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Simulation of finding the optimized gravel radius of the arrester bed on truck escape ramp

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Abstract. Propose a simulation method of finding the optimized gravel radius of the arrester bed on truck escape ramp in order to obtain the shortest stopping distance of runaway vehicle. A simulation model between gravel and tire is generated and calibrated by PFC2D (Particle Flow Code in two-dimensions) respectively. Utilize the model to simulate the relationship between radius and stopping distance at varied slopes and initial vehicle speeds. Simulation shows that whatever the slopes and the speeds are, the shortest stopping distance corresponds to gravel radius range is between 8.3mm and 15.7mm, that average radius is 12mm. The average radius is basically consistent with the ideal gravel radius 12.7mm, which indicates that the method is effective and could be a substitute for the full-scale test.

Keywords. truck escape ramp; stopping distance; gravel; simulation

1.Introduction

At present, aggregate of the arrester bed on escape ramp is composed of gravel, sand and broken stone etc. The round gravel becomes an ideal aggregate due to its small particle radius and single gradation [1]. According to the results of the full-scale test on truck escape ramp in USA, the most ideal gravel size recommended by American Association of State Highway and Transportation Officials (AASHTO) is 12.7mm, the minimum is 0.63cm, and the maximum is 3.81cm[2]. These full-scale tests provide a reliable basis for the arrester bed design, while also paying huge economic costs [3]. Due to the huge cost and limited by the experimental site, vehicle, personnel, weather and the safety, there is not much domestic full-scale test in China [4]. Because the test conditions are relatively ideal and aggregate will be maintained in time after test, the loose, flat and clean aggregate ensures the good braking effect of the arrester bed. However, as the usage frequency increases, the rolling resistance of the arrester bed become smaller, the braking effect decrease, the longer stopping distance is required, which means the possibility of rushing out of the arrester bed increases. If the aggregate lacks maintenance timely, it is prone to stagnation, which can easily cause wheels uneven subsided, body roll and deviation of vehicle gravity centre, which all may cause roll over[5].

In summary, the existing researches have limits on the braking effect of gravel radius under varied conditions. In practical applications, it is hoped that stopping distance could be calculated and determined by the aggregate state, so as to guide maintenance, maintain good braking effect and avoid accident caused by the shorter stopping distance. Therefore, this paper dedicates to establish a numerical simulation method for the relationship between gravel radius and stopping distance, which could provide a guide for length design of the arrester bed.



2. Methodology

2.1 Simulation model

The runaway vehicle is assumed to be rigid and brakeless. Its weight is assumed to be equally distributed on each tire. The tires are assumed to be rigid free-rolling wheels. The gravels are assumed to be rigid, spherical, homogeneous, and uniform. The tire and the aggregate are abstracted into a big particle unit and particle combination unit consisting of large amount of aggregates, respectively. The tire-particle unit is generated by PFC2D, which properties were represented by particle radius, particle density, particle normal stiffness, particle tangential stiffness [6-7]. The aggregate-particle unit is generated by PFC2D, which properties were represented by particle radius, particle density, particle normal stiffness, particle tangential stiffness and friction coefficient between particles [6-7]. Steps are the following[8]:

Step 1: Establish the wall. Generate a polygon with certain length and wide according to the actual arrester bed scale.

Step 2: Randomly generate a certain radius of particles. Let the particles fill the whole wall, and then compaction particles to achieve stability. Here is the stability condition: the ratio of the average contact force and the average unbalanced force is less than 1%.

Step 3: Initialize settings. It is mainly the setting of gravity acceleration and friction coefficient.

Step 4: Load experiments. Remove the wall and represent the tire with a big particle unit. Impose a downward force on the big particle, which is equivalent to the actual load of the tire.

Step 5: Run the program. Give the tire a running speed until it stops. The running speed is equal to entry speed of runaway trucks. Calculate the distance from the running to the stopping, which is called stopping distance.

2.2 Calibration of model

There are two steps for calibration.

Step1: Referencing to the static tri-axial test results, three groups of numerical simulation were carried out by PFC2D embedded fish language program^[9-10]. (a) The relative density of 25%, confining pressure of 69,138kpa; (b) The relative density of 50%, confining pressure of 69,207kpa; (c) The relative density of 75%, confining pressure of 138,207kpa. The results are shown in table 1.

Step2: The parameters of the tire-particle unit and the gravel -particle unit are determined (see table 2 to table 3). Referencing to the data from the reference [4,11], which are results of the full-scale test. The aggregate filled arrester bed on G139 highway section is river gravel with 4.75mm-53mm radius.

2.3 Validation of model

2.3.1. *Data*. The stopping distance is chosen as an indicator of the validation. The validation of model is to compare to full-scale test and see whether simulation accuracy of model is acceptable. Only the verified model can be applied to simulation. The results of predicting and full-scale test are shown in table 4. Test numbers 1 to 4 represent the data from G139 highway section^[4].

2.3.2. *Analysis*. In table 4 the average error between predicting and full-scale test is equal to or below 10.0%, which shows that the predicting accuracy is good. When the vehicle weight is the same, the larger the speed and the longer the stopping distance. The minimum difference between predicting and full-scale test is 0.3m for all the 11 data. Though four predicted stopping distances are longer than the full-scale measured, which means that the application of simulation model tends to be a little risky. The reason is probably the state of aggregates-filled on arrester bed is too ideal for simulation. Usually the ideal aggregates should be spherical, rigid, homogeneous, and uniform.

Table 1. Calibration of model compared to static tri-axial test

Relative Density/%	Confining Pressure/kpa	Peak press/kpa		Peak strain		Volume strain	
		Test	Simulation	Test	Simulation	Test	Simulation
25	69	284	220	0.073	0.03	+0.0032	-0.025
	138	459	410	0.077	0.05	-0.0046	-0.004
50	69	332	310	0.037	0.03	-0.0012	-0.02
	207	558	630	0.066	0.07	+0.002	-0.05
75	138	518	550	0.033	0.06	-0.0037	-0.045
	207	692	760	0.057	0.08	+0	——

Table 2. The parameters of tire-particle unit on G139 site

radius (m)	normal stiffness (N/m)	shear stiffness (N/m)	friction parameters
0.6	2.5e5	2.5e5	0.25

Table 3. The parameters of gravel- particle on G139 site

radius (mm)	density (kg/m ³)	number	Normal stiffness (N/m)	Shear stiffness (N/m)	friction parameters
4.75-53	2630	42000	4.8e6	2.4e7	30

Table 4. Stopping distance compared to full-scale test

Num.	vehicle weight (t)	Entry speed (km/h)	Stopping distance (m)		
			Measured	Predicting	Relative error (%)
1	12.4	40	18.0	16.2	10.0%
2	12.4	50	13.6	12.8	6.0%
3	22.46	45	18.8	17.4	7.0%
4	22.46	48	25.8	27.3	6.0%
5	13.02	27.4	19.4	20.6	6.0%
6	13.02	40.2	32.3	31.9	2.0%
7	13.02	41.8	31.5	33.5	6.0%
8	40	24	9	9.6	6.0%
9	40	28.8	12.2	11.9	2.0%
10	40	28.8	12.4	11.9	4.0%
11	56.5	120	126	135	4.0%

3.Simulation

The length and width of the gravel arrester bed are 80 meters and 0.6 meter respectively. The gravel radius range is divided into four groups with an 7.4mm interval: (a) 8.3mm-15.7mm; (b) 15.8mm-23.2mm; (c) 23.3mm-30.7mm;(d) 30.8mm-38.2mm.

The simulation results of the stopping distance on the gravel arrester bed at various parameters are shown in table 5. For a given grade and entry speed, the stopping distance with radius 8.3mm-15.7mm is less than the other three radius groups. And the influence of the gravel radius on stopping distance shows some certain regularity. For a given grade, the stopping distance increases with the increasing

speed and radius. For a given speed, the stopping distance decreases with the increasing grade and decreasing radius. The mechanism is that the smaller the gravel radius, the deeper the tire falling into the aggregate. The contact surface of tire and gravel becomes larger with larger subsidence, so the friction is bigger and the resistance of the vehicle is increased. That's the reason why the stopping distance becomes smaller. So it is found that when the radius scope is between 8.3mm and 15.7mm or average radius is 12mm, the stopping performance is the best. This average radius is very close to the AASHTO recommended ideal 12.7mm. The results of simulation are in good agreement with the experimental results.

Table 5. Results of the stopping distance at varied parameters

Grade	radius (mm)	Entry speed (km/h)		
		72	90	108
		Stopping distance (m)	Stopping distance (m)	Stopping distance (m)
5%	8.3-15.7	61.43	83.89	94.68
	15.8-23.2	63.27	85.08	95.21
	23.3-30.7	63.42	85.44	95.40
	30.8-38.2	66.18	87.97	96.60
10%	8.3-15.7	45.98	71.43	83.27
	15.8-23.2	47.25	73.17	83.74
	23.3-30.7	47.32	74.16	86.15
	30.8-38.2	47.74	77.16	86.58
15%	8.3-15.7	36.07	48.98	71.80
	15.8-23.2	37.12	50.82	72.94
	23.3-30.7	38.11	52.96	74.74
	30.8-38.2	39.47	53.87	76.82

4. Conclusion

Analyse the relationship between the gravel radius and the stopping distance and the following conclusions are drawn.

- Aggregate filled on the arrester bed is an important factor affecting the stopping distance of runaway vehicle on the escape ramp. The smaller gravel radius is, the easier tires are to fall into the aggregate. So the greater the amount of subsidence, the greater the resistance, and the shorter the stopping distance required for the same driving vehicle speed.
- The simulation data shows that the stopping distance is the shortest when the gravel radius is between 8.3mm and 15.7mm. Adjusting the gravel radius is an effective measure to adjust the stopping distance when the terrain is limited.
- Through numerical simulation of varied gravel radius at different loads, speed and slope, stopping distance can be obtained, which can provide a guide for length design of the arrester bed.

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