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Duning in Rills on Unpaved Roads in Uganda

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ABSTRACT

Dunes on non-paved roads develop as a result of general construction designs especially in the drainage. They are active features which block up drainage rills and parts of the roads causing road rutting, deep mudding and flooding. Shear stress, erosion, and deposition due to the discharge were the main factors in the equation formation and analysis. An equation is constructed to determine their formation and effects on gravel road dunes. It is finally tested with a numerical example using cross-sectional field and laboratory results data. Various experiments like sieve analysis, measuring road dune sizes with respect to slope size, rain intensity, and road widths were used in the formulation and evaluation of the equation for this study. Key findings of this paper include among others dune formation rates in road rills and possible timely control. The model equation constructed is expected to help in various road design and maintenance practices.

Keywords: Equation; Dune; Road; Runoff.

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1. INTRODUCTION

Erosion from features formed on roads has become a new research area in the recent years because of the inadequate maintenance and construction schemes in developing countries [1]. Generally, erosion and deposition modeling has originally been on agricultural plots with regard to yields. Dunes are formed when deposition occurs or when the transport capacity of sediment is exceeded. They are also formed out of cohesive sediments that include clay, mud, and fine silt. They stick together due to flocculation or the action of electrostatical forces. Flocs are transported convention, turbulent diffusion, and gravitational settling [2]. These variations in flow conditions may cause sediment deposition and erosion. Conditions for depositional duning were considered in this study.

Although environmental issues have been considered as one of the stages in road constructions no attention has been put on the rates of formation of dunes especially on non-paved roads yet they affect road safety significantly.

Construction of the dune equation was therefore the main objective of the study. The equation developed was both material and mathematical, with unsteady-state conditions. The focus of this paper is on the unsteady states because dunning in rills has sediment conditions which are not constant. Existing models do not specifically look at the gravel road as one of the most dune-able surfaces with unique characteristics [3].

A gravel road is type of an unpaved road surfaced with gravel that consists of varying amount of crushed or uncrushed stone, sand and fines [4]. It also refers to all unpaved road ways in particular regions [5] or even rural or dirt roads. Such roads constitute a big percentage of the total road network for most developing countries [1]. Most rural roads in developing countries are unpaved yet more than 80% of the population in Africa still live in rural areas [6]. These are mostly built from locally-available natural materials. These granular materials are often obtained from nearby quarries along the road [1]. This study therefore aimed at basically modeling deposition on such roads with respect to formation of dunes in road ditches or drainage channels along roads and the possible effects on the road surface, size and structure.

2. MATERIALS AND METHODS

2.1 Introduction

In this section, various parameters regarding erosion and deposition on roads are listed. They are then modeled using various facts. The mathematical equation is constructed and was comparable to some renowned sediment models [7]. Finally, a numerical example is done using the field data regarding the dune on the gravel road. The equation is expected to take in to account the rate of development of simple dunes that form with flows in rills [1]. It should also take in to account the rate of deterioration of constructed drainage channels and consequent flooding. The model equation developed has mathematics, physics, hydrology, and geo-engineering as the main subjects. Its main applications are expected to be decision making in road construction, maintenance, and further research.

2.2 Model parameters

The following parameters were used in the construction of the model:

a) Nature or make of the structure(k_e, C_i, S_c)

b) Sediment water discharge in rills (q, v)

c) Time and stress factors (t, τ)

The study used the quantitative methods, which mainly involved experimental and observational designs. Some of these experiments were carried out in the field and others in the research laboratories. The lateritic soil sample used in this research work was collected, by method of bulk disturbed sampling, from four borrow pits at a depth of up to 2.0m in four different regions of the country-Northern, Western, Eastern and Central. The tests conducted for this research were conducted in Makerere University soil mechanics laboratory in accordance with procedures outlined in references [8] and [9] for natural as well as stabilize soils respectively. Specifically the experiments involved: Hydrometer analysis, Compaction Test, Sieve analysis among others. Other experiments done along the roads included Identification and measuring erosion dune sizes, gradation tests, runoff speed, and road size versus dune sizes. The runoff speed was done with respect to the rainfall intensity and road slope for the given regions [1].

Cross sectional measurements of the drainage channels already affect ted by the 'first' erosion and deposition were taken on the blocks. These measurements were used on the discharge calculation within the rill. The relative discharge was finally used to estimate dune formation and deformation through rilling. Five measurements were taken for each 100m block (20m apart). The time interval was taken per rain day. An average time of one and a half an hour was taken for this study including sediment flow time. The slopes measured for all experiment spots ranged between 2^0 and 42^0 or 3.5% and 90%.

The dunes considered in this paper are those that develop in one of the four main ways in [1]: Dunes that develop along rill depending on the discharge flow, and stress factors. It was observed also that when grass grows along the drainage, it becomes a major roughness factor and eventually creates dunes. This partially or completely blocks the runoff process resulting into depositions and eventual flooding.

3. FINDINGS`

3.1 The Equation Formulation

The model constructed is comparable to other erosion /deposition equations like those of Maria Exner [10], [11], and other erosion models [12], and [13]. The most comparable parameters are the erodibility (k_e), discharge (q) parameters, and shear stress (τ) dynamics. The parameters were constructed to the following dune equation:

$$\frac{\partial S_d}{\partial t} = \frac{\partial v}{\tau_c \partial t} - k_e C_i \tau S_d \qquad (1)$$

$$\tau = \tau_o - \tau_c, \qquad \tau_c < \rho_i.$$

Where C_i= Compaction index based on average dry density, S_d = Specific rill area affected by deposition (m^2/kg), gorge, dune, t = time effect, v= flow velocity in the discharge rate, k_e= erodibility parameter, τ_c = critical shear stress, ρ_i is some value depending on the size class i of the sediment particles. Looking at the critical shear stress, there is a particular size class i of sediment /borrow pit particles which are not moved at some instances to cause deposition, hence dunning.

S_c depends on various factors like volume of water, frequency of runoff, erodibility factor, runoff speed, and shear strength. The assumption here is that the dune is constructed with in the flow of the rill. The flow rate or discharge rate velocity was modeled from Manning's equation in this study [1]. It relies solely on channel characteristics where a rill dune falls characteristically. It is given by the formula:

$$v = \frac{R^{\frac{2}{3}} S^{\frac{1}{2}}}{n} \qquad (2)$$

v is the discharge velocity (m/s), R is the hydraulic radius (m), S is the slope of the water surface., and n is the roughness coefficient. This coefficient depicts values between 0.01 to o.1. See table 1 for n values that were used:

Table 1. Manning's n for Natural Stream Channels (Highway Task Force, 1971) [14]

	n
Some weeds, heavy brush on banks	0.060 - 0.080
Irregular sections, with pools, slight channel meander; increase values given above by	0.010 - 0.020

The hydraulic radius is given by $R = \frac{A}{Wp}$, (3)

Where Wp is the wetted perimeter, and A is the cross-sectional area calculated from some trapezoidal shape. Shear stress is a force applied by flowing liquid to its boundary. Channel bed turbulence and rill bed roughness complicate the measurement of this force. It is calculated based on the conservation of momentum. The critical shear stress τ_c occurs when the shear force τ_o exceeds the critical limit for soil detachment [15]. The following formula was used in this study with varying flow depth, D (m), and flow slope, S (%). The hydraulic radius R was used for D in the model evaluation.

$$\tau_o = \gamma RS \qquad (4)$$

Where γ (kN/m^3) is the unit weight of water or the specific gravity of water, D(m) is the depth of the flow (sometimes taken as a hydraulic radius), and S (m/m) is the energy gradient. It should be noted that the maximum depth of the flow shall be used for the critical stress. The deposition potential can also be predicted by the shear stress because it considers the actual force of the water on the boundary of the rill. Rills wherein dunes are formed, have temporally flows that normally depend on the rainfall and sediment flow period. Reduced or zero velocity within rill flows causes deposition after the raining-flow process to cause dunes. From the experiments carried out, most our sediment soils were found to be incoherent (sands or gravels)[1]

When the resistance of a particle to movement is more than the shear stress acting on it, the particle will be stationary. For the erosion flow channels (rills), the critical condition is at the start because mud will appear in the flow right away. This means that dunes form as soon as the flow stops. The particle size was analyzed from the sieve analysis in relation to the maximum critical shear stress required for dunning. Accurate estimations of the critical shear stress requires accurate characterizations of various parameters like turbulence [16].

In this paper, we used one of the equations listed by Fischenich [17] to calculate the critical shear stress for sands and silts.

$$\tau_c = \frac{g d_p (\rho_s - \rho_w) \tan\theta}{4 d_*^{\frac{3}{5}}} \quad (5)$$

$$d_* = d_p [\frac{(G-1)g}{v^2}]^{\frac{1}{3}}$$

Where θ is the particle's angle of repose taken as 32^o or non-cohesive sediments [2] and [18] for which rill dunes fall. G is the specific gravity of sediment, which is the ratio between the sediment density, $\rho_s$and the water density, ρ_w. v is the kinematic velocity, $d_p$is the particle size of interest, and g is the gravitational acceleration. It should be noted that the τ_c was evaluated for minimum and maximum values regarding sand and silt in the Rijn specification in table 2 below.

Table 2: Particle Diameter Classifications [19].

SOIL TYPE	PARTICLE DIAMETER(mm)
Gravel	Greater than 2
Sand	0.063 to 2
Silt	0.004 to 0.063
Clay	Less than 0.004

3.2 The Equation Evaluation

The model equation was evaluated by mathematical methods to the following S_d:

$$S_d = \frac{v}{\tau_c (1 - k_e c_i \tau t)} \quad (6)$$

Two values of the $\tau_c$that were used are $\tau_c = 0.04$ and $\tau_c = 47.99$ for particle diameters $0.004mm$ and $2mm$ respectively. The erodibility parameter (k_e) was evaluated for the minimum value in the interval 0.002 to 0.05 $m^{-1}s$ [20] necessary for dunning. Laboratory results for sediments showed an average dry density value of $1654kg/m^3$. The main varying factor for this study is time. This depended on a given experiment day or rain day. An average time of 5400s or 1.5 hours was used in this evaluation including the rainfall and flow time. This is also because deposition also takes place during this process.

The standard unit of water was taken as $\gamma_w = 9.806kN/m^3$ [21], [22] and [2]. This was used together with the hydraulic radius calculated from the cross-sectional drainage channel measurements taken, to calculate the shear stress. The particle diameter, $d_p = 6.1\ mm$ was used because it is within the sieve analysis laboratory results for the borrow pits($i.e\ 2mm\ to\ 14mm$).

The velocity was evaluated with the following values from one of the experiment spots in this study with the following measurements: $A = 0.2859\ m^2$, $Wp = 1.1785\ m$, $R = 0.2426\ m$, $n = 0.1$ for the maximum résistance to engage dunning. The lowest slope index was taken, $S = 0.035$ which eventually supports the low flow velocity [23] of $0.7279\ m/s$. Evaluation results were summarized in the table below:

Table 3. S_d Values for the Variables t and c_i

$\tau_c\ (N/m^2)$	TIME, t(s)	DRY DENSITY, $c_i\ (kg/m^3)$.	SPECIFIC AREA FOR DUNE DEVELOPMENT, $S_d(m^2/kg)$
47.99	0	1654.2	0.01517
47.99	5400	1654.2	0.00257
0.04	0	1654.2	18.19750
0.04	5400	1654.2	0.03684

On the other hand, the dune equation was analyzed using the discharge, $q = 0.2081$ (by Mann's formula) and initial dune sizes, $\alpha = 0.6858m$ or $\alpha = 0.1524m$ identified from some experiment spot handled in this study. The use of q for $\frac{\partial v}{\partial t}$ leads to the following equation and results in the table for discussion and analysis in his study:

$$S_d = \frac{qt + \propto}{\tau_c (1 + k_e c_i \tau t)} \quad (7)$$

Table 4. S_d Values for the Variables t, $\propto$ and c_i

$\propto$ (**m**)	τ_c (N/m^2)	TIME, t(s)	DRY DENSITY, c_i (kg/m^3).	SPECIFIC AREA FOR DUNE DEVELOPMENT, $S_d(m^2/kg)$
0.6858	47.99	0	1654.2	0.0143
	47.99	5400	1654.2	0.00010
0.1524	47.99	0	1654.2	0.00320
	47.99	5400	1654.2	0.00010
0.6858	0.04	0	1654.2	17.1450
	0.04	5400	1654.2	19.7357
0.1524	0.04	0	1654.2	3.8100
	0.04	5400	1654.2	7.9592

4. DISCUSSION AND ANALYSIS

The maximum resistance from Manning's n in table1 above reduces the velocity of the discharge. The rate of dune development in rills depends much on the discharge. Reduced velocities increase the rate of dunning. High velocities are also much induced by bigger road slopes. This means that road construction strategies should avoid sloppy areas as much as possible. Scouring in rills helps the dune development and happens when $\tau_o < \tau_c$ [22] and this was true for $\tau_c = 47.99\, N/m^2$ and $\tau_o = 0.08\, N/m^2$. The smaller τ_c value arising from various experimental effects can be used to show evidence of rilling during the dune formation process within a specific flow interval. Smaller critical stress, τ_c has a slightly higher effect on the dune development than the higher τ_c according to this equation evaluation whatever the initial effect.

From table 4, whatever the initial size of the dune in terms of height or width, the effect on dune formation is almost the same, $S_d = 0.00010 m^2/kg$ for the $\tau_c = 47.99\, N/m^2$which supports dunning and caters for the largest grain size with the sediment/dune classification. On the other hand, the value $\tau_c = 0.04\, N/m^2$ as used in equation (1) signifies some rilling according to the condition $\tau_o < \tau_c$. In this equation (7) above, the results signify that rilling at particular height and width level of the dune size. For example the width 0.6858m shows a rill development of 109% because basically dunning is a rilling process. Dunes finally spread in the road through the rilling and flooding processes.

Although the derivation of the equation was analytically processed, there are still issues that may bring variations in this evaluation. The use of the hydraulic radius or the hydraulic depth instead of the dune depth, may bring out variations in the evaluations among other factors.

5. CONCLUSION

It should be noted that non-paved roads in most developing countries suffer the effects of rilling even with well designed drainage. The equation suggests various methods of controlling such effects. They include among others, controlling the discharge factors like stress through drainage perennial grassing to increase the roughness coefficients, increased and applied compaction on high dry density soil profifiles , and other engineering improvements on the borrow pit materials used in road construction.

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