

Experimental study on scour at unpaved road shoulder

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Abstract. Scour is often found along the shoulder of the road, especially the shoulder without pavement in suburban and rural areas. This can reduce the function of the road shoulder and increase the risk of traffic accidents. The mechanism and form of scour have not been widely discussed and need to be studied to improve road safety aspects. This study aims to investigate scour occurrence along the unpaved road shoulders. An experiment was conducted in the laboratory by creating a physical model to simulate the scouring process at unpaved road shoulder. The laboratory test used varying rainfall intensities, slopes, and sediment diameters. Results show that the scour depths are influenced significantly by those three factors. Scour depths resulting in 25% longitudinal slope is around twice deeper than these in 0% longitudinal slope. The scour depth in border between the paved road lane and the unpaved road shoulder is deeper than other part of the shoulder. It shows that the location is a susceptible-part to scouring.

1 Introduction

The growing prosperity brings the impact of increasing the number of vehicles. This causes long travel distance, long travel time and increased density. The consequence that arises is the increased chance of accidents. It was reported that the number of mortality from road traffic accidents is 1.25 million per year [1]. This number is relatively constant for 3 consecutive years from 2013. In fact, in the next 3 years, a similar report shows that the problem is getting worse. Deaths from road traffic crashes have increased to 1.35 million a year. That's nearly 3700 people dying on the world's roads every day [2]. Another impact is permanent disability that reaches 20-50 million people per year. In addition, material and non-material (socio-economic) losses are estimated to be close to 1 to 3% of total gross domestic product.

The cause of road accidents has 3 factors, namely human factors, road environment, and vehicles. Road factors can be detailed into various items. It was stated that things that can be classified into road factors are the design of roads, road conditions, lighting, air conditions, speed limits, and facilities for pedestrians [3]. Road design can have a considerable impact on safety. Ideally, roads should be designed with the safety of all road users in mind. This means ensuring that there are adequate facilities for pedestrians, cyclists and motorcyclists. More attention needs to be taken to suburban and rural roads. Improved urban road construction has also increased vulnerability to accidents in the area. For example, by the end of 2012, China's rural roads are 3,678,000 km with an accident of 40.76% of all road accidents [4]. One important part of the road, especially rural road, is the road shoulder, which is located on the right and left side of the road lane.

Shoulders are an important element of the highway system, providing space for emergency stops, a recovery zone for errant vehicles, structural support for the pavement, drainage, improved sight distance, a passage for bicyclists, and increased roadway width to accommodate agricultural vehicles [5]. The road shoulder is more required on the rural road while its existence is not necessarily existence on the urban road. For unpaved or granular shoulders, the most serious types of deterioration include rutting and edge drop-off. They most often occur within the first two ft. from the pavement edge due to settlement of the shoulder, degradation of the granular material, wind or water erosion, and/or vehicle off-tracking. The initial construction costs for granular shoulders can be about 70% of the construction costs for paved shoulders. However, maintenance costs for granular shoulders are much higher than those of paved shoulders [5].

Deterioration of road shoulder by water erosion can be triggered by rainfall that falls on the surface of the road lane and road shoulder. Although shoulder erosions have been occurring frequently and widely, this problem is still limited discussed. [6] identified that erosion is one of factors causing drainage failure. A simulated rain-field experiment on unpaved roads to determine the effect of erosion components due to splashing and flow to sediment transport was conducted by [7]. Where 38-45% of total sediment output was caused by rain splash. Data from natural runoff plots at three locations on the loess plateau in China were used by [8] to assess the effect of slope gradient on soil loss for slopes ranging from 9 to 55% steepness. [8] explained the relationship of initial sediment motion and channel slope using a simple force-balance model, including drag from channel walls and bed morphology, change to the local

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flow velocity and turbulent fluctuations. [9] assessed the effects of unpaved roads on runoff and erosion at different spatial scales, and provided the process-based understanding necessary for planning, improved road design and mitigation. [10] conducted a field investigation of scour on the shoulder of the road. Investigations were carried out on several main rural roads in Indonesia. A sample photo of their investigation can be seen in Figure 1.



Fig. 1. Scouring occurs in a shoulder of rural road in Indonesia. A sign of "6" is a site number of a survey

This study intends to investigate the process of scour in road shoulder, observe the formed configuration and find the scour depths under influence of some rainfall and road condition. A physical model was made to mimic the scour process at a road shoulder caused by the rainfall spills on a surface of paved road lane. This rainfall would turn into a surface runoff that had the ability to carry material in the transition between the lane and the shoulder of the road. Material that moved from the place will cause scouring. An experiment was made in the laboratory to model a cross section of the road. Artificial rain was made with a rainfall simulator. The scour depth was measured after one simulation has ended.

2 Method

The method used in this study is an experiment by making a physical model in the laboratory. Two scenarios were tested, namely the model without longitudinal slope and the model with longitudinal slope. Equipments and running procedures were same for the two model. The sketch of the model can be seen in Figs. 2 and 3. Experiments are one of the most popular methods to explain the physical mechanisms and interactions of scour events. [11] reviewed papers in order to update research on scour. The majority of the papers examined the subject from the empirical or experimental approach (64%), the others are founded on the numerical and field approaches, and a review paper. It should be noted this study reviews a special part of a structure that has not been discussed much. Most of the research topics concern scour around bridge piers, mono piles, propellers, turbines, weirs, grade-control structures, and pipelines. [11] also noted that of the 14

papers reviewed, 36% of them discuss scour around piers.

2.1 Model without longitudinal slope ($S_l = 0$)

This model represents a flat road. As the road does not have a slope. However the slope of the transverse direction remains as can be seen in a typical cross section of a road. In some road design standards, the slope of this transverse direction is about 2 s.d. 4%. The slope of the road shoulder is generally made sharper i.e. 4 s.d. 6%.

The set up model can be seen in Figure 2. An asphalt-lined field was created to mimic the road lane. This field was placed on a steel frame. The slope of the plane could be set which in this test was used varied slope i.e. 2%, 3%, 4%, 5%, 6% and 10%. A 10% slope to accommodate the maximum super elevation on the road curve. In the lower sections of the field were connected with a box containing sand as an imitation of the road shoulder. The shoulder surface was adjusted to a 4% tilt constant even though the inclination of the lane plane varies. A rainfall simulator installation was made by assembling a perforated pipe with a water supply from a tank with constant head. The faucet, pressure gauge, and flowmeter completed the installation (not shown in Figure 2).

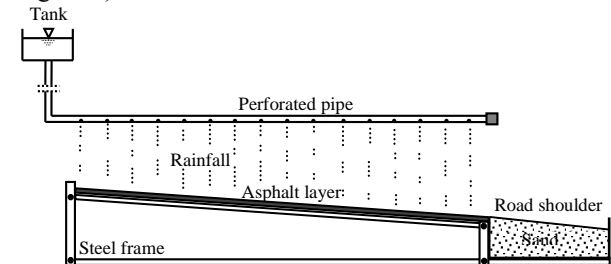


Fig. 2. Experimental setup

Running model was done by activating rainfall simulator. Artificial rain that fell on the surface of the asphalt turned into a surface runoff that flows towards the shoulder of the road. This stream has energy that can move sediment grains to create scours on the model of road shoulder. For models with longitudinal slope = 0, rain intensity was made varying i.e. 5, 10, 12, 15, 20, and 25 mm/hr. While the diameters of granulated sands were 0.26 and 0.38 mm.

2.2 Model with longitudinal slope ($S_l \neq 0$)

This model represents an uphill and downhill path. The longitudinal slope is the slope of the road that can be seen in a vertical alignment of the road. In contrast to the transverse slope associated with the drainage function, the longitudinal slope is made to follow the topographical tendency of the field where the road is under construction. The longitudinal slope used in this model was 3, 8, 10 and 25%. The first three values were adopted from the road design standard for Indonesia where each plan was designed for speeds of 110, 60, and 40 km/h. While the last value was used to test a very steep road conditions, which although not according to

standards but may be found on roads in mountainous areas in Indonesia.

Tools and materials for models with longitudinal slopes $\neq 0$ equaled those used with longitudinal slopes = 0 (Fig. 3). Slight modifications were made in order to obtain an elongated slope. The rainfall used was also the same as the model shown in Figure 2 but not shown in Figure 3. The diameters of the sand grains were more various than they were used in the model without the longitudinal slope. The sand diameters (d_{50}) were 0.21, 0.24, 0.26, 0.27, 0.29, and 0.38 mm. All sediment material were taken from site where scouring at road shoulder occurred. In addition, all sediment gradation have nonuniform size so that for evaluating initial of motion using Shields diagram, sediment diameter d_{35} is applied. Furthermore, the rainfall intensity used 3 variations that was 10, 15, and 25 mm/hr.

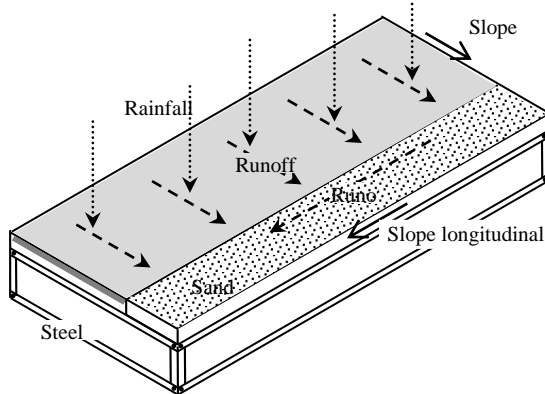


Fig. 3. Model with longitudinal slope

2.3 Relevant variables

Several variables influencing scour in unpaved shoulder have been identified as shown in Figure 4. They consist of flow variables and sediment characteristics. Flow variables are rainfall intensity (I), rainfall duration (t), superelevation or slope of road lane surface or transversal slope (S_t), surface runoff depth (y_0), runoff velocity (U), water density (ρ), water viscosity (ν), and gravitational acceleration (g). While, sediment characteristics are represented by sediment density (ρ_s) and median diameter (d_{50}). The variables are suspected influencing the scour depth at road shoulder (Y_s).

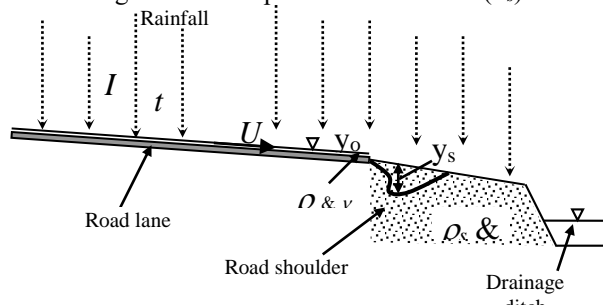


Fig. 4. Relevant variables on road shoulder scour

The maximum local scour depth can be expressed as a function of the independent variables,

$$Y_s = f(I, t, S_t, S_l, U, y_0, \rho, \mu, \rho_s, d_{50}, g) \quad (1)$$

Moreover, in this study ρ was constant for all experiments, so ρ has a negligible influence on scour

and can be neglected. By applying the Buckingham π theorem, dimensionless groups of variables was obtained:

$$f\left(\frac{Y_s}{d_{50}}, S_t, S_l, \frac{Y_s \cdot I \cdot t}{y_0 \cdot d_{50}}, Fr\right) = 0 \quad (2)$$

where $Fr = U/\sqrt{gy_0}$ is the Froude number of surface runoff.

3 Result and Discussion

3.1 Scouring Process

Scouring process on a road shoulder model can be observed in this experiment (Figure 5). The rainfall spilling on the surface of the road lane will convert to a surface runoff which is a very small depth flow. This runoff flows over the surface of the asphalt layer which is an imitation of the road lane surface. It will leave the road surface and move to the road shoulder. The road shoulder consists of loose material and will be wetted by the surface runoff. Scouring has not occurred at this stage because most of the surface flow seeps into the road shoulder layer. When the layer has saturated it will occur runoff flow on surface of the shoulder following the slope of the road shoulder. The flow coming from the asphalt surface remains in place resulting in a slight turbulence at the transition boundary between the asphalt surface and the unpaved shoulder surface. It stir the loose material and with the force impulse from the stream coming from the asphalt surface causes scouring begins to occur. The scour will increase in time, but will reach a stable condition when the surface runoff has found a flow path that is in the form of small trenches towards the lower elevation. The process of scouring on the shoulder of the road will not occur if there is no rain. Rain will change the water content of the soil on the shoulders. [13] concluded that although the road shoulder was constructed at very low initial moisture content, the moisture contents in the road shoulder quickly increased to a high level after the first rainfall but never dropped to the initial moisture content.

Figure 5 provides the result obtained from three experiment using 25 mm/hr rainfall spill to road lane surface model. The model had cross slope 2% constantly, but it was altered for its longitudinal slope. The longitudinal slope varies from flat to steep, i.e. 2%, 7%, 10%, and 25%. Scouring cannot be seen obviously in flat surface road, although some spot experienced scouring. When longitudinal slope increase to be 10%, scouring was formed narrower in upstream and wider in downstream. This formation occurred at 26% longitudinal slope as well in which scouring was deeper and a small gully was created. Sand grain migrated from higher to lower elevation transported by flowing water.

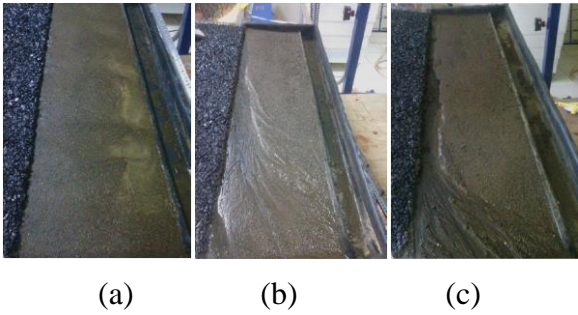


Fig. 5. Scour at shoulder road results in rainfall of 25 mm/hr, with longitudinal slope of 0%, 10%, and 25% shown by (a), (b), and (c) respectively

The assessment of initiation of motion is based on the Shield parameter. From 71 times running model, all have shear velocity and shear stress conditions above the critical limit of Shields diagram. Thus, the sediment is in a state of motion. The minimum value of all running quantities is found in the test variation where the road lane slope is 0.5%, the rain intensity is 10 mm/h, and the sediment diameter (d_{35}) is 0.17 mm. In this condition the surface runoff on the road lane has a shear velocity of 0.007 m/s. Based on the Shields diagram on the shear velocity value and the sediment diameter of 0.17, particles are in the motionless condition. But scours are still detected even the smallest among the other test results. This is because the road shoulder has a bigger slope than the road lane. Therefore, if the shear velocity is calculated based on the slope on the shoulder of the road (%) then the value is 0.019 m/s which results in the condition of the moving particles. For other tests the value is above this value so that the sediment particles are in a moving condition and allow sediment transport to occur.

3.2 Configuration of scoured road shoulder

The experimental observations show that when equilibrium conditions are reached the eroded shoulder shapes have stabilized and form a different configuration than when it has not been eroded. This configuration can be observed more clearly in dry conditions. This condition can be obtained by stopping the rainfall simulator which means also stop the surface runoff leading to the shoulder of the road. Figure 6 shows a three dimensional configuration of the running model with rain intensity of 15 mm/hr on a 10% longitudinal slope. The scour depths look irregular but there is a tendency that scours go deeper and wider on the downstream of the shoulder of the road in the longitudinal direction. This tendency occurs in almost all configurations of the running model.

When erosion continuing, a tiny gully began to be created. It was formed at road shoulder around border of two different structure i.e. paved road lane and unpaved road shoulder. It can be seen in Figure 5 (b) and (c) and Fig 6 as well. Gully is defined as the erosion process whereby runoff water accumulates and often recurs in narrow channels and, over short periods, removes the soil from this narrow area to considerable depths [8].

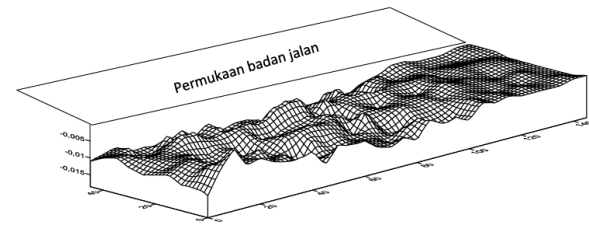


Fig. 6. Configuration of scoured road shoulder

The bed configuration of the channel can be formed due to the flow over it. This has been widely discussed in sedimentation techniques or river engineering. For example the experiment by [14] Kim et al. (2021) regarding the effect of stability evaluation on particle size characteristics of bed materials at high-velocity flow. While the configuration due to erosion by rain can also be formed as the results of experiments by [15] about soil slope erosion test by rainfall. The configuration of the shoulder surface due to scouring as shown in Figure 6 can affect road safety. Although there has been no direct research on the effect of shoulder roughness on safety, the effect of pavement surface conditions on road safety has been discussed for example by [16].

3.3 Scour depth

Scour depth is the main objective of this observation. In reality, deep scour at shoulder road may trigger road accidents. The slope of the paved road lane surface according to the highway engineering is generally 2-6% to ensure good drainage. However, in this experiment, a slope of less than 2% that is 0.5% and a slope of more than 6% - 10% is also tested to see a more extended trend of the relationship between the transversal slope of the road and the scour depth. There are several points of scour depth at one slope value. For an example on the slope of 0.5%, 2%, 6%, and 10%. This is due to the repetitive testing of the slope with the modified parameters (rain intensity, duration, and sediment diameter). From Figure 6 it can be seen that a steeper slope will tend to increase the scour depth.

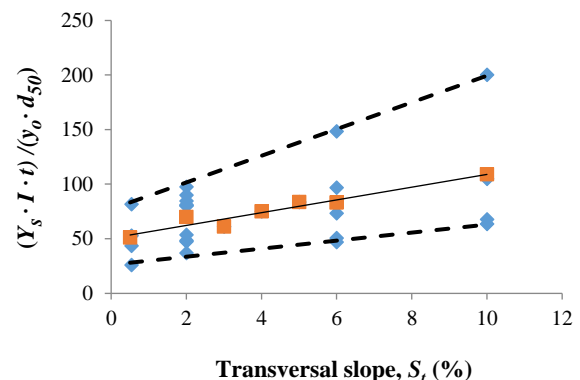


Fig. 7. Increasing transversal slope resulting increasing scour depth

The effect of the longitudinal slope on the maximum scour depth can be seen clearly in Figure 8. The graph is obtained from the test for a condition consisting of a 2% transverse slope, a median diameter of 0.26 mm and a rainfall of 25 mm/h. Longitudinal slopes vary a

minimum of 0% and a maximum of 25%. The scour depth increases with increasing longitudinal slope. The presence of scours indicates the presence of sediment transport. This means that the critical shear stress as the initial limit of sediment grain motion has been exceeded even exceeded. So this result is not contradictory to the standard model which predicts reduced stability with increasing slope due to the addition of the gravitational force downward. Moreover, this result also does not conflict with observations by [17] Lamb et al. (2008) which indicates that the critical stress of the Shield for the beginning of sediment motion increases with the channel slope, which indicates that particles of the same size are stable in the sharper slope.

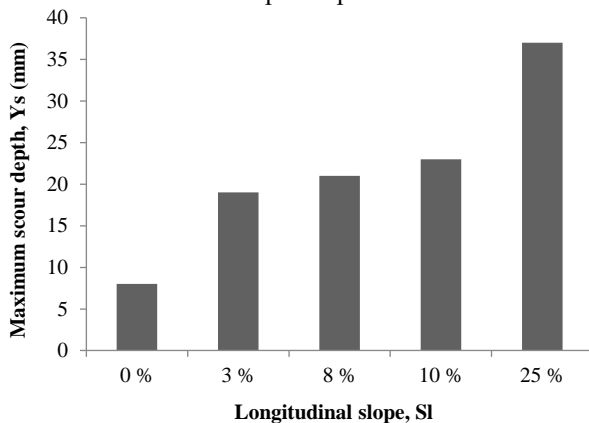


Fig. 8. Influence of longitudinal road slope to scour depth

The more general relationship between the longitudinal slope and the scour depth is shown by Figure 9. The dimensionless parameter of scour depth is represented by Y_s/d_{50} which is a function of the longitudinal slope S_i .

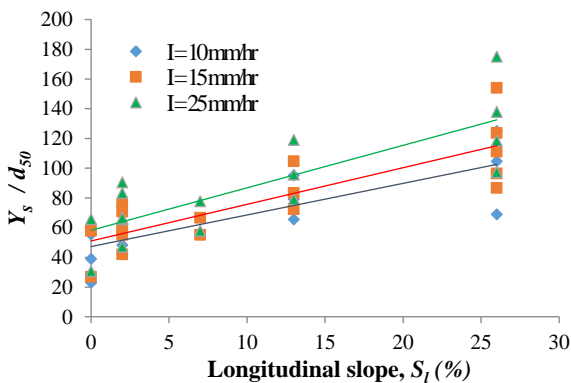


Fig. 9. Longitudinal slope increasing scour depth

With a constant transversal slope of 2% and rain intensity varies from 10 mm, 15 mm and 25 mm, there is a tendency of increased scour depth to longitudinal slope. In addition, from the graph can also be detected that the increased rain intensity will result in a deeper scour. Repetition of the test at the same slope value yields several points of scour depth with significantly different ranges. In the longitudinal slope equal to 0 there is a scour. This is caused even though the longitudinal slope is the same 0 but the 2% transversal slope is proved to be capable of producing a scroll like the previous graph of Figure 7.

Fig 10 is the relationship between two dimensionless parameters, they are Froude number and scour depth. Higher Froude number will tend to result in a deeper scour. In this experiment, many data collected have a Froude number between 0.22 to 0.27. This is a narrow range of Froude number. At these values, the scour depth has a wide enough range that is between 50 to 225. So, a narrow range of Froude value can produce varying scour depths. Several data have Froude number more than 1 so that it means supercritical flow. Nevertheless, the higher froude number is not included in graph because of a few number of data and jumping value of the Froude number.

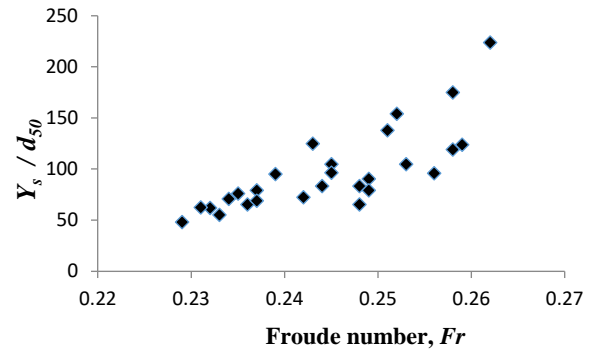


Fig. 10. Froude number influence toward scour depth

In this experiment, amount of sediment transported from road shoulder was measured, but it has not been discussed in this paper yet. It may be future work to analyze and discuss it. Experiments to test scour on the shoulder of the road with cohesive sediment material need to be done because in fact many road shoulders are made of cohesive soil.

This physical model covered only for rainfall spilled on road lane surface and did not cover rainfall spilling on the unpaved road shoulder. Rainfall spilling on the shoulder may generate splash and has significant impact to scour depth. Finally, a protective structure for unpaved shoulders needs to be considered. The weakest part of the road shoulder is the transition between the paved road lane and the unpaved road shoulder. As studied by [18] and [19] Islam et al. (2019), the width of shoulders influences the crash risks. The protective structure should be prioritized in this section.

4 Conclusion

A laboratory study has been carried out to investigate scour at an unpaved road shoulder caused by rainfall. Rainfall converts to surface runoff flowing from road lane to shoulder. When the shoulder achieves saturation condition, surface runoff on the shoulder begins to flow to lower level of surface. It is able to transport sediment grains and forms a certain configuration when equilibrium state is achieved. The configuration consists of a tiny gully and an uneven surface. The gully mainly forms at the border between an asphalt pavement and an unpaved road shoulder. It denotes that scour occurs more intensively at the border. In other word the border is susceptible part towards scouring.

In a flat road model with a longitudinal slope equal to zero, the scour depth is affected by the transverse

slope. The graph of the relationship between the transversal slope and the dimensionless number of scour depth indicates a tendency that the scour will deepen with increasing transverse slope. Similarly, for uphill road models with longitudinal slopes not equal to zero, there is a hint that the steeper the longitudinal slope the deeper the scour occurs. Scour depths resulting in 25% longitudinal slope is around twice deeper than these in 0% longitudinal slope. Moreover, the intensity of rain also affects the scour depth where the higher the intensity of rain the deeper the scour is generated. Most types of streams in this experiment are subcritical with a range of Froude numbers between 0.22 to 0.27. Subcritical flow capable of transporting sediment grains to form scour. The scour is increasing as Froude become higher. Various tests in this study shows that the scour depth is influenced by several variables: rainfall intensity, rainfall duration, transversal slope, longitudinal slope, and sediment diameter. Future work mainly involves experiments for storm water fall not only on the road but also on the shoulder surface, the use of cohesive sediment materials, and the more volatile design of the shoulder.

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