

# Parameter Identification of Sled Test Method to Simulate Vehicle Soil Trip Rollover Dynamic Accurately by Numerical Simulation Considering Soil-Vehicle Interaction

Tatsuya Fukushima, Masafumi Shitamichi, Toshikazu Torigaki and Hidetoshi Sokusai  
Nissan Motor Company, Ltd.

Masato Nishi and Takahiko Miyachi  
JSOL Corporation

## ABSTRACT

FMVSS 226 will become effective on September 1, 2013 with the purpose of mitigating occupant ejections through the vehicle side windows. In order to use deployable counter measures to mitigate ejection, vehicle rollover tests are needed to design deployment algorithms for rollover conditions. Vehicle manufacturers have to define their own test procedures, because FMVSS 226 does not define any rollover test methods.

The soil trip rollover test is a vehicle rollover test method in which a vehicle is propelled into a soil pool to measure its rollover characteristics. Some of difficulties in soil trip rollover tests include proper maintenance of soil, for example, under fluctuating humidity and homogeneity of soil in the pool, so as to ensure stable repeatability of test results. Protection of onboard measurement equipment in a test vehicle from soil incursion when the vehicle rolls over can also be a challenge. Therefore, sled test methods without a soil pool that can simulate a soil trip rollover test with a soil pool are helpful in ensuring repeatability of results and maintenance of onboard equipment.

Sled test methods that do not use a soil pool are needed to simulate the interaction between a vehicle and the soil that is greatly deformed by the vehicle. Sled test methods should simulate the interaction force and the loading position from the onset to the completion of vehicle rollover. This is important because dynamic rollover tests are necessary for deployable device to determine the firing time of deployment. However, it is generally not easy to measure soil deformation behavior and interaction force with the vehicle at every instant.

In contrast, numerical simulation can be an effective way to obtain time history data of soil deformation behavior and interaction force. Eulerian description was used in this study for modeling a soil pool with extremely large deformation in order to secure computational stability and accuracy. A vehicle for this simulation was modeled by Finite Element Analysis (FEA) to simulate tire deformation so as to obtain a highly accurate solution for the interaction between the tires and soil. The simulated vehicle-soil trip rollover dynamics agreed well with test results. This model can simulate soil deformation behavior and the contact pressure distribution between the tires and soil at each moment of the soil trip rollover event.

Various sled test methods based on a curb trip rollover test procedure to simulate a soil trip rollover test using a soil pool were also simulated by numerical simulation and evaluated in comparison with the simulation results for soil trip rollover using a soil pool. Sled lateral deceleration, curb movement for depth and tilting, and curb material used in the sled test methods were evaluated using time histories of the vehicle roll angle and roll rate and pressure distribution on the tires. Time histories of the roll angle and roll rate are used to design deployment algorithms. The pressure distribution on the tires indicates the tripping force and its loading position.

**CITATION:** Fukushima, T., Shitamichi, M., Torigaki, T., Sokusai, H. et al., "Parameter Identification of Sled Test Method to Simulate Vehicle Soil Trip Rollover Dynamic Accurately by Numerical Simulation Considering Soil-Vehicle Interaction," *SAE Int. J. Trans. Safety* 1(2):2013, doi:10.4271/2013-01-0459.

## INTRODUCTION

Federal Motor Vehicle Safety Standard (FMVSS) 226-Ejection Mitigation, which takes effect on September 1, 2013, mandates the installation of a system for mitigating occupant ejection through a side window in a rollover accident[1]. Inflatable curtains are one type of occupant restraint system that could be deployed in a vehicle rollover to prevent occupant ejection through a side window. To accomplish that, it is necessary to judge whether the vehicle is about to roll over or not based on measurements of vehicle behavior. If a rollover is deemed imminent, the rollover curtains can then be deployed. In order to determine the conditions for judging the likelihood of a rollover, it is necessary to conduct rollover tests to measure the characteristics of vehicle rollover behavior. Because FMVSS 226 does not specify any rollover test procedure, vehicle manufacturers and occupant restraint system suppliers are obliged to establish a vehicle rollover test method by themselves.

The U.S. National Highway Traffic Safety Administration (NHTSA) has classified different types of vehicle rollover behavior as shown in Figure 1, based on the various rollover patterns displayed by vehicles in rollover accidents in the U.S. These different types of vehicle rollover behavior must be reproduced experimentally in tests in order to determine the conditions for activating the occupant restraint systems in a manner corresponding to each of these rollover patterns. One type of rollover test is a soil trip rollover test as shown in Figure 2, which corresponds to the trip-over type of rollover behavior. With this trip-over test procedure, a lateral force is applied to the tires/wheels of the test vehicle to induce a roll moment in the vehicle that causes it to turn over. One method for applying a lateral force to the tires is to trip over a solid block that simulates the curb. Another method is to cause the leading wheels to trip over soft soil such as dirt or sand. The former method is referred to as a curb trip rollover test and the latter method as a soil trip rollover test.

This paper focuses on the soil trip rollover test method. In order to define the conditions for activating the occupant restraint systems in a soil trip rollover test, vehicle behavior must be measured in both rollover and non-rollover situations.

Vehicle rollover in a soil trip rollover test occurs in the following manner. As the vehicle slides sideways, the tires/wheels dig into the soft soil, the leading wheels form a bank-like wall of soil in contact with the side surfaces of the tires/wheels. The wall of soil exerts resistance against the vehicle's side-slip motion and generates a lateral force in the opposite direction of the side-slip of the tires/wheels. That lateral force induces a roll moment in the vehicle causing it to roll over. If the soil resistance acting on the tires/wheels of the vehicle slipping sideways is sufficiently small, a roll moment large enough to overturn the vehicle is not generated. If the side-slip velocity is sufficiently small, the vehicle's side-slip motion stops before a rollover occurs.

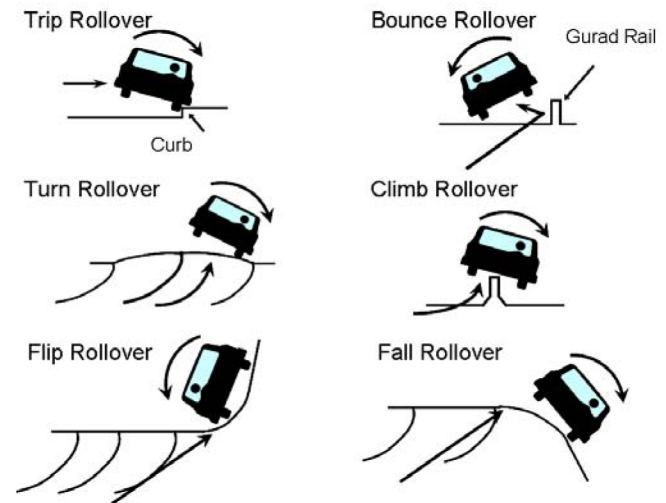


Figure 1. NHTSA's classification of types of rollover accidents

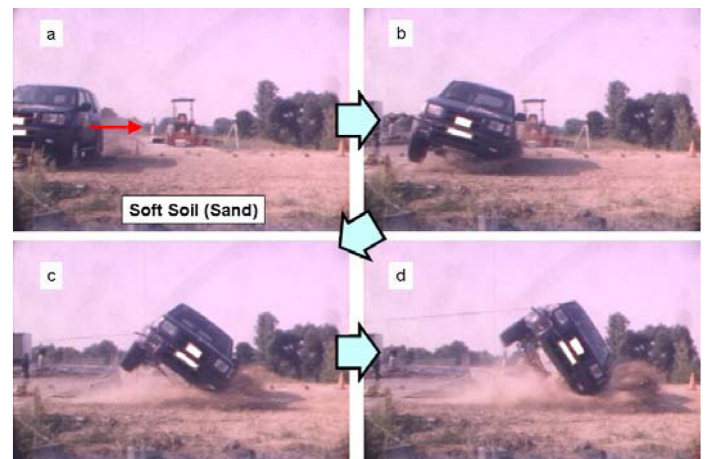


Figure 2. An example of a soil trip rollover test

As noted above, FMVSS 226 does not prescribe any rollover test procedure for use in detecting vehicle rollover behavior in which inflatable curtains or some other type of restraint system should be deployed as a means of mitigating occupant ejection from a vehicle. Accordingly, manufacturers themselves have to define the test conditions for determining the parameters for activating the occupant restraint systems in soil trip rollover or other kinds of rollover tests. In a soil trip rollover test, one method of causing a vehicle rollover is to propel a test vehicle laterally into a pool filled with sand, soil, gravel or the like. O'Brien-Mitchell et al. reported that the characteristics of the soil used must be carefully controlled to ensure reproducibility of the measured vehicle rollover behavior[2]. They noted that soil control required considerable time and effort and that the incursion of soil into the vehicle when it rolled over might cause the measurement instruments installed in the interior to malfunction. For those reasons, they decided not to use a pool filled with sand, soil,

gravel or the like in conducting soil trip rollover tests. Instead, they used the deceleration history of the sled employed in curb trip rollover tests to simulate the deceleration history of the test vehicle in a soil trip rollover test. They also placed sandbags between the tires/wheels and the solid curbs in an effort to simulate vehicle rollover behavior in a soil trip rollover event. Similarly, Zagorski et al.[3] and E. Castro et al.[4] also used a sled rather than a pool filled with soil in an effort to reproduce vehicle rollover behavior in a soil trip rollover event. They placed hinge joints, capable of rotating in the direction of vehicle roll, near the bottom of the tires/wheels on the rollover side of the vehicle and decelerated the sled in the vehicle's lateral direction.

In order to use a sled instead of a pool filled with soil to simulate vehicle behavior in a soil trip rollover test, it is necessary to make clear what sort of roll moment acts on the vehicle when the tires/wheels trip over the dug out soil and the associated mechanism must also be simulated. However, in the process in which the tires/wheels dig into the soil and markedly deform it, it is not easy to measure the distribution of the force that the soil applies to the tires/wheels. It is desirable to have a method of determining the deformed soil shape and the force distribution applied to the tires/wheels by means of a numerical simulation of the interaction between the deforming soil and the tires/wheels. Palmer et al. reported a numerical simulation method for a replicating a soil trip rollover event[5]. They attempted to simulate vehicle rollover behavior by conducting a FEA of soil deformation caused by the interaction between the tires/wheels and the soil. In addition, Linstromberg et al. described a method for simulating vehicle rollover behavior by taking into account the interaction between the tires/wheels and the soil in a mechanism analysis in which the particle method was used to express the soil[6]. While all of these studies succeeded in describing vehicle rollover behavior, they did not go so far as to quantify the level of interaction between the tires/wheels and the soil at which a vehicle rolls over, such as by analyzing the force distribution between them, nor did they present an analysis of the mechanisms involved in a soil trip rollover event.

In this study, therefore, we conducted numerical simulations of a soil trip rollover test by applying continuum dynamics with Eulerian description used to express soil deformation. An attempt was made to analyze the conditions causing a vehicle to roll over by investigating large soil deformation and the force distribution on the tires/wheels and at the interface with the soil. In addition, this numerical simulation method and a numerical simulation model of a sled were used to investigate methods of simulating a soil trip rollover test in which a sled is used instead of a soil pool.

## NUMERICAL SIMULATION METHOD

In order to accurately investigate vehicle behavior in a soil trip rollover test, whether with a test method that employs actual soil or with a substitute sled test method, the numerical simulation must sought to reproduce vehicle behavior as accurately as possible. Numerical simulation methods can be divided into two types. One type seeks to identify vehicle behavior, and the other type seeks to identify how the reaction force of the soil dug out by contact with the tires/wheels of the vehicle sliding sideways actually acts on the vehicle. In order to substitute a sled in place of actual soil in a soil trip rollover test, it is necessary to have a method for determining the mechanisms and behavior of the sled. Therefore, it was decided to conduct an integrated numerical simulation using the LS-DYNA FEA software[7]. This general-purpose FEA program is capable of treating vehicle behavior, contact between the soil and the vehicle and the resultant soil deformation, and the action of the sled all as a dynamic deformation problem in a numerical simulation.

The numerical simulation method applied respectively to treat the test vehicle, soil and sled is described in the following discussion. It will be noted that the LS-DYNA program was used in the numerical simulation of a soil trip rollover test and in the numerical simulations of a curb trip rollover test in which a sled test procedure was substituted. This numerical simulation software is well suited to treating such dynamic large deformation problems involving all the related structures and continua.

### 1. Numerical Simulation of Vehicle Behavior

The vehicle behavior treated in this study occurs under extreme conditions, not in ordinary driving, and is accompanied by changes in the characteristics of the tires that undergo large deformation, large motions by the suspension system and large changes in vehicle behavior. We have previously used the finite element method to conduct numerical simulations of vehicle behavior that occurs under such extreme conditions, including investigations of riding up on the curb[8], cornering at the limit of performance, braking[9], vehicle collision analysis in emergency avoidance maneuvers[10], and a ditch fall-over test procedure[11]. Based on that experience, it was decided to conduct a structural analysis of vehicle behavior in a soil trip rollover test using the finite element method.

Because a numerical simulation of a soil trip rollover test treats phenomena that occur in approximately 0.5 sec, it was necessary to reduce the degrees of freedom of the vehicle model to the minimum necessary number in order to perform the calculations in a reasonable amount of time. Therefore, post-rollover vehicle deformation that was not measured experimentally was not modeled, nor were aspects that are needed to perform a numerical simulation of occupant

behavior. The vehicle's parts supported by the suspension systems were combined into a single rigid body model to which experimentally measured data were input for mass, center of gravity and inertial tensor value. The deformation of the suspension system links was modeled in the numerical simulation, considering that the forces input from the soil or the sled to the suspension via the tires/wheels might be extremely large compared with ordinary driving and that the effect of suspension link deformation on vehicle behavior is not clearly known. The operation of the suspension system was also simulated by modeling the joints, bushings, suspension springs and shock absorbers that are related to the motions of the link mechanisms and their characteristics. That was done because the suspension system mechanisms might operate at the time the lateral force acting on the vehicle from the actual soil or the sled through the tires/wheels becomes a roll moment that acts on the vehicle. The springs, shock absorbers, bushings and other parts were modeled using one-dimensional discrete elements incorporating the respective properties of these parts for the purpose of reducing the degrees of freedom of the vehicle model and lengthening the time integration interval.

In a soil trip rollover test, it is assumed that the tires are deformed by a force input from the soil. The actual tire shape and inner structure were faithfully represented in the FE model. In this study, the test vehicle was propelled laterally without actually running, so the stiffness of the tires in the vehicle's vertical direction and that in the lateral direction of the tires were adjusted in the tire model to match the stiffness of actual tires. Owing to the foregoing modeling method, the tire model accounted for many of the degrees of freedom of the vehicle model used in the numerical simulation of the soil trip rollover test. That resulted from the faithful modeling of the shape and structure of the tires that induce the roll moment in the vehicle owing to their contact with the soil.

The vehicle model used in this study is shown in Figure 3. In this model, the panel parts forming the outer shape of the vehicle body, floor, wheel housings, side windows, headlamps and radiator grill openings are expressed, but all of them together represent one part of the rigid body supported by the suspension system and they do not undergo deformation. It was observed that when the soil model, which will be described later, was used in a numerical simulation of a soil trip rollover event with actual soil, some of the soil entered the vehicle, unlike what happens in an actual physical test. Therefore, the parts mentioned here were expressed in the vehicle model so as to avoid that incursion and prevent any influence on vehicle rollover behavior. The total mass, the position of center of gravity of the vehicle model, and inertial moment are fitted to actual vehicle. The total mass of this vehicle model is 2,146kg including mass of two occupants and measurement equipments. All cases of soil trip rollover analysis including various conditions of simulator with sled equipments have conducted under 13.9m/sec (50km/h) as initial velocity for lateral direction of the vehicle model.

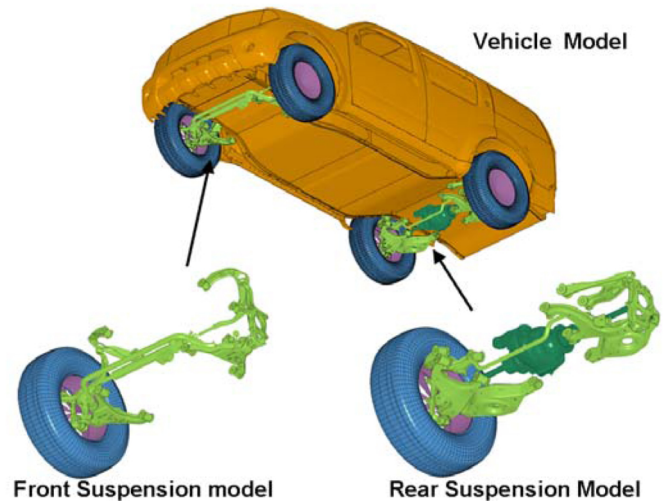


**Figure 3. Vehicle model used in the numerical simulations**

Figure 4 shows the FE tire model that was used in the numerical simulation to represent the tire deformation caused by contact with the soil or the curbs. The stiffness values applied to this tire model agreed well with the measured values in both the vertical and lateral directions of the tires as shown in Figure 4.

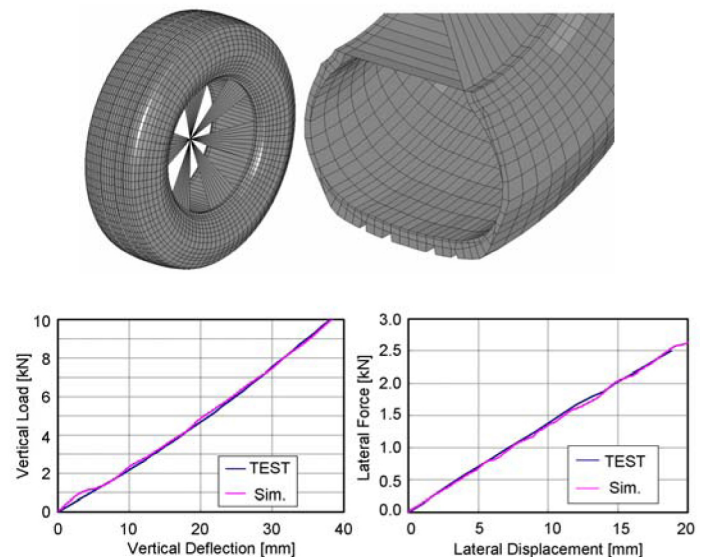


**Figure 4. FE tire model and comparison of experimental and calculated tire stiffness**

The validity of the vehicle model was verified by conducting a numerical simulation of a curb trip rollover test. A curb trip rollover test is performed by decelerating a rigid sled that is moved laterally to simulate the side-slip of a vehicle. The test vehicle is overturned when the side surfaces of its tires/wheels come in contact with rigid curbs provided on the sled. Because the sled's shape and its deceleration time

history are clearly known, this approach is suitable for verifying the validity of the vehicle model.

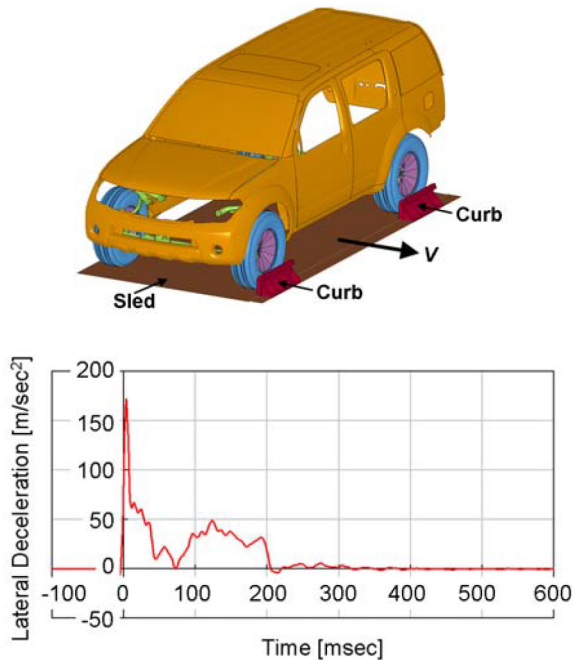


**Figure 5. Sled used in the numerical simulations and measured time history of the sled's lateral deceleration**

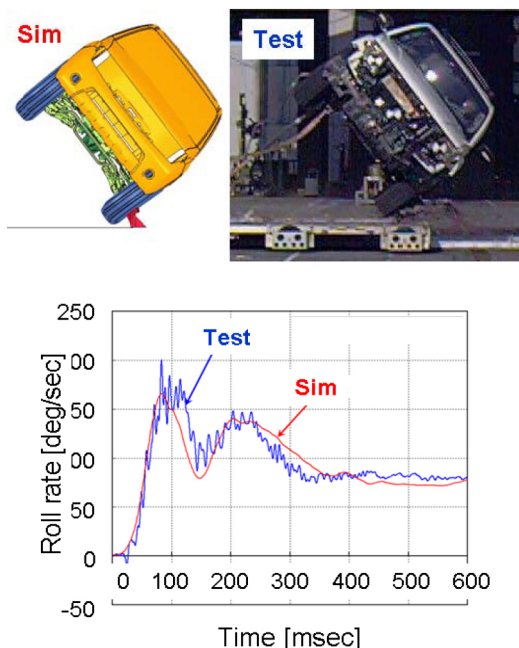


**Figure 6. Comparison of simulated and experimental vehicle rollover behavior and vehicle roll rates in a curb trip rollover test**

Figure 5 shows the simulation model of the sled used in the numerical simulation of the curb trip rollover test. Figure 5 also shows an experimentally measured time history of the

lateral vehicle deceleration that was actually applied to the sled model when conducting the numerical simulation of the curb trip rollover test to validate the vehicle model. Figure 6 shows the rollover behavior of the vehicle that was numerically simulated when the lateral deceleration of the sled in Figure 5 was input to the model. The vehicle roll rate was measured on the vehicle body in both the numerical simulation and the test. It is seen in Figure 6 that the roll rate obtained in the numerical simulation agreed well with the corresponding test result. Therefore, it was decided to use this vehicle model in the numerical simulation of a soil trip rollover test using actual soil and in the investigation of a sled test method for use in simulating a soil trip rollover test.

## 2. Numerical Simulation of Deformation of Soil

In a numerical simulation for analyzing the interaction between the tires/wheels and the soil, it is necessary to simulate numerically the transfer of force between the tires/wheels and the soil under a condition of large soil deformation like what occurs in a soil trip rollover test. In order to numerically simulate the force distribution between the tires/wheels and the soil with good accuracy, it was decided to conduct a numerical simulation by means of continuum dynamics with Eulerian description used for modeling as is done in fluid dynamics simulations. This method was thought to be more effective than other approaches such as a FEA using Lagrange description as is often done in solid dynamics simulations, or use of the particle method that facilitates relatively stable numerical simulations of objects undergoing large deformation[12]. This method has been used in numerical simulations of the driving force of agricultural tires in soft soil, as reported by Oida et al. [13] and Varghese et al. [14]. In both of these studies, the distribution of driving force generated on the tire surface under large soil deformation was found by using the soil-tire interaction. Therefore, we attempted to apply continuum dynamics using Eulerian description for soil deformation in the numerical simulation of the soil trip rollover test.

Figure 7 shows the calculation mesh based on Eulerian description for expressing the soil. Eulerian description was also used to express the void above the soil surface as pore space in order to represent the condition of the soil scattering. The soil and the void above it were represented using an orthogonal rectangular mesh. The mesh size of the soil and the void was 20 mm in all directions, which was the same as the mesh size of the tire tread surface. If calculation mesh based on Eulerian description is used to represent all the soil that is dug out and scattered as the vehicle slips sideways, the mesh number would increase enormously, making it difficult to perform the calculations in a realistic amount of time. To avoid that problem, the mesh for calculating the soil deformation was limited to the area around the tires/wheels as shown in Figure 7. The mesh was moved together with the

vehicle, making it possible to express all the soil that was dug out and scattered by the vehicle sliding sideways. For that purpose, an inflow boundary condition was defined at the front edge of the moving area representing the soil and an outflow boundary condition was defined at the rear edge of the area. The apparent force observed on the Eulerian mesh was applied as an external force according to the deceleration of the side-slip of the vehicle.

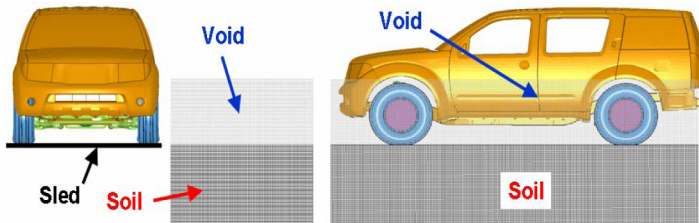
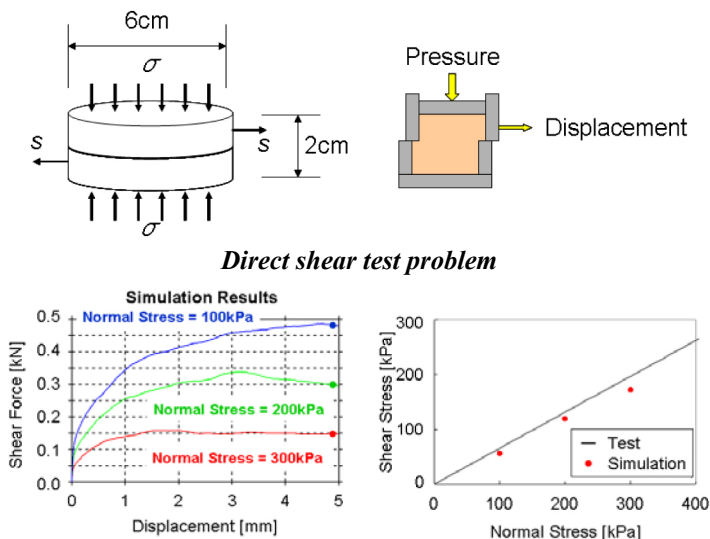


**Figure 7. Soil calculation mesh expressed in Eulerian description**

A numerical simulation was conducted of a soil trip rollover test in which dried sand was used as the soil. MAT\_SOIL\_AND\_FOAM (MAT 005) in LS-DYNA was used for the material model of the sandy soil. The parameters of the material model were defined as a direct shear test problem as shown in the upper diagram in Figure 8. The graphs on the lower of Figure 8 show that the results obtained with the soil simulation model agreed with experimental data reported in the literature[15], [16].



**Direct shear test problem**

**Numerical simulation results for the dried sandy soil used in this study**

**Figure 8. Direct shear test problem used in defining the material property parameters of the sandy soil**

### 3. Numerical Simulation of Vehicle Soil Trip Rollover

The vehicle model shown in Figure 3 was then combined with the soil model that was created as explained here using Eulerian description. A numerical simulation of a soil trip rollover test was conducted under the conditions given in Table 1 and with gravity applied to the vehicle and the soil as the load. The vehicle was propelled into the sandy soil at a lateral vehicle velocity of 13.9 m/sec (50 km/h). The numerical simulation results presented in Figure 9 indicate that contact between the tires/wheels and the sandy soil digs out the soil and causes some of it to scatter, and the vehicle then trips over the soil and rolls over. A comparison with the photographs of the test scene in Figure 3 indicates that the scattering of some of the sandy soil and the rollover behavior of the vehicle are consistent.

**Table 1. Conditions defined for numerical simulation of the soil trip rollover test**

|                                  |                       |
|----------------------------------|-----------------------|
| Initial lateral vehicle velocity | 13.9 m/sec (=50 km/h) |
| Soil                             | Dry sandy soil        |
| Depth of the Soil                | 1.5 m                 |

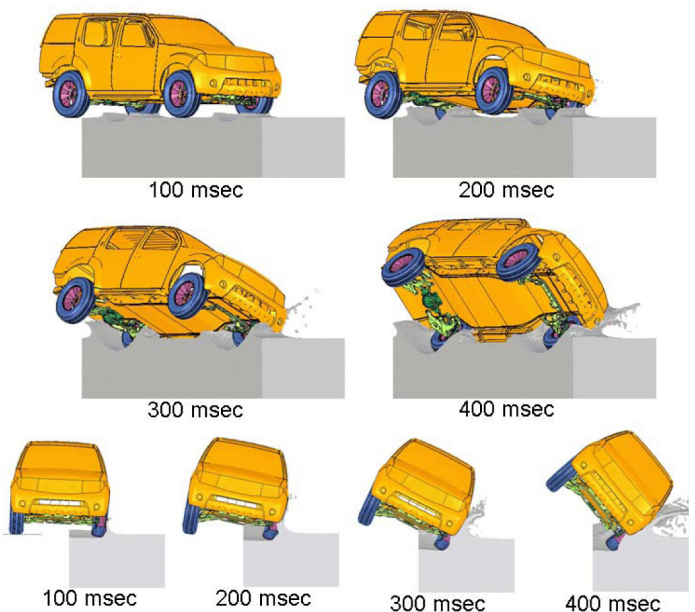


**Figure 9. Vehicle overturn behavior and sandy soil deformation obtained in the numerical simulation of the soil trip rollover test**

Figure 10 compares the lateral vehicle deceleration and the roll rate obtained in the numerical simulation with corresponding experimental data. The positions where the lateral deceleration and the roll rate were found were defined on the vehicle body in the vicinity of the vehicle's center of