Erosion Features on Gravel Roads in Uganda–Formation and Effects

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***Abstract*—In the event of erosion flows, the road is one unique surface with various flow and deposition characteristics. Earlier studies focus on erosion features on shores and coasts and sometimes on desert plains as a result of wind erosion, but hardly on roads. Erosion features are detrimental to road designers, constructors, and users. This paper focused on gravel roads which constitute a larger percentage of the rural roads. These are a key to accumulation of wealth for developing countries. It also looked at the identification, formation, and extracting effects of features as a result of erosion on the road surface pertaining to various road surface characteristics. Rills and dunes on roads are active features which gully up bigger parts of the roads causing flooding and other dangerous effects. Various experiments like sieve analysis, runoff speeds and measuring road rill/dune sizes with respect to slope size, rain intensity, and road sizes were considered for this study. The main data analysis tool used was STATA V11. Findings included higher runoff speed on roads than other erosion fields, determination of the rate of road reduction, flooding by rills or dunes and provision of good background to modeling erosion on roads.**

***Index Terms*—Dune, erosion, modeling, rill.**

I. Introduction

Like in agricultural plots, erosion on roads is based on the concept of transport capacity of running water, and the deposition that occurs when the capacity is exceeded. Several approaches to erosion and deposition modeling have been developed since 1950's [1]. Although environmental issues are considered as one of the stages in road constructions, no much attention has been put on the rates of formation of the erosion features on roads. These affect road safety significantly. No soil phenomenon is more destructive world wide than the erosion caused by water and wind [2]

A road is a route, or way on land between two places, which typically has been paved or otherwise improved to allow travel by some conveyance, including a horse, cart motorcycles, bicycles and motor vehicles [3]. It is defined as "a line of communication using a stabilized base other than rails or air strips open to public traffic, primarily for the use of road motor vehicles running on their own wheels," which includes "bridges, tunnels, supporting structures, junctions, crossings, interchanges, and toll roads, but not cycle paths [4].

Stones, tree logs and timber were used in the making of roads in the Middle East and Europe in 4000BC [3]. Similarly, there were brick-paved roads in India about 3000BC, and eventually roads paved with tar in Iraq about the 8th century AD [4]. Most rural roads in developing countries are unpaved (Gravel), or paved with a thin, low cost asphalt surface. These are mostly built from locally-available granular materials which are often obtained from nearby quarries along the road.

In Uganda, roads are managed by various authorities that include Uganda National Roads Authority, Municipals, Local Governments and local communities. General classifications include the National, District, Urban, and Community Access roads. It should be noted that as of today, over 70% are still gravel roads as seen in Fig. 1 below:

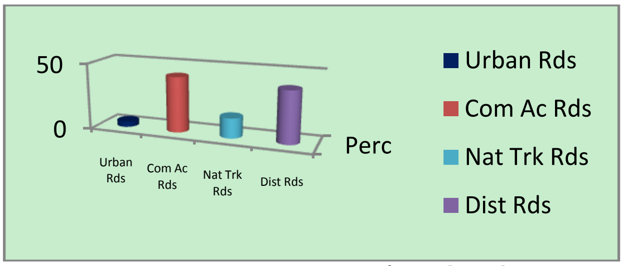

Fig. 1. Percentage composition of Uganda roads.

This brings the concern of this paper because most developing countries like Uganda have economies which majorly depend on rural roads. Most of these roads are in a poor state majorly because of erosion. There are various effects of the heavy rains on the country's road network. They include damage to bridges, culverts, rutting and gulling among others [5]. Yet remedies like provision of simple bridges, and installation of new culverts are temporary and costly [5].

Current road designs in most developing countries are standard and to some extent realistic. They are however not fully followed when undergoing construction or repairs of such roads. This tends to give erosion practices along roads a gap to create such serious impacts which are dangerous to road users. The paper's concern was on the formation and effects of these features under the influence of rain. This will in turn help in better road designs and maintenance strategies. The erosive power of the flow can be achieved by reducing its velocity as should be done by road constructors. Alternatively, gravel road surfaces need to be hardened or protected to reduce on erosion effects through standard compaction. Experiments and field surveys in this paper showed that compaction is rarely done especially if the road is not to be paved. This is partly brought about by inadequate funding and possibly corruption.

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II. METHODOLOGY

The study basically used the quantitative methods, which mainly involved experimental and observational studies. Some of the designs were carried out in the field and others in the laboratory. The field experiments were carried out in Uganda in four different regions of the country-Northern, Western, Eastern and Central. The roads considered included among others: Tororo-Nagongera road, Mpigi-Gombe road, Nakirebe-Buyala road, Kamwezi road, Butobere-Muyumbu-Rwamucucu road and Nyio-Ala road, among others.

The experiments involved gradation of road soil samples from both borrow pits and road sides as silt or sediment by strictly following the sampling procedures, identification and measuring erosion features and their effects and runoff speed. Some experiments like runoff speed were majorly done during rainy seasons for the given regions. In this case, the effects were the experimental factor, and the various features were the experimental units.

Non randomized complete block design (NRCBD), which is somehow similar to stratified sampling, was applicable. The strata were the region of study focused on dirt roads. The block was that part of the road of at most 100 meters. Units were relatively homogeneous and treatments were assigned at random to the experimental features within each block. These blocks were of the same size and took the same number of treatments on the features. The blocks were simulated from erosion plots as illustrated by various authors like [6].

III. RESULTS AND DISCUSSION

This study based on results from the experiments done. Five experiments were done to fulfill the objectives of this paper.

A. Extracting Road Soil Type

Road soils generally comprised the Alluvial, Collovial, Aeolian, Caliche, Laterite and loam soils [7]. These soils are affected by some or all the processes that include among others; water erosion and transportation, wind effects (dust on roads), cementing with iron oxides and mixed as sand, silt and clay. However the Laterite classification was considered with main soil type as brown grey clay course sand by sieve analysis. The AASHO classification was not considered in this paper.

B. Erosion Features and Effects

This paper's interest was only on few but main features due to erosion on roads. It focused on dunes and rills which are common on non-paved roads.

1) Dunes

Dunes comprised of the Aeolian and alluvial types. The Aeolian dune usually found in desert areas, have various shapes that include the crescent, linear, star, dome, and parabolic shapes [3]. Dunes formed as a result of erosion processes that act on roads through rills and gorges so formed were the main concern. Road side dunes are more periodic [8] because they depend on rainfall intensities that affect road surfaces and surrounding areas. Dunes on roads were found to be a result of one or more of the following processes:

Dam dunes form along the road side drainages when agriculturalists pile grass wastes in erosion paths while digging.

Similarly, it was observed 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.

Residents along such roads create humps to control vehicle speed and dust. They violate sediment and erosion controls (because they are not specialists) to create dunes (See Fig. 2). Such humps are normally out-of-proportion for road users like motorists. They also use non-standard culverts to connect their constructions (houses) to the roads. They are blocked by erosion processes and eventually create dunes. Some dunes result from landslides where water infiltrates the side hills on the sides of the road and large pieces of soil/rock slide into road side drainage. When it rains the size of this dune keeps on increasing hence flooding the roads or even blocking the entire road [9].

Fig. 2. Dunes by land slide (Kabale), vegetative cover's effect (Tororo), & humping (Mpigi).

2) Rills

Rills on roads develop as small, ephemeral concentrated flow paths after construction in four main forms: First they develop along and across drainage channels constructed on the sides of the road. They also form on the road by following weak points along the road as a result of inadequate compaction.

They sometimes develop when the runoff chooses a different path on the road after dunes from landslides block road side drainage channels.

Rills function as both sediment source and sediment delivery systems for erosion on road slopes. Runoff in rills is influenced by different hydraulic environment than typically found in channels of streams and rivers. With time and space road rills evolve morphologically and the rill bed surface changes as soil erodes, which in turn alters the hydraulics of the flow [10]. The dynamic hydraulic patterns cause continually changing erosional patterns in the rill. Thus, the process of rill evolution involves a feedback loop between flow detachment, hydraulics, and bed form. Flow velocity, depth, width, hydraulic roughness, local bed slope, friction slope, and detachment rate are time and space variable functions of the rill evolutionary process.

Rills turn in to gullies after some time. The narrow channels, or gullies, may be of considerable depth, ranging from 0.3m to 0.61m to as much as 22.9m to 30.5m [2]. For instance, the study experiments taken on some particular road showed an average width of 1.0668m and a height of 13.57m.

A road surface may become a gulley feature when gulley erosion acts on it. Some erosion through mudding sheets away parts of the road reducing its height as compared to the surroundings. It is one of the effects of erosion by the impact of rain drops on the road surface. These detach soil particles which may either be washed away down a slopy road by water.

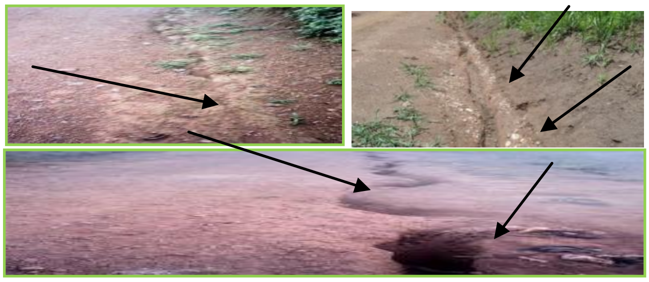

Fig. 3. Rills development on roads in Arua, Uganda.

C. Sieve Analysis

Eight samples were obtained from the partitioning regions of Uganda from borrow pits and from along the roads as deposited silt (Sediment). In this analysis, only four samples were considered to avoid the bulk handling. Initial dry weights were taken and sieve analysis was done. Two samples for each partition were combined for analysis, that is the sediment/silt (MS) and borrow pit (MBP) samples.

TABLE I: SIEVE ANALYSIS FOR MPIGI BORROW PIT (MBP) AND SEDIMENT (MS) SAMPLES

B.S. sieve (mm)	Percentage retained (%) (MBP)	Percentage retained (%)(MS)	Percentage Passing (%)(MBP)	Percenta (%)(MS)
75	0.0	0.0	100	100
50	0.0	0.0	100	100
37.5	0.0	0.0	100	100
28	0.0	0.0	100	100
20	0.0	0.0	100	100
14	8.0	2.2	92.0	97.8
10	10.6	7.4	81.4	90.4
5	28.3	7.7	53.1	82.7
0.43	1.0	11.4	31.9	51.4
0.075	1.9	2.6	26.4	20.7

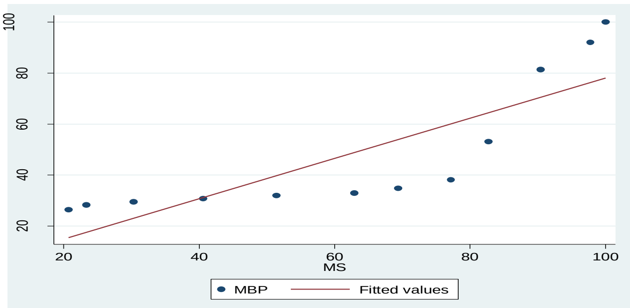

Fig. 4. Fitted scatter graph for MBP and BSSIEVE.

The sediment silts carried are finer that the borrow pit samples used to make the road. For example a difference of 5.7% in Mpigi samples was realized for this analysis. Similarly, a bigger percentage of the borrow pit soil that was used to make gravel roads is washed away by rain. This justifies the fact that compaction or the use of lime and the like, are majorly ignored or done in a substandard way when making gravel roads. Table I, Fig. 4-Fig. 5 show a relatively positive correlation between BTS and BS meaning that for some time interval, most soils used to construct the roads are eroded as sediments along the rills. It was noted from Fig. 5 was that about 70% of the MBP samples was found to be outside the range for gravel specifications. The same observation was taken for the eastern samples as seen in Table II and Fig. 7-Fig. 9 below. However the TBP samples were found to be by a bigger percentage of about 92%. Thus blending was suggested to comprise of lime use, compaction and others. However, this is not the case on most gravel road construction in developing countries.

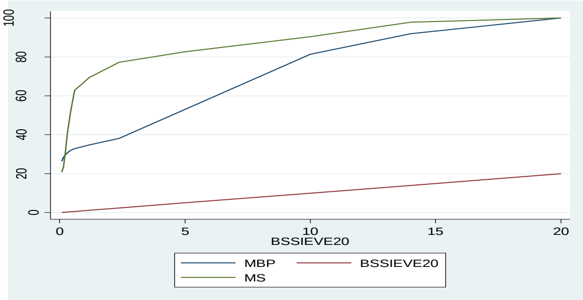

Fig. 5. Line graph for MBP, MS and BSSIEVE.

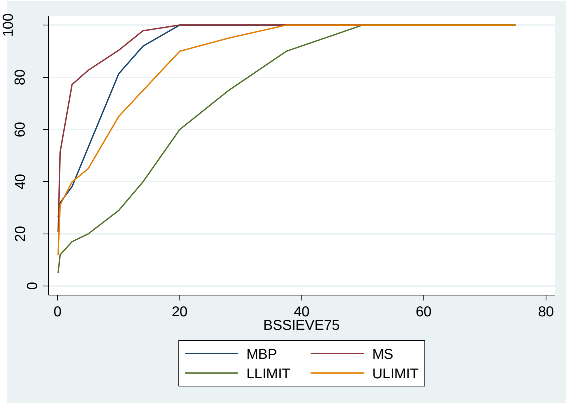

Fig. 6. Line graphs for MBP, MS, BSSIEVE and standard gravel specifications.

Similarly for the Eastern samples, that is Tororo borrow pit (TBP) and Tororo sample (TS) went through the sieve analysis and the graphs were derived by STATA statistical analysis tool as follows:

TABLE II: SIEVE ANALYSIS FOR TORORO BORROW-PIT (TBP) & SEDIMENT (TS) SAMPLES

B.S. sieve (mm)	Percentage retained (%) (TBP)	Percentage retained (%)(TS)	Percentage Passing (%)(TBP)	Percentage Passing (%)(TS)
75	0.0	0.0	100	100
50	0.0	0.0	100	100
37.5	0.0	0.0	100	100
28	0.0	0.0	100	100
20	0.0	0.0	100	100
14	0.0	0.0	100	100
10	5.6	0.0	94.4	100
5	10.8	0.0	83.7	100
2.36	9.9	12.8	73.7	87.2
0.43	3.1	13.2	58.3	30.1
0.075	6.4	0.9	37.6	14.7

Observed was the fact that TBP samples need much more blending before they are used for road constructions.

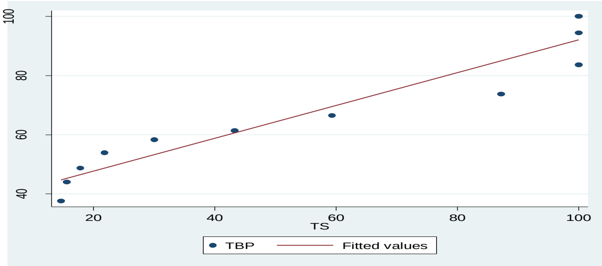

Fig. 7. Fitted scatter graph for TBP and BSSIEVE.

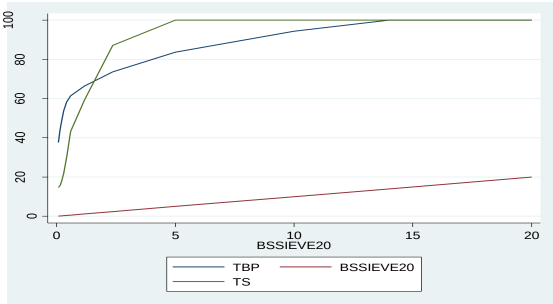

Fig. 8. Line graph for TBP, TS and BSSIEVE.

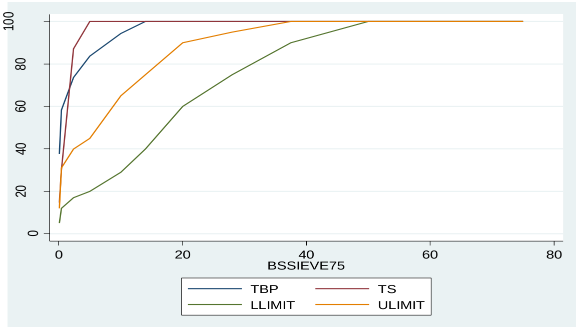

Fig. 9. Line graphs for TBP, TS, BSSIEVE and Standard gravel specifications.

D. Run Off Speed

There are various runoff speeds that were captured in this experiment: They were classified according to rainfall intensity, runoff volume in rills, and rill roughness factors like varying depths and widths. The following table summarizes the results:

TABLE III: RUN OFF SPEED ON ROADS

RAINFALL INTENSITY	TIME (s)	DISTANCE (m)	SPEED (m/s)
Low	12	2.1343	0.1779
	14.51	3.1242	0.2153
Moderate	2.6	1.8294	0.7036
	9.65	5.1068	0.5292
High	8.75	11.5862	1.3241
	1.51	3.175	2.1026

It was noted that high rainfall intensity increases the volume of running water in rills and eventually increases the runoff speed. This speed is also affected by the size of rills in relation to the volume of runoff. Bigger but shallow rills increase rill roughness which reduces the speed. The proportion of rainfall that eventually becomes stream flow or runoff volumes depend on various factors. They include the size and slope of the drainage area, soil and design characteristics like compaction.

Rill roughness is affected among others by silting which causes dunes. These eventually affect the speed of the running water. Runoff speed on roads is relatively higher than that of erosion plots with different roughness and volume factors. For example, [11] quoted a runoff speed of 0.00001m/s and an erodibility factor ranging from 0.02 m/s to 0.05m/s. So it was seen from the experiment results that the range for runoff speed was 0.18m/s to 2.1m/s which is quite high. It is possibly accelerated by road design factors like compaction, cbr, among others.

Because of blocked or divided flows in drainage, runoff water in road rills crosses the roads at some points. This causes various problems like flooding of roads, and tire flattening when runoff carries sharp materials. It should be noted that drainage installations are sized according to the probability of occurrence of expected peak charges during the design life of the installation [3]. Various methods used in predicting peak flows include among others the flood frequency analysis. It is the most accurate when sufficient data and specification of the risk of failure over the design life must are specified. It is based on the formula:

$$p = 1 - n(1 - \frac{1}{T}) \quad (1)$$

p is the probability of failure, n is the design life in years, and T peak flow recurrence interval (years). This particular method needs appropriate stream flow data and therefore recommended for channels draining less than 200 acres [3], [12]. The road is one feature that cannot drain to this extent and therefore the Manning's formula can be used. More so gravel roads in developing countries like Uganda have very short design lives not exceeding 5 years. However, erosion through rilling, dunning and gulling destroys such roads within a year or two because several standard designs are applied on paved types. Similarly it was analyzed that road rills have their peak flow recurrence $T = 1$, implying that chances of failure are high i.e $p = 1$. Manning's formula relies solely on channel characteristics where a road rill can be classified. In developing our rill or dune size model, this formula quoted below shall be used to estimate the discharge of water in road rills.

$$Q = \frac{AR^{\frac{2}{3}}S^{\frac{1}{2}}}{n} \quad (2)$$

Q is the discharge (m^3/s), A is cross sectional area of the stream (rill) (m^2), R is the hydraulic radius (m), S is the slope of the water surface., and n is the roughness coefficient [3]. The discharge in any rill directly affects the runoff speed.

E. Road Size versus Rill/Dune Enlargement

The following experiment data was recorded between May and December, 2012 from various experiment spots. Only six spots were considered for rills and dunes. A simple analysis was made on actual increaments and decreaments on dunes and rills with respect to rainfall intensity, roadway width, and time (days).

The rills are originally initiated as road side drainage channels by road constructors. Measurements taken show that these drainage channels have a simple trapezoidal or triangular form with smaller measurements as compared to the standard designs. They normally measure between 0.05m and 0.31m wide and less than 0.3049m deep after some erosion effect. The experiments considered measurements to be taken after some erosion effects on the rills or dunes.

TABLE IV: RILL SIZES VERSUS ROADWAY WIDTH FOR VARIOUS RAIN SEASONS

F_{1i} - Rills	Width Difference (Rwd)(m)	Height Difference (Rhd) (m)	Rainfall intensity difference(Rin) (mm)	Road width(m)	Days
F_{11}	0.1016	0.1778	16.2	6.4	74
	0.1016	0.2845	13.5	6.4	22
	-0.0635	0.0203	63	6.4	25
	0.1397	0.0279	11.1	6.4	16
	0.1016	0.0	10.2	6.4	4

TABLE V: DUNE SIZES VERSUS ROADWAY WIDTH FOR VARIOUS RAIN SEASONS

F_{2i} - Dunes	Width Difference(Dwd) (m)	Height Difference(Dhd) (m)	Rainfall intensity difference(Rin) (mm)	Road width(m)	Days
F_{21}	0.9398	0.0762	16.2	6.4	74
	0.1778	0.0178	13.5	6.4	22
	0.0635	-0.0051	63	6.4	25
	0.0254	0.0076	11.1	6.4	16
	0.0381	0.0051	10.2	6.4	4

Only one experiment point for the rill (F_{11}) and one for the dune (F_{21}) were considered for analysis in this paper. Other experiment areas were considered in rill or dune model development. It was noted that high rainfall intensity leads to high runoff rate which eventually increases the width and height of rills. Some rill heights reduce because of the silting process which also affects the rate at which gulleys may form from rills. According to this experiment, it was noted that increased rill width eats up the standard size of the road at a rate of 0.003m/day or 0.01m/month at some rainfall intensity. The negative values in rill widths show that dunning sometimes squeezes the rill at some erosion intervals. Simple regression analysis shows the following relation equations:

$$\begin{Bmatrix} Rwd = 0.0756 + 0.00002Days \\ Rhd = 0.0436 + 0.0021Days \end{Bmatrix} \quad (3)$$

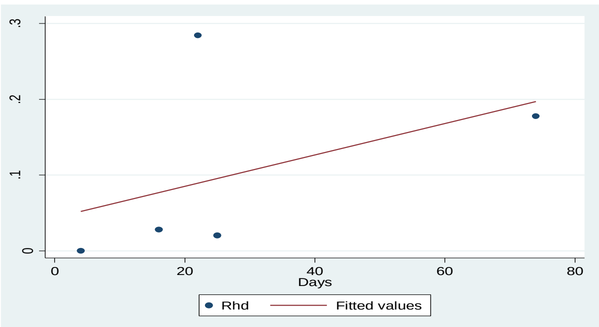

Fig. 10. Scatter graph for rill heights in relation to rainfall days.

It was also noted that at least 20% of the variance in the rill depth is supported by the second model in (3). At zero rain days the rill depth of 0.0436m can still fit the range of drainage sizes after some erosion. Similarly 0.00002% of the variance in the road rill width is supported by the first model in (3). At zero days, the rill width of 0.0756m falls within the range of the initial sizes of the rills after some erosion effect.

The rate at which rills cut deep in to drainage channels is a bit higher than that of the width as seen in (3) above. The rainfall intensity relationship is not at all supported by the linear regression models for this selection. The scatter graph below showed that the rill heights actually deepen with more rainfall days.

It was noted that over 84% of the dune width and height is supported by first and fourth models in (4) below. Various estimates can be done in estimating the dune width and heights in relation to time in terms of days and the rainfall intensity. For example after 30 days, the dune width for this experiment would be 0.2754m.

$$\begin{Bmatrix} Dwd = -0.1476 + 0.0141Days \\ Dwd = 0.3168 - 0.0030Rin \\ Dhd = 0.03178 - 0.0005Rin \\ Dhd = \ -0.1081 = 0.0011Days \end{Bmatrix} \quad (4)$$

Dunes enlarge by more and more silting or deposition or sedimentation. The negative values showed that some dune heights are reduced during and depending on the flow. The more positive values in Table V above support the fact that dunes on roads keep growing.

IV. CONCLUSION

Most rural roads in developing countries are unpaved yet they are keys to accumulation of their wealth. The action of erosion on roads creates features which are detrimental to road designers, constructors, and users. Quantitative methods that included experimental and observational studies were used and the findings included among others:

Higher runoff speed on roads than other erosion surfaces, and the rate of road reduction by rills is rather high as 1.095m/year. Flooding chances resulting from erosion dunes are also highly chanced on these roads. A bigger percentage of the borrow pit soil that was used to make such roads is actually out of the standard gravel specifications and therefore easily washed away by rain. Therefore there is need to blend the gravel material and to strictly follow the standard road design procedures. Standard and timely maintenance is necessary (say after a period of one year maximum) and models on erosion on roads should be developed to assist in road maintenance.

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