A PFC2D model of the interactions between the tire and the aggregate filled arrester bed on escape ramp

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Abstract. The stopping distance of a runaway vehicle is determined by the entry speed, the design of aggregate-filled arrester bed and the longitudinal grade of escape ramp. Although numerous previous studies have been carried out on the influence of speed and grade on stopping distance, taking into account aggregate properties is rare. Firstly, this paper analyzes the interactions between the tire and the aggregate. The tire and the aggregate are abstracted into a big particle unit and a particle combination unit consisting of lots of aggregates, respectively. Secondly this paper proposes an assumption that this interaction is a kind of particle flow. Later, this paper uses some particle properties to describe the tire-particle unit and aggregate-particle unit respectively, then puts forward several simplified steps of modeling by particle flow code in 2 dimensions (PFC2D). Therefore, a PFC2D micro-simulation model of the interactions between the tire and the aggregate is proposed. The parameters of particle properties are then calibrated by three groups of numerical tests. The calibrated model is verified by eight full-scale arrester bed testing data to demonstrate its feasibility and accuracy. This model provides escape ramp designers a feasible simulation method not only for predicting the stopping distance but also considering the aggregate properties.

1. Introduction

Decades of traffic engineering practice all over the world shows that the escape ramp is the most effective engineering measure to improve highway safety on continuous downhill section [1]. Since the first escape ramp was constructed in California during the 1950s, the United States, Australia, South Africa and Japan have carried out extensive research in order to guide escape ramp design [2]. Unfortunately, China’s research lags behind. The first escape ramp and related infrastructure were set up on the Beijing Badaling highway section in only 1998 [3]. Until now perfect design standard and specification of the escape ramp are not yet developed in China.

The length of arrester bed is the key part of escape ramp design, which is determined by the stopping distance [4]. Factors effecting stopping distance are the entry speed of runaway trucks, the aggregate filled arrester bed and the longitudinal grade of escape ramp [5]. Although Al-Qadi (1991) developed an arrester bed stopping model using gravel properties, the complexity of the model application in engineering practice becomes its weakness. Full-scale arrester bed testing is the most effective method to predict the stopping distance, but huge cost and safety limits its application. The traditional kinematic method has limitations such as the description of the interactions between the tire and the aggregate, but discrete element methods such as particle flow code in 2 dimensions (PFC2D ) does not have such limitations. The PFC2D software can simulate the motion and interaction of circular granular media by the discrete element method. So the PFC2D has become an effective method to simulate solid mechanics and particles problems and often used as an alternative to very costly experiments [6].
2. The PFC2D micro-simulation model

2.1. The assumption of model
There are seven forces resisting the motion of the tire on the arrester bed [7]: (a) direct momentum transfer from the tire to the aggregate particles; (b) the rolling resistance; (c) air drag; (d) grade resistance; (e) compaction resistance; (f) bulldozing resistance; (g) side-shearing resistance. The arrester bed usually is filled with loose aggregates (such as gravel, broken stone, etc), rolling resistance generates by sinking into the aggregates. The more the tire sinkage, the more the rolling resistance and the less the stopping distance. Meanwhile, the tire has a compaction effect on the aggregate particles, consuming part of the kinetic energy of the tire. Because of compaction resistance, an aggregate height is created before and after the tire. The tire needs to consume a certain amount of kinetic energy to push aside the aggregates in front, so there are bulldozing resistance and side-shearing resistance. Because of the gravity, the tire on a certain grade produces grade resistance.

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 aggregates 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. This research proposes an assumption that the tire-aggregate interaction is a kind of particle flow.

2.2. The steps of modeling
Based on previous assumption, the steps of modeling using PFC2D are proposed. The steps are the following:
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.

The tire-particle unit properties were represented by particle radius, particle density, particle normal stiffness, particle tangential stiffness. The aggregate-particle unit properties were represented by particle radius, particle density, particle normal stiffness, particle tangential stiffness and friction coefficient between particles.

3. The calibration of model
There are two steps. Step1: The numerical simulation of calibration. Referencing to the static triaxial test results [8, 9], three groups of numerical simulation were carried out by PFC2D embedded fish language program. (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 aggregate-particle unit are determined (see Table 2 to Table 5). Referencing to the data from the literature [10, 11], which are results of the full-scale arrester bed testing. The aggregate filled arrester bed on G139 highway section is river gravel with 4.75mm-53mm radius. The aggregate filled arrester bed on Zhanglong highway section is broken stone with 20mm-50mm radius.

4. The validation of model

4.1. Data
The stopping distance is chosen as an indicator of the validation. The validation of model is to
compare indicator values to full-scale arrester bed testing data and to see whether simulation accuracy of model is acceptable. Only the verified model can be applied to various simulations. The results of predicting and full-scale measured stopping distance are shown in Table 6. Test numbers 1 to 4 represent the data from G139 highway section [10]. Test numbers 5 to 8 represent the data from Zhanglong highway section [11].

4.2. Results and analysis

In Table 6 the average error between predicting and full-scale measured stopping distance is 13.16% for gravel aggregate and 7.14% for broken stone aggregate respectively, which shows that the latter’s predicting accuracy is better than the former. When the aggregate is gravel or broken stone and the vehicle weight is the same, the larger the entry speed, the longer the stopping distance, and the average error is decreased. The minimum difference between predicting and full-scale measured stopping distance is 0.4m among the 8 data. All the predicted stopping distances are less than the full-scale measured, which shows that the application of simulation model tends to be risky. This is probably because the state of aggregates-filled on arrester bed is ideal for simulation. Usually the ideal aggregates should be spherical, rigid, homogeneous, and uniform [8, 9].

### Table 1. Calibration simulation results compared to static triaxial test results.

| 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/m³) | number | Normal stiffness (N/m) | Shear stiffness (N/m) | friction parameters |
|-------------|-----------------|--------|-----------------------|----------------------|---------------------|
| 4.75-53     | 2630            | 42000  | 4.8e6                 | 2.4e7                | 30                  |

### Table 4. The parameters of tire-particle unit on Zhanglong site.

| radius (m) | normal stiffness (N/m) | shear stiffness (N/m) | friction parameters |
|------------|------------------------|-----------------------|---------------------|
| 0.5        | 2.5e5                  | 2.5e5                 | 0.10                |

### Table 5. The parameters of gravel-particle on Zhanglong site.

| radius (mm) | density (kg/m³) | number | Normal stiffness (N/m) | Shear stiffness (N/m) | friction parameters |
|-------------|-----------------|--------|-----------------------|----------------------|---------------------|
| 20-50       | 2600            | 71500  | 1e8                   | 1e8                  | 22                  |
Table 6. Predicting the stopping distance compared to full-scale measured values.

| Num. | Aggregate type | Vehicle weight (t) | Entry speed (km/h) | Stopping distance (m) | Measured | Predicting | D-value | Relative error(%) |
|------|----------------|-------------------|-------------------|----------------------|----------|------------|---------|-------------------|
| 1    | gravel         | 12.4              | 32                | 11.7                 | 10.3     | 1.4        | 11.97%  |
| 2    | gravel         | 12.4              | 40                | 18.0                 | 16.21    | 1.8        | 9.94%   |
| 3    | gravel         | 22.46             | 33                | 14.6                 | 11.2     | 3.4        | 23.29%  |
| 4    | gravel         | 22.46             | 45                | 18.8                 | 17.4     | 1.4        | 7.45%   |
| average |                |                    |                   |                      |          |            | 2       | 13.16%            |
| 5    | broken stone   | 18                | 44                | 29.3                 | 24.13    | 5.2        | 17.65%  |
| 6    | broken stone   | 18                | 51                | 35.4                 | 32.17    | 3.2        | 9.12%   |
| 7    | broken stone   | 18                | 61                | 45.3                 | 44.8     | 0.5        | 1.10%   |
| 8    | broken stone   | 18                | 70                | 59.0                 | 58.59    | 0.4        | 0.69%   |
| average |                |                    |                   |                      |          |            | 2.3     | 7.14%             |

5. Conclusions
This study aims to propose a simulation model of the interactions between the tire and the aggregate and provides a feasible method to escape ramp designers for predicting the length of arrester bed through the stopping distance. A micro-simulation model of the interactions between the tire and the aggregate were done using PFC2D software. The calibration of model was done using numerical simulation data. The verification of model was done using full-scale arrester bed testing data. The study shows the accuracy of predicting stopping distance is acceptable, which is important in two respects. First, it confirmed that the assumption of the interactions between the tire and the aggregate is a kind of particle flow is right through PFC2D software. Second, it provided confidence that some dangerous and infeasible full-scale experiments would probably be feasible through PFC2D software at a low economic cost.

6. Acknowledgements
The authors gratefully acknowledge the support of the Guangxi Natural Science Found, Project 2015GXNSFAA139280, in supporting portions of this study.

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