268.6
	3	75	1.6	90.7	80.4	100.0	271.1
	2.5	75	1.6	93.0	80.4	100.0	273.4

Rejected | Top 5% | 5-10% | 10-15%

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