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Seismically induced clastic dikes as a potential approach for the estimation of the lower-bound magnitude/intensity of paleoearthquakes

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ABSTRACT

We compiled a database that includes 36 sites wherein the injection and neptunian dikes associated with 16 instrumental seismic events were studied. Some information in the database was obtained from our field work in the epicentral area of the 2003 $Ms = 7.5$ Chuya and the 1950 $Ms = 7$ Mondy earthquakes. The bounding relationships between the surface-wave magnitude (Ms) and maximum width (w_{cd}), visible maximum height (h_{cd}) and intensity index of clastic dikes (I_{cd}), and local macroseismic intensity (I_L) and the same three parameters were established. As was hypothesized, larger metrics of clastic dikes can be expected from earthquakes with higher magnitudes and macroseismic intensities. The analysis of the obtained relationships showed that when estimating the lowest potential magnitude or local macroseismic intensity, it is better to use all three parameters of clastic dikes and take the maximum level for seismic hazard evaluation. This reduces the underestimation of the earthquake potential. Thus, clastic dikes can be applied as a potential approach for a lower-bound magnitude/intensity estimation of paleoearthquakes, which is particularly important in the construction of critical facilities. This work should stimulate geologists to record the metrics of seismically induced clastic dikes to improve the equations proposed in the present paper.

1. Introduction

Considerable attention has been devoted recently to clastic dikes and their use in earthquake studies (Audemard and de Santis, 1991; Demoulin, 1996; Lunina et al., 2012; Mohidra and Bagati, 1996; Obermeier, 1996, 1998, 2005, 2009; Bezerra et al., 2005; González de Vallejo et al., 2005; Kuhn, 2005; Obermeier et al., 2005; Quigley et al., 2013; Talwani et al., 2011; Van Loon and Maulik, 2011). These dikes are classified into two different groups. The first one includes injection (intrusion) dikes formed by fluidized injection of clastic material into the host sedimentary layers and associated with overpressure buildup and hydraulic fracturing (Levi et al., 2009, 2011; Obermeier, 1996, 1998; Obermeier et al., 2005). The second group contains neptunian dikes formed by the introduction of material either under pressure or by the simple filling of pre-existing fissures from above (Montenat et al., 1991, 2007). In most cases, injection dikes are considered for engineering geologic analysis of paleoseismic shaking because they are indicators of seismic liquefaction, and their relation to earthquakes is quite certain. In fact, different plastic intrusions and convolutions develop during seismic liquefaction, but dikes providing numerical characteristics are the most informative soft-sediment deformation structures to reconstruct paleoearthquake parameters. For example, the width and height changes of coeval dikes allow for the accurate contouring of the epicentral area and of estimating the energy center (Green et al., 2005; Obermeier et al., 2005). Additionally, for the same purpose, the number of dikes normalized to the section length was used, as well as the intensity index of their manifestation, which was expressed in terms of the product of various dike parameters normalized to the section area (Lunina et al., 2011, 2012).

To measure the energy of an earthquake on the basis of liquefaction features, empirical relationships between the magnitude and the epicentral or fault distance are applied (Ambraseys, 1988; Galli, 2000; Kuribayashi and Tatsuoka, 1975; Liu and Xie, 1984; Lunina et al., 2014; Papadopoulos and Lefkopoulos, 1993; Papathanassiou et al., 2005; Wakamatsu, 1993; Youd and Perkins, 1978). These relationships are effective in the case of a known location of the seismogenic source that is responsible for liquefaction. Castilla and Audemard (2007) suggested the additional use of the curve of the sand-blow diameter versus the epicentral distance and noted that the resulting magnitudes should mostly be considered to be underestimated. Regression analysis shows that surface rupture parameters (e.g., length and displacement) are more dependent on the magnitude (Bonilla et al., 1984; Vakov, 1996; Pavlides and Caputo, 2004; Wells and Coppersmith, 1994). However, surface ruptures on flat areas covered with unconsolidated sediments are difficult to recognize after decades because of erosional truncation.

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Table 1
Collected database of clastic dikes associated with worldwide earthquakes.

No of site	Earthquake information						Log characteristics		Clastic dike information					Reference
	Earthquake name/country, region	Date	Location		Magnitude (*Ms*)	Local intensity (I_L) on MSK-64 macro-seismic scale	Square of detail studied log (*S*), m^2	Number of dikes	Composition	Type	Maximum width (w_{cd}), m	Maximum height (h_{cd}), m	Maximum intensity index (I_{cd})	
			Latitude, °	Longitude, °										
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Alaskan/USA, Alaska	22.07.1937	64.58	−145.83	7.3			1	Mud deposits	Injection	0.38			Bramhall (1938)
2	Mondy/Russia,	04.04.1950	51.77	101.00	7	9	2.1	1	Fine-grained sand	Injection	0.35	0.8	1333.3	Baikal Branch of the
3	East Siberia					9	17.5	3	Sandy-boulder-pebble	Injection	0.23	0.78	410.1	Geophysical Survey, Lunina
4						9	1.96	1	sediments	Neptunian	0.55	1.12	3142.9	et al. (2015); own data
5						9	17.5	1	Fine-grained sand with pebbles	Neptunian	0.22	0.66	83	
6	Middle Baikal/	29.08.1959	52.68	106.98	6.8	8.5			Fine-grained uliginous	Injection	0.1			Baikal Branch of the
7	East Siberia					7.5	3.5	1	sand	Injection	0.03	0.7	60	Geophysical Survey, Solonenko and Treskov (1960), Rubtsov et al. (1960)
8	Mogod/Mongolia	05.01.1967	48.10	102.90	7.8	9	27	1	Quartz sand	Injection	0.3	1.7	377.8	Rogozhin et al. (2008), (2011)
9						9	27	1	Topsoil	Neptunian	0.08	1	29.6	
10	Inangahua/ New Zealand	24.05.1968	−41.77	172.01	7	9			Fine-grained uliginous sand	Injection		1.8		Fairless and Berrill (1984)
11	Kinnaur/India	19.01.1975	32.46	78.34	6.8	8	80	1	Sandy sediments	Injection	0.2	1.5	37.5	Mohidra and Bagati (1996)
12*	San Juan/Argentina	23.10.1977	−31.04	−67.76	7.4				Mud deposits	Injection	0.48			Youd and Keefer (1994)
13	Northwest Venezuela	30.04.1989	11.07	−68.17	5.7	6.5	0.75	2	Fine-grained sand	Injection	0.07	0.55	1026.7	Audemard and de Santis (1991), Castilla and Audemard (2007)
14	Loma Prieta/USA, California	17.10.1989	37.04	−121.88	7.1	8		1	Sandy sediments with a mud	Injection	0.04	0.3		Sims and Garvin (1995)
15	Uttarkashi/India, Himalaya	20.10.1991	30.78	78.77	6.8	6	4	16	Mud and fine-grained sand	Injection	0.05	0.2	400	Pandey et al. (2009)
16	Chamoli/India, Himalaya	28.03.1999	30.41	79.42	6.6	6	4	17	Mud and fine-grained sand	Injection	0.04	0.18	306	Pandey et al. (2009)
17	Chuya/Russia, Gorny Altai	27.09.2003	50.09	87.98	7.5	9.5	3.49	1	Sand and sandy loam with gravel, debris and pebble	Injection	0.81	1.82	4224	Lunina et al. (2008); own data
18						9.5	2.6	1	Mud and fine-grained sand	Injection	0.09	0.56	193.8	
19						9.5	3.16	2	Sand	Injection	0.11	0.93	5965.2	
20						8.5	1.25	3	Sandy loam, sand	Injection	0.33	1.2	9504	
21	Chuya/Russia,	27.09.2003	50.09	87.98	7.5	8.5	1.25	2	Sand	Injection	0.13	0.86	1788.8	Lunina et al. (2008); own data
22	Gorny Altai					8.5	1.54	3		Injection	0.25	0.3	1461	
23						8.5	2.42	3	Limonitized sandy loam	Injection	0.087	0.44	474.5	
24						8.5	2.28	3	Sand with fine pebble	Injection	0.35	0.7	3223.7	
25						8.5	1	1	Sand with gravel	Injection	0.08	0.37	296	
26						8.5	0.77	1	Sandy loam	Injection	0.005	0.14	981.8	
27						9.5	3.16	11		Neptunian	0.145	1	5047.5	
28						8.5	0.77	2		Neptunian	0.06	0.42	654.5	
29	Olyutor/Russia,	20.04.2006	60.98	167.37	7.8	8.5	2.4	1	Sandy loam with	Injection	0.14	1	583.3	Rogozhin et al. (2010), (2011)
30	Kamchatka					8.5	2.4	3	pebble	Injection	0.2	0.72	1800	
31*	Skovorodino/Russia,	16.10.2011	54.11	123.84	6.1	7			Sand	Injection	0.1			Ovsyuchenko et al. (2013)
32*	Amur area					8				Injection	0.05			Ovsyuchenko et al. (2013)
33*						8				Injection	0.2			Ovsyuchenko et al. (2013)
34*						7				Injection	0.05			Ovsyuchenko et al. (2013)
35*	Tuva/Russia	26.02.2012	51.74	95.99	6.8	9			Sand	Injection	0.15			Ovsyuchenko et al. (2014)
36*	Emilia/Italy	20.05.2012	44.89	11.22	6.1				Sand	Injection	0.2			Global CMT Catalog; Papathanassiou et al. (2015)

* A fracture gap whereof the mud and sand deposits outgushed was taken as the dike width.