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Full Length Article

The relationship between diameter and depth of potholes eroded by running water

Shaocheng Ji [a,*], Le Li [a], Wei Zeng [b]

[a] Département des Génies Civil, Géologique et des Mines, École Polytechnique de Montréal, Montréal, Québec, H3C 3A7, Canada
[b] Faculty of Architecture and Urban Planning, Chongqing University, Chongqing, 430045, China

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ABSTRACT

Geometrical analyses of 3930 potholes (3565 fluvial potholes, 237 marine potholes and 128 hillside potholes) from 33 localities in the world reveal a consistent, linear relationship: $D = Nh + M$, where h and D are, respectively, the depth and mean diameter of pothole, M is a critical size of the initial concavities (seminal potholes) that subsequently underwent growth, and N is the ratio of diameter expanding (wall erosion) speed to deepening (floor abrasion) speed. For the stream potholes, N is generally less than 1 with an average value of 0.67, M varies from 5.3 cm to 40.5 cm with an average of 20 cm, and N decreases gently with increasing M. However, the marine and hillside potholes are generally characterized by $N > 1$ and $M < 10$–14 cm, and a power-law relationship $N = 4.24M^{-0.78}$ (coefficient of determination $R^2 = 0.75$, M is in cm) exists. The results indicate that depth increases faster than diameter for stream potholes due to the larger size of grinding stones (>5–10 cm), while depth increases slower than diameter for marine potholes and hillside potholes due to the smaller size of grinding stones (<5–10 cm). The pothole h-D relationship is nearly independent of rock type. Knowledge of the pothole depth–diameter relationship is useful in a number of contexts, including simulation of hydraulic dynamics, theoretical considerations of erosion, comprehension of channel incision and development of canyons and gorges, and accurate estimation of excavation volume and mechanical strength of potholed bedrock in the design and stability analysis of hydraulic and environmental engineering projects (e.g. dam construction and river dredging).

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1. Introduction

Eddy-hole-type potholes are one of the most spectacular examples of clearly visible, abiotic features formed on bedrock by rapidly swirling flow of water, which has enough potential energy to carry sediments (i.e. sand, pebbles, cobbles and boulders) to erode deflation hollows through abrasion and corrosion (e.g. Alexander, 1932; Hancock et al., 1998; Springer and Wohl, 2002; Richardson and Carling, 2005; Wang et al., 2009; Ortega et al., 2014; Lima and Binda, 2015; Ortega-Becerril et al., 2016; Dhali and Biswas, 2017a). Continuous channels can be formed into the river bedrock by agglomeration of multiple, initially separate, enlarging and overlapping potholes during their progressive growth, creating canyons of sculpted rocks (e.g. Longyin Canyon (Chongqing) and Yucha Canyon (Shanxi) in China, and Buckskin Gulch (Utah) and Antelope Canyon (Arizona) in USA). Knowledge of the pothole depth–diameter relationship is required for the solution of a number of very practical problems in the design and stability analysis of hydraulic and environmental engineering projects, such as excavation, dam construction, and river dredging. In order to estimate the cost of rock excavation, for example, one need calculate the total volume of rock excavation and the mechanical strength of the channel bedrock, both of which largely depend on accurate estimate of the volume fraction of potholes (e.g. Ji and Xia, 2002; Ji, 2004; Ji et al., 2006; Yu et al., 2016). Each vertical pothole can be approximated by a circular or elliptical cylinder characterized by the following geometrical parameters: the lengths of its major and minor axes (a and b) and the mean diameter ($D = \sqrt{ab}$) of the horizontal section and the depth (h). If a relationship between h and D is known, one can indirectly determine the depths and further the volumes of potholes based on the D data obtained from aerial photos taken by a drone. Additionally, it is important to determine if the h-D relationships differ by lithology and have generic implications for pothole development over time.

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[*] Corresponding author.
E-mail address: sji@polymtl.ca (S. Ji).
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Table 1
A new global database consisting of 3930 potholes from 33 localities in the world.

Type of potholes	Location	Bedrock lithology	n	a (cm)		b (cm)		a/b		D (cm)		h (cm)		D/h		M (cm)	N	R^2	Reference
				Value	St.D.	Value	St.D.	Value	St.D.	Value	St.D.	Value	St.D.	Value	St.D.				
Stream potholes	Kurokawa River, Shikoku, Japan	Chert	120	218.5	191.9	177.3	155.7	1.33	0.59	194.8	168.4	206.7	193.7	1.41	1.2	40.53	0.7	0.44	Sato et al. (1987)
	Shelburne Falls, Deerfield River, MA, USA	Felsic and mafic gneisses	154	108.4	83.2	78.9	63.6	1.49	0.6	91.7	71	85	73.2	1.58	1.59	31.31	0.71	0.54	This study
	Gatineau River, Quebec, Canada	Felsic and mafic gneisses	212	43.2	27.2	31.2	19.6	1.4	0.33	36.5	22.5	40.7	24.5	0.96	0.33	5.71	0.76	0.68	This study
	Augrabies, Orange River, South Africa	Granitic gneiss	193							73.6	73.2	73.6	73.2	1.15	0.75	20.83	0.46	0.53	Springer et al. (2005)
	Sandy River, Phillips, Maine, USA	Granite	137	86.2	54.5	61.8	38.3	1.43	0.39	72.5	44.4	65.1	48	1.6	1.26	27.44	0.69	0.55	This study
	Kharsoti River, Tetuldanga, India	Granite	29							75.4	42.9	69.1	48.8	1.27	0.58	26.7	0.7	0.64	Dhali and Biswas (2017a)
	Mino River, Iberian Peninsula, Spain	Granite and granodiorite	59							56.7	26	55	38.1	1.13	0.25	23.32	0.61	0.79	Álvarez-Vázquez and Uña-Álvarez (2017b)
	Indrayani knickpoint, Maharashtra, India	Basalt	633							24		24		1		18.54	0.8	0.52	Kale and Shingade (1987)
	Kurokawa River, Shikoku, Japan	Metabasalt	53	106.5	81.5	74.7	55.4	1.48	0.81	87.9	64.2	87.4	57	1.13	0.57	15.13	0.83	0.55	Sato et al. (1987)
	Reach 1, Ocoee River, Tennessee, USA	Metasediment	105							31		17.1	6.1	1.81		27.33	0.44	0.4	Goode (2009)
	Reach 2, Ocoee River, Tennessee, USA	Metasediment	296							41		21.8	8.1	1.88		32.5	0.56	0.39	Goode (2009)
	Reach 3, Ocoee River, Tennessee, USA	Metasediment	176							49.2		27.9	11.8	1.76		34.95	0.54	0.26	Goode (2009)
	Reach 4, Ocoee River, Tennessee, USA	Metasediment	146							43		36.8	12.9	1.17		30.19	0.33	0.2	Goode (2009)
	Kakamas, Orange River, South Africa	Phyllitic quartzite	64							68.7	105.9	56.3	71.1	1.33	0.57	14.18	0.84	0.75	Springer et al. (2005)
	Boegoebeg, Orange River, South Africa	Metasediment	216							35.8	21.1	27.2	19.3	1.56	0.83	10.91	0.92	0.7	Springer et al. (2005)
	Wubu River, Chongqing, China	Mudstone and sandstone	179	27		21		1.3						1.13		19.71	0.5	0.56	Ren et al. (2015)
	Site 1, Sunxi River, Chongqing, China	Sandstone	90	58.7	50.6	50.6	48.7	1.2	0.24	54.3	49.4	66.2	64.2	1.06	0.48	11.02	0.65	0.72	This study
	Site 2, Sunxi River, Chongqing, China	Sandstone	202	34.1	18.5	27.7	14.3	1.23	0.22	30.6	16.1	36.3	19	0.92	0.42	7.38	0.64	0.6	This study
	Site 3, Sunxi River, Chongqing, China	Sandstone	38	16	6.9	13.7	6.1	1.18	0.21	14.7	6.3	17.1	9.8	1.02	0.45	5.9	0.52	0.65	This study
	Site 4, Sunxi River, Chongqing, China	Sandstone	75	33.9	24.9	27.3	18.2	1.26	0.31	30.2	20.8	32.9	25.3	1.03	0.41	7.81	0.68	0.69	This study
	Site 5, Sunxi River, Chongqing, China	Sandstone	100	51.8	37.3	39.9	25.2	1.27	0.27	45.2	30.1	34.5	22.5	1.29	0.5	6.09	1.07	0.63	This study
	Site 6, Sunxi River, Chongqing, China	Sandstone	100	33.6	19	26.4	14.1	1.27	0.2	29.7	16.2	23.9	11.5	1.28	0.43	5.32	1.05	0.68	This study
	Site 7, Sunxi River, Chongqing, China	Sandstone	43	33.3	17.8	26.7	14.9	1.26	0.22	29.7	16	23	18.5	1.64	0.68	16.61	0.61	0.5	This study
	Longxi River, Liangping, Chongqing, China	Sandstone	145	23.3	13.9	18.7	9.7	1.23	0.24	20.8	11.3	25.2	15.1	0.93	0.37	6.05	0.59	0.61	This study
		Average	3565	62.5	48.2	48.3	37.2	1.31	0.36	53.8	44.8	50.1	39.6	1.29	0.65	18.56	0.67	0.57	

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