

Modeling and Reproducibility Verification of Vehicle Rollover Behavior Induced by Entry into Gravel

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In the United States, occupants ejected through side windows during a rollover have a markedly higher fatality rate than those who remain inside. To mitigate such ejections, FMVSS No. 226 "Ejection Mitigation" has been phased in since September 2013, and the combination of seat belts and rollover-activated curtain air bags is estimated to reduce the probability of ejection by 99 percent.

Meanwhile, vehicle configurations continue to diversify with the rapid growth of EVs, and comprehensive verification of all vehicle types and test conditions by full-scale testing is becoming increasingly difficult in terms of both development lead time and cost. For these reasons, evaluation by computer aided engineering (CAE) is regarded as a practical alternative to full-scale testing.

In conventional rollover simulations, however, it is difficult to prescribe soil properties such as friction and hardness directly. Simplified modeling based on the sinkage depth of the tire, or a continuum representation of dry sand using the arbitrary Lagrangian–Eulerian (ALE) method, has therefore been reported. In contrast, few studies have addressed gravel, in which the particle size is large and the effects of interlocking and particle shape are dominant. The objective of this study is to model gravel using the discrete element method (DEM), to identify the inter-particle friction coefficients, and thereby to propose a desk-based prediction method that is generally applicable to vehicles with a wide range of weights and center-of-gravity heights.

Modeling approach

Since it is impractical to measure all the physical properties of gravel, such as particle shape, size, density and friction coefficients, and to reflect them directly in a model, DEM was adopted, which solves the equation of motion of each particle to obtain the bulk behavior. Two sequential approaches were then applied. In the first approach, the interaction between gravel particles is reproduced. Because gravel is represented by spherical particles in DEM, the effect of the complex particle shape is expressed indirectly by the resistance to rolling, that is, the rolling friction. In a bench test, a 300 mm cubic box was filled with gravel and one face was removed to let it collapse, and the angle of repose was measured (Fig. 1). The same configuration was reproduced in CAE, and the static and rolling friction coefficients were calibrated to 0.3 and 0.18 so that the calculated angle agreed with the measurement, with a particle radius of 5 to 15 mm and a density of $2.67 \times 10^{-3} \text{ g/mm}^3$.

In the second approach, the calibrated gravel model was applied to vehicle rollover simulations. Three vehicle models with different vehicle weights and center-of-gravity heights were selected so as to cover the distribution range of existing vehicles, and the lateral acceleration (GY), roll rate (RR) and roll angle (RA) obtained by CAE were compared with those measured in full-scale vehicle tests.

Results and conclusions

The simulated waveforms agreed well with the full-scale test results for all three channels. In particular, the roll angle showed close agreement over the whole time range, and the initial peak of the lateral acceleration caused by contact with the gravel was also reproduced (Fig. 2). The rollover behavior is governed by the way the gravel collapses and accumulates in front of the vehicle, that is, by the interaction between the gravel particles, which the calibrated model reproduces with high fidelity.

The reproducibility was also evaluated quantitatively using the normalized root mean square error (NRMSE), which expresses the agreement of the amplitude, and the correlation coefficient, which expresses the agreement of the waveform shape and timing. The evaluation interval was 0 to 400 ms, in which the rollover occurs. For the three channels of the three vehicles, the NRMSE ranged from 2.4 to 14.7 percent and the correlation coefficient was 0.9 or higher, with a maximum of 0.99 (Fig. 3). These results show that the proposed gravel model reproduces the rollover behavior accurately for vehicles with different weights and center-of-gravity heights, and confirm the general applicability of the proposed method.

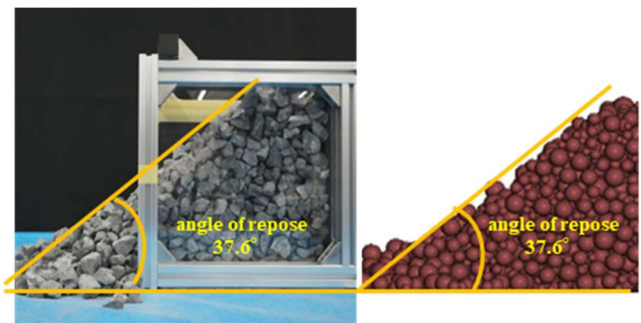


Fig. 1 Angle of repose : test (left) and simulation (right)

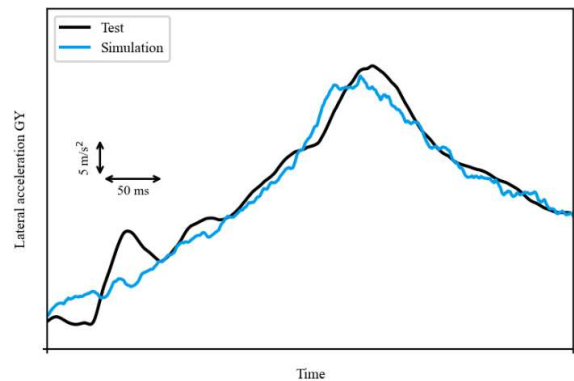


Fig. 2 Lateral acceleration GY of Vehicle A (test vs. simulation)

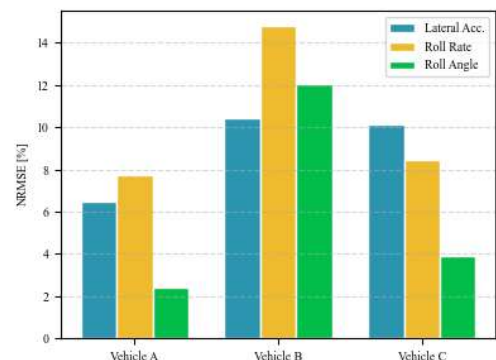


Fig. 3 NRMSE between test and simulation for each vehicle