

Timing and Spouting Height of Sand Boils Caused by Liquefaction during the 2010 M_w 6.9 Yushu Earthquake, Tibetan Plateau, China

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Abstract

The 2010 M_w 6.9 Yushu earthquake produced a ~33-km-long co-seismic surface rupture zone along the pre-existing active Yushu Fault on China's central Tibetan Plateau. Sand boils occurred along the tension cracks of the co-seismic surface rupture zone, and locally spouted up above the ground to coat the top of limestone blocks that had slid down from an adjacent ~300-m-high mountain slope. Based on our observations, the relations between the arrival times of P- and S-waves at the sand-boil location and the seismic rupture velocity, we conclude that 1) the sand boils occurred at least 18.24 s after the main shock; 2) it took at least 4.09 - 9.79 s after the formation of co-seismic surface rupture to generate liquefaction at the sand-boil location; 3) the spouting height of sand boils was at least 65 cm. Our findings help to clarify the relationships between the timing of liquefaction and the spouting height of sand boils during a large-magnitude earthquake.

Keywords

Liquefaction, Sand Boil, 2010 $\rm M_w$ 6.9 Yushu Earthquake, Co-Seismic Surface Rupture, Tibetan Plateau

1. Introduction

The M_w 6.9 Yushu earthquake occurred on 14 April 2010 in Qinghai Province of the central Tibetan Plateau, *Corresponding author.

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Figure 1. Location maps of the study area, showing topographic features and the distribution of the co-seismic surface rupture zone of the 2010 Yushu earthquake. (a) Index map showing the major active faults of northern Tibet. ATF, Altyn Tagh Fault; HYF, Haiyuan Fault; KLF, Kunlun Fault; GZ-YSF, Ganzi-Yushu Fault Zone; LMSTB, Longmenshan Thrust Belt; SCB, Sichuan Basin; BHB, Bayan Har Block; AN-XJF, Anninghe-Xiao-jiang Fault. The large arrow indicates the motion of the Indian Plate relative to the Eurasia Plate; (b) SRTM (Shuttle Radar Topography Mission; 90 m resolution) color-shaded relief map showing the tectonic landforms of the Yushu region (fault data from [2]). The white solid circle indicates the location of Jiegu Town (the prefecture seat of Yushu), and the red star indicates the epicenter of the 2010 Yushu earthquake, as determined by the China Earthquake Networks Center [23]; (c) Distribution map of co-seismic surface ruptures, showing the sand-boil locations referred to in this study (modified from [1]). Locations 1 - 3 are the sand-boil locations referred to in this study (Loc. 1: 32°59'3.6.7"N, 97°00'14.4"E; Loc. 2: 32°58'14.0"N, 97°01'22.2"E; Loc. 3: 33°03'9.3"N, 96°51'28.9"E).

[5]. However, there is still a lack of detailed description and analysis of liquefaction that took place during the earthquake. In this short article, therefore, we focus on this issue.

Liquefaction caused by large-magnitude earthquakes has been responsible for a tremendous amount of damage to buildings and infrastructure, including roads [6]-[11]. Liquefaction, induced by an earthquake in non-cohesive soil and sand layers, is generally generated by the horizontal vibration of S-waves, which causes increased pore pressures and which induces effective stresses [4] [12] [13]. In contrast, during the 1995 M_w 7.2 Kobe earthquake [14], earthquake-induced liquefaction was produced by instantaneous vertical shaking caused by P-waves. The timing of liquefaction and sand boils caused by P-waves can be constrained by the time difference between the velocities of P-waves and the seismic rupture velocity during a short period of up to 3 - 4 s [14]. However, the situation regarding the timing of liquefaction caused by S-waves, and the spouting height of boiled sands, remains unclear, due to a lack of case studies. The lack of observations on the spouting behavior of sand boils during earthquake-induced liquefaction hinders assessment of the physical processes of liquefaction and the seismic hazards of non-cohesive sediments. In this short article, we provide data on the timing of liquefaction and the spouting height of sand boils caused by the 2010 M_w 6.9 Yushu earthquake.

2. Geological Setting and the Yushu Co-Seismic Surface Rupture Zone

2.1. Geological Setting

The study area is located in a high mountain region on the central Tibetan Plateau, with an average elevation of ~4000 m, along the strike-slip Ganzi-Yushu Fault Zone (**Figure 1**). The Ganzi-Yushu Fault Zone (GZ-YSF) strikes WNW-ESE for more than 500 km, parallel to the left-lateral strike-slip Kunlun Fault, and it forms the northern tectonic boundary of the Bayan Har Block (**Figure 1**). The Yushu Fault is a 75-km-long segment of the GZ-YSF, located on the central-western side of the fault zone (**Figure 1**). Previous studies have shown that the Yushu Fault is active, with a slip rate of 3 - 12 mm/yr, mainly based on long-term geological data [2] [15]-[17]. Paleoseismic studies, carried out after the 2010 Yushu earthquake, show that for the past 1000 years, the average recurrence interval for large-magnitude earthquakes (M > 7) on the Yushu Fault has been 450 - 680 yrs, and that the average slip rate is ~5 mm/yr [2], consistent with GPS observations [18] [19]. These long-term geologic and paleoseismic data, as well as GPS observations, show that the Yushu Fault has repeatedly triggered large-magnitude earthquakes during the late Holocene.

Straight valleys trending WNW-ESE mark the position of the Yushu Fault, and the topography is characterized by sags and saddles, fault depressions, systematically offset gullies, river channels, and ridges (Figure 1(b)) [2] [5]. The basement consists mainly of Triassic sedimentary rocks, including limestones, sandstones, mudstones, and shales, as well as minor volcanic rocks. Quaternary sediments are distributed mainly in the lowlands along valleys and gullies, and they generally consist of unconsolidated alluvial and fluvial deposits.

2.2. Outline of the Yushu Co-Seismic Surface Rupture Zone

The 2010 M_w 6.9 Yushu earthquake produced a 33-km-long co-seismic surface rupture zone characterized by tension cracks, mole track structures, and discrete shear faults, most of which developed in unconsolidated alluvial and fluvial deposits along the pre-existing left-lateral strike-slip Yushu Fault [1] [2] [5]. The tension cracks generally exhibit a right-stepping en echelon pattern (**Figure 2(a)**), whereas the mole track structures show a left-stepping pattern. The geometry of these co-seismic surface ruptures indicates a left-lateral strike-slip movement [1] [2]. Field measurements indicate co-seismic left-lateral strike-slip displacements of approximately 0.3 - 3.2 m (typically 1 - 2 m), accompanied by a minor vertical component of <0.6 m [1]. InSAR (interferometric synthetic aperture radar) observations reveal that the maximum left-lateral displacement is up to ~2.6 m [20]. The co-seismic surface rupture zone consists of three distinct segments, which are, from southeast to northwest, the Changu Temple (length, 8 km), Buqionggei (17 km), and Ganda Village (8 km) segments (**Figure 1**) [1].

3. Liquefaction

3.1. Distribution of Sand Boils

Sand boils caused by the 2010 Yushu earthquake occurred mainly in the lowland areas of the Changu Temple



Figure 2. Photographs of representative sand boils and co-seismic surface ruptures related to the 2010 Yushu earthquake. (a) Co-seismic surface ruptures developed in a lowland area, where the sand boils formed within tension cracks that exhibit a right-stepping en echelon pattern (Loc. 3; see **Figure 1** for location details); (b) Sand boils along a tension crack at Loc. 1; (c) Sand forming a circular sand volcano on a flood plain.

and Buqionggei segments, where fluvial deposits are developed (Figure 1 & Figure 3). In general, the sand boils developed around and within the tension cracks that formed along the co-seismic surface rupture zone, and at Locs. 1 - 3, the sand sometimes forms small circular sand volcanoes with a diameter of 10 - 100 cm (Figure 2) (see Figure 1 for location details). The close association of the sand boils and the tension cracks indicates that liquefaction occurred after the formation of these co-seismic surface ruptures. At the southeastern end of the Changu Temple segment, at Loc. 2, sand boils formed over a wide area of the flood plains and the terrace risers of the Baqu River, where there are many limestone blocks that slid down from the mountain during the earth-quake (Figures 3(a)-(c)). The boiled sands we observed in the field have been sun-dried and solidified (Figure 3(d)). The boiled sands, forming jet-like shapes, can be found on the side surfaces of these stone blocks, the largest of which is ~65 cm high (Figure 3(e) and Figure 3(f)), indicating the height of sand spouting at this location (see discussion for detail below).

3.2. Grain Size Distribution of Boiled Sands

Grain sizes of the boiled sands at Loc. 2 were analyzed by a Master Sizer 2000 instrument, and the analytical results are shown in **Figure 4**. The boiled sands consist of fine-grained sands and silts, ranging from 0.01 to <1 mm in grain size. The grain-size distribution is similar to that in boiled sands formed elsewhere during large earthquakes [6] [14], indicating the potential for liquefaction of the fluvial deposits in the flood plain of the Ba-qu River.

4. Discussion

4.1. Timing of Liquefaction

As stated above, the sand boils observed at Locs. 1 - 3 are distributed within and along both sides of the tension cracks that form part of the co-seismic surface rupture zone, and they sometimes form circular sand volcanoes



Figure 3. Photographs of representative sand boils related to the 2010 Yushu earthquake (Loc. 2). (a) Sand boils on a river flood plain along the co-seismic surface rupture zone; (b) Close-up view of (a); (c) Stone block, on the flood plain, topped by boiled sands; (d) Close-up view of the gray fine-grained boiled sand shown in (a)-(c); (e) Close-up view of the stone block, shown in (b), that slid down from the top of the adjacent mountain; (f) Boiled sands on top of the stone block, indicating that the boiled sands spouted up to a height of at least 65 cm, above the height of the block.

(Figure 2). This observation indicates that the liquefaction occurred after the formation of the co-seismic surface ruptures, and that the boiled sands were squirted out from the tension cracks.



Figure 4. Cumulative frequency curves for the grain sizes in the sand boils (samples sand-01 and sand-02) at Loc. 2.

The seismic inversion results reveal an S-wave velocity (Vs) of 3.4 km/s for the Yushu earthquake [21]. Based on the analytic results of seismic reflection-refraction profiles in the eastern Tibetan crust, P-wave velocities (Vp) to depths of 1 - 17 km are calculated to be 5.4 - 6.0 km/s with a Vp/Vs value of 1.73 [22]. As shown in **Figure 5**, the horizontal distance from the epicenter, and the distance directly from the hypocenter to Loc. 2, are calculated to be 43.8 and 45.98 km, respectively. Using the values of 1.73 for Vp/Vs and 3.4 km/s for Vs, Vp is calculated to be 5.88 km/s, and the arrival times for P- and S-waves from the hypocenter to Loc. 2 are 7.82 s and 13.52 s, respectively. We used a focal depth of 14 km for these calculations [23] [24].

The rupture velocity is generally less than that of the P- and S-waves [11]. The average rupture velocity for the 2010 Yushu earthquake is estimated to have been 3.25 km/s for a 16 s rupture process [21]. Therefore, the time required for co-seismic surface rupture formation at Loc. 2 can be estimated to be 14.15 s (Figure 5), which represents a slower velocity than the S-wave velocity. Based on the formula for a free-fall stone block, as shown in Figure 6:

$$L = at^2/2 \tag{1}$$

where *L* in the length of the slope (274 m), g is acceleration due to gravity (9.8 m/s²), a is the sliding velocity of stone block along the slope ($\sin 31^{\circ}$ g), and t is the time taken for the stone block to fall down the mountain to the sand-boil location (10.42 s), assuming the friction resistance of the slope is zero. If we consider the collapse of the stone blocks to have been caused by S-wave shaking, the time taken for the stones to arrive would be 23.94 s after the main shock (which equals the arrival time of the S-wave, plus the time taken for the stone block to drop down to the sand-boil location), 9.79 s after the formation of co-seismic surface rupture in this location.

If the collapse of stone blocks had been caused by P-wave shaking, then the arrival time of stone blocks at the sand-boil location would have been 18.24 s after the main shock (which equals the arrival time of the P-wave, plus the time taken for the stone block to drop down to the sand-boil location), 4.09 s after the formation of co-seismic surface rupture in this location.

Liquefaction is a physical process that occurs during large-magnitude earthquakes, and it may lead to a reduction in strength and stiffness of a saturated granular sand layer. Our findings indicate that the time required to generate liquefaction, subsequent to the formation of co-seismic surface rupture during the Yushu earthquake, was at least 4.07 - 9.77 s, at which time the strength of the sediment was reduced and ground failure started to develop.

4.2. Spouting Heights of Boiled Sands

Boiled sands observed on the ground surface were extruded from water-saturated soil-sand layers in which the





Figure 6. Diagram showing the topographic profile of the mountain slope down which the stone block slid to the sandboil location (Loc. 2).

shear strength approached zero. The extrusion of the boiling soils and sands indicates that high hydro-pressures must have existed in these water-saturated soil-sand layers. If the high pressure of the water-saturated sand had been released rapidly as a result of fluid extrusion, the boiling sand deposits would have been squirted upwards to a certain height above the ground, similar to a volcanic eruption. In fact, water-sand mixtures were reported to have reached heights in excess of 0.9 m above the ground during the 2000 M_s 7.2 Tottori earthquake, western Japan [10]. As noted above, the presence of boiled sands on the top of stone blocks indicates that during the Yushu earthquake, boiled sands were squirted by high hydro-pressures to heights in excess of 65 cm.

5. Conclusions

Based on our observations of liquefaction caused by the 2010 M_w 6.9 Yushu earthquake, and using the data presented above, we arrive at the following conclusions:

1) During the earthquake, the time at which ground strength was reduced to the point of failure, causing liquefaction, was at least 4.09 - 9.79 s after the formation of co-seismic surface ruptures at the sand-boil location. The time scale is in consideration of possibility of either P-wave shaking or S-wave shaking induced liquefaction.

2) During liquefaction, the boiled sands were spouted up by high hydro-pressures to heights in excess of 65 cm. The height of boiled sand provides referable evidence for study of pure pressure status during liquefaction caused by earthquakes.

Our findings help to clarify the relationships between the timing of liquefaction and the spouting height of sand boils during a large-magnitude earthquake.

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