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Near-synchronous and delayed initiation of long run-out submarine sediment flows from a record-breaking river flood, offshore Taiwan

L. Carter

JD Milliman
Virginia Institute of Marine Science

PJ Talling

R Gavey

RB Wynn

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L. Carter,[1] J. D. Milliman,[2] P. J. Talling,[3] R. Gavey,[3] and R. B. Wynn[3]

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[1] Subsea fiber-optic telecommunication cables can break under fast sediment flows that travel 100s of kilometers through the deep ocean in response to earthquakes and submarine landslides. Similar flows are inferred to form from major river floods whose sediment-laden waters plunge and travel along the seabed. However, the complex initiation of flood-related flows and their hazard potential have not been observed until now. Here we use cable fault data from the Gaoping Canyon/Manila Trench off Taiwan to show that a major river flood, formed during Typhoon Morakot (2009), generated two, long run-out, destructive sediment flows; one during peak flood and the other 3 days later. The latter flow was more damaging with speeds and run-out similar to that of landslide-triggered turbidity currents formed in the same catchment. If the second flow was due to remobilized canyon sediment, it occurred during low earthquake (>M_w 2.0) activity, suggesting other triggering mechanisms. **Citation:** Carter, L., J. D. Milliman, P. J. Talling, R. Gavey, and R. B. Wynn (2012), Near-synchronous and delayed initiation of long run-out submarine sediment flows from a record-breaking river flood, offshore Taiwan, *Geophys. Res. Lett.*, *39*, L12603, doi:10.1029/2012GL051172.

1. Introduction

[2] Submarine landslides and sediment flows (a generic term used here for hyperpycnal plumes, turbidity currents and debris flows) are volumetrically one of Earth's key transport mechanisms that transfer large amounts of sediment from coastal seas to the abyssal ocean [e.g., *Talling et al.*, 2007]. Such flows are also a significant natural hazard for seabed infrastructure. Indeed, it was the breakage of trans-oceanic telegraph cables in response to the 1929 Grand Banks earthquake that drew attention to the presence of landslides, debris flows and turbidity currents in the deep ocean [*Heezen and Ewing*, 1952]. However, such flows are difficult to observe because of their destructive behavior [*Inman et al.*, 1976] and there are only a few locations world-wide where such abyssal flows have been measured [e.g., *Mulder et al.*, 1997; *Piper et al.*, 1999; *Khripounoff et al.*, 2003; *Vangriesheim et al.*, 2009; *Hsu et al.*, 2008; *Xu*, 2010].

[3] It has also been inferred that river floods form long run-out sediment flows by the plunging of sediment-laden flood water to the seabed as a hyperpycnal plume [e.g., *Mulder et al.*, 2003]. Using subsea cable breaks, we present evidence of multiple, long run-out sediment flows from a major flood to highlight their complex initiation, with one flow during and another well after the flood's hyperpycnal phase. Such observations add to our sparse knowledge of sediment flow speeds and also reveal the hazard posed by floods to deep ocean infrastructure, in this case the network of fiber-optic cables that carries ca. 95% of trans-oceanic voice, data and internet traffic [*Carter et al.*, 2009].

1.1. Taiwan Setting

[4] Residing between the Eurasian and Philippine Sea plates, Taiwan is one of the most tectonically active regions on Earth [*Liu et al.*, 1997; *Ramsey et al.*, 2006; *Wu et al.*, 2008]. Taiwan also receives monsoonal rains and ca. 3–4 typhoons annually that erode a human-modified landscape [*Chen et al.*, 2004]. Consequently, erosion is impressive [*Dadson et al.*, 2004]; the sediment yield of the island's 16 largest rivers averages ca.10,000 t/km^2/yr [*Kao and Milliman*, 2008], ca. 50 times more than the global average. Moreover, much of the fluvial discharge to the ocean is at hyperpycnal concentrations [*Milliman and Kao*, 2005; *Kao and Milliman*, 2008, *Liu et al.*, 2012].

[5] The main fluvial source for the Strait of Luzon is the Gaoping River whose average sediment discharge is ca. 20 Mt/y [*Kao and Milliman*, 2008]. Historically the Gaoping River tends to reach hyperpycnal thresholds when its discharge is >15,000 m^3/s. This occurred on at least 5 occasions between 1951–2004. The last time was in 1996, but no cable damage was reported. Most of the Gaoping discharge enters Gaoping Canyon [*Huh et al.*, 2009] situated <1 km from the river mouth (Figure 1). The canyon guides sediment to abyssal depths [*Lee et al.*, 2009; *Liu et al.*, 2009; *Yu et al.*, 2009] via a pathway that initially meanders across the continental shelf and upper slope to ca. 1000 m water depth where it switches to a linear course running obliquely along-slope to ca. 2200 m depth (mid-canyon). Here the path meanders across a submarine fan (lower canyon) that extends into the Manila Trench at 3400 m where sediment moves south to >4000 m depth.

2. Data

[6] Non-public information on cable faults comes separately from the various owners and operators of subsea

[1]Antarctic Research Centre, Victoria University of Wellington, Wellington, New Zealand.
[2]Virginia Institute of Marine Science, Gloucester Point, Virginia, USA.
[3]National Oceanography Centre, Southampton, UK.

Corresponding author: L. Carter, Antarctic Research Centre, Victoria University of Wellington, PO Box 600, Wellington 6021, New Zealand. (lionel.carter@vuw.ac.nz)

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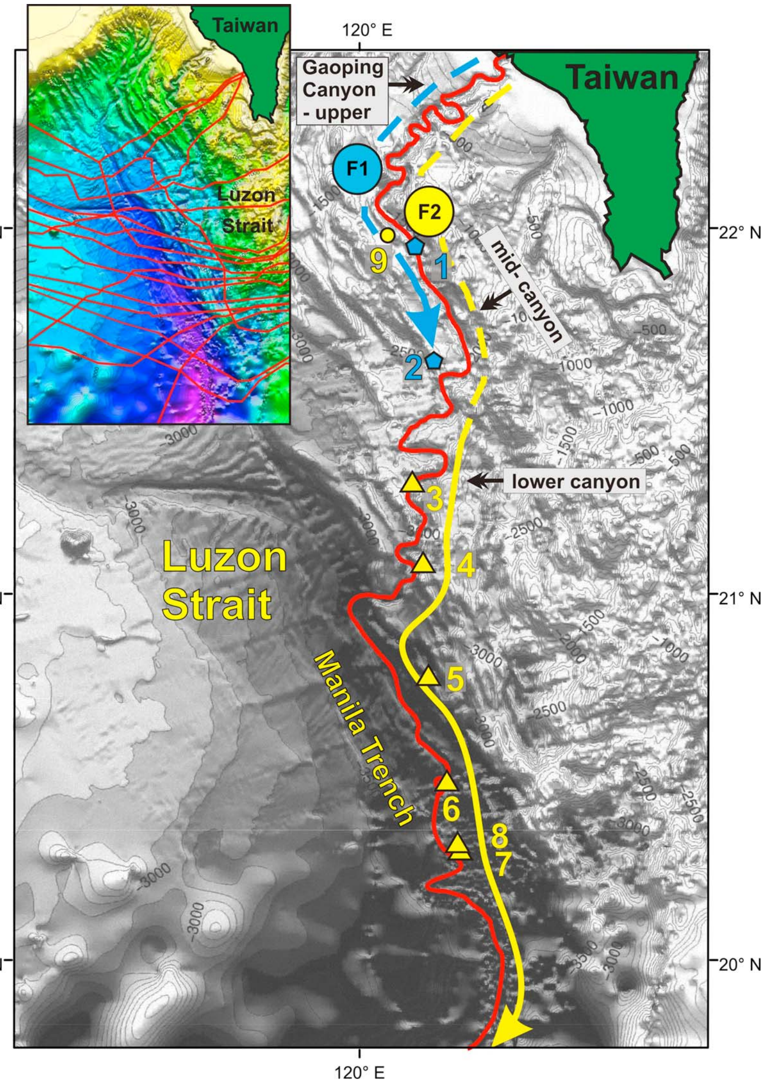

Figure 1. Cable faults along Gaoping Canyon and Manila Trench (axes = red line) during Typhoon Morakot. Cable faults 1–9 are numbered sequentially according to the time of damage. F1 (blue polygons and line) and F2 (yellow triangles and line) refer to Flow 1 and Flow 2 formed from a hyperpycnal plume and remobilized sediments respectively. Cable fault 9 (yellow circle) occurred after Flows 1 and 2 and is discussed in the auxiliary material. Inset is regional metric bathymetry with the approximate positions of fiber-optic telecommunications cables (red lines), which are uncorrected for displacements by sediment gravity flows formed in 2006 [*Hsu et al.*, 2008], 2009 (this study) and 2010.

cables with additional data from cable repair authorities. Locations, depths and times of cable faults are archived in a GIS information system along with multibeam bathymetry used to identify the canyon/trench pathway, which is generally well defined except for the trench south of 20°N (Table 1 and auxiliary material).[1] Distances between cable faults were measured from the canyon head (0 km) along the canyon/trench axis to yield run-out distances of the sediment flows. The times and distances between successive cable faults allowed calculation of flow speeds (i.e., a non-vector rate of motion) that were assessed in relation to seabed slope and run-out distance. Flow data and a solitary suspended sediment measurement for the Gaoping River are from Li-Lin Bridge, which covers 89% of the Gaoping catchment [*Water Resources Agency*, 2010]. Earthquake magnitudes and ground-acceleration data are from the Central Weather

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL051172.

Table 1. Cable Fault Data Used in This Study

Fault	Date	Time UTC	Latitude	Longitude	Flow	Speed m/s
1	9/08/09	02:28	21.95^0	120.17°	F1	Mid canyon
2	9/08/09	03:16	21.65	120.22		16.6.
3	12/08/09	01:47	21.32	120.15	F2	Lower canyon
4	12/08/09	02:45	21.08	120.17		10.3.
5	12/08/09	05:34	20.77	120.20		5.4
6	12/08/09	06:56	20.48	120.25		8.2
7	12/08/09	08:01	20.30	120.28		6.5
8	12/08/09	08:02	20.32	120.28		6.6
9	12/08/09	17:31	21.98	120.08		No info.

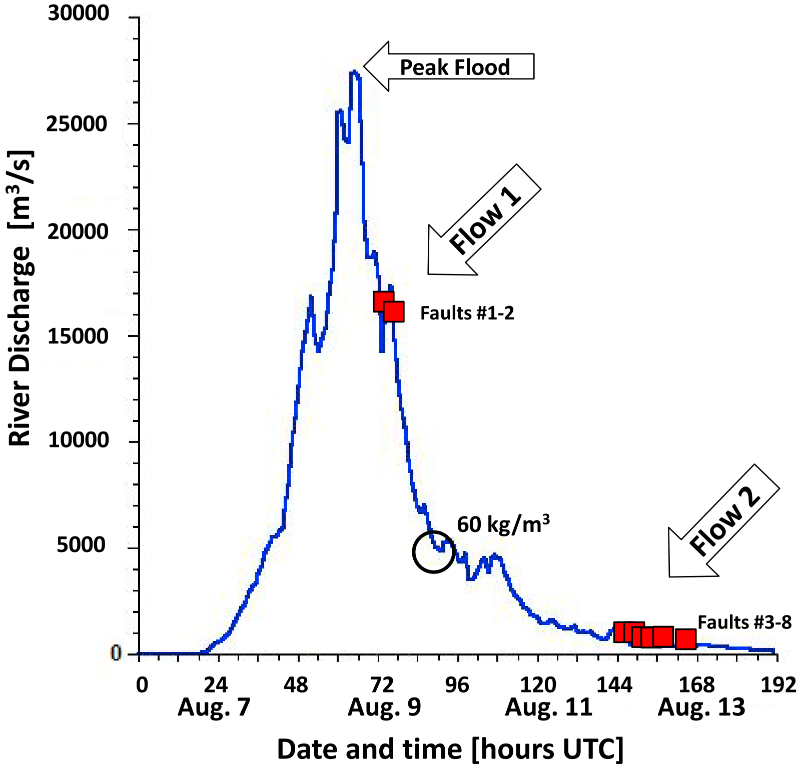

Figure 2. Discharge curve for the Gaoping River during Typhoon Morakot. A single measurement made on 9 August, 2009 (black circle) recorded a suspended sediment load of 60 kg/m^3 [*Water Resources Agency*, 2010]. Such conditions favoured hyperpycnal Flow 1 that subsequently caused Faults #1 and 2. Most cable faults (Faults #3–8) occurred 3 days after the peak flood when the river was near normal. We suggest canyon sediments were remobilized to form the more destructive Flow 2.

Bureau (Climate statistics and earthquakes, 2011, available at http://www.cwb.gov.tw/V6e/index.htm).

3. Observations

[7] On 7–9 August 2009, southern Taiwan was struck by Typhoon Morakot. This was Taiwan's wettest tropical cyclone on record yielding up to 2777 mm of rain in 3 days [*Ge et al.*, 2010]. The Gaoping River discharge exceeded 20,000 m^3/s for over ca. 9 hours and peaked at 27,447 m^3/s (Figure 2). Although reliable data on sediment concentrations are unavailable for those peak conditions, they surely exceeded the 60 kg/m^3 that was recorded on 9 August during waning flood conditions (Figure 2); this concentration surpassing the hyperpycnal 40 kg/m^3 threshold of *Mulder et al.* [2003]. From this single measurement (Figure 2) we tentatively estimate the Gaoping discharged at least 150 Mt of sediment, most of which entered Gaoping Canyon judging by the budget of *Huh et al.* [2009].

[8] On 9 August, the first subsea cables were disrupted by sediment Flow 1 that formed ca. 8 hours after peak flood in the Gaoping River (Figures 1 and 2). While failing to fully break the first cable it met, Flow 1 broke the next 2 cables down-slope where an interim speed of 16.6 m/s was recorded (Figure 3). However, Flow 1 failed to damage cables in water depths >2100 m yielding a run-out distance of ca.168 km, assuming it formed at the canyon head. A second, more damaging Flow 2 occurred 3 days later when the river level was near-normal (Figures 1 and 2). At least 6 cables broke in the lower canyon/trench down to >4000 m depth. The run-out was 157 km, but this was a minimum because the flow source and the run-out distance after the last cable break are unknown. If Flow 2 formed near the canyon head, the run-out was at least 384 km (Figure 1). Flow 2's speed in the lower canyon was 10.3 m/s that reduced to an average of 6.7 m/s in Manila Trench; this change coincident with declining seabed slope and increasing run-out (Figures 3 and 4). Five to six days after peak flood, a 250 m-thick benthic layer of turbid, low-salinity water was detected at 3000–3700 m depth [*Kao et al.*, 2010]. As these measurements post-date Flows 1 and 2, it is unclear which flow created the turbid, low salinity layer. Like *Kao et al.* [2010] we favour a hyperpycnal origin, i.e., Flow 1 whose coincidence with the main flood infers that its freshwater content probably exceeded that of Flow 2.

4. Discussion and Conclusions

[9] Sediment Flows 1 and 2 were related to the extreme fluvial discharge accompanying Typhoon Morakot, but under different circumstances. It is unlikely that earthquakes played a direct role because magnitudes and ground accelerations during the typhoon were very low ($\leq M_W$ 2.0 and 0.8–2.5 cm^2/s respectively (http://www.cwb.gov.tw/V6e/index.htm)). The coincidence of Flow 1 with hyperpycnal conditions (Figure 2) suggest it formed from plunging river water. However, its occurrence ca. 8 hours after peak flood and its apparent high speed (16.6 m/s) does not preclude an ignitive,

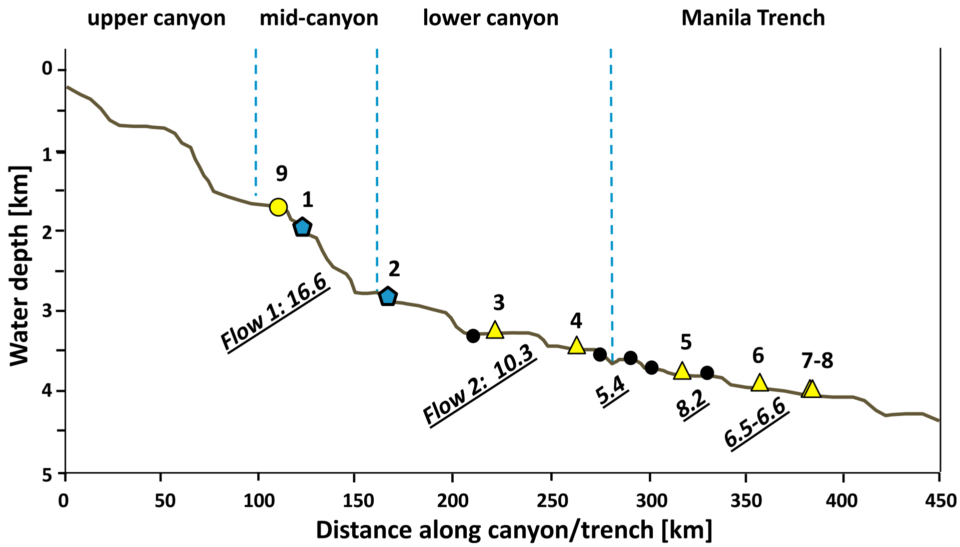

Figure 3. Bathymetric profile along Gaoping Canyon/Manila Trench with flow speeds (underlined and in m/s) between cable faults (1 to 9) caused by sediment Flow 1 (blue polygons) and Flow 2 (yellow triangles) along the mid Gaoping Canyon to Manila Trench. Black circles are cables for which we have no fault data and yellow circle is fault 9, which occurred after Flows 1 and 2 (auxiliary material).

local remobilisation of flood sediment. Indeed the speed is similar to maxima of landslide-triggered turbidity currents, e.g., ca. 19 m/s for 1929 Grand Banks event [*Piper et al.*, 1999] and 20 m/s for the 2006 Gaoping event [*Hsu et al.*, 2008]. Even so, the impact of Flow 1 was confined to 2 mid-canyon cables in water depths <2100 m. In contrast, Flow 2 was more destructive breaking at least 6 cables. Its initiation 3 days after the flood peak is inconsistent with a direct hyperpycnal origin. More likely, Flow 2 came from remobilized sediment. Certainly its speed and associated cable damage resemble that of turbidity currents formed from earthquake-triggered landslides, e.g., 6.7 m/s along the Manila Trench (this study) versus 5.7 m/s along the same trench in 2006 [*Hsu et al.*, 2008] and 6.2–8.2 m/s over the Sohm Abyssal Plain [*Heezen and Ewing*, 1952]. However, low seismicity during Flow 2 suggests an alternative trigger, the nature of which is open to speculation, e.g., turbulence caused by internal or surface waves as observed in Gaoping Canyon [*Lee et al.*, 2009; *Liu et al.*, 2012] or increased excess pore pressures formed within rapidly deposited flood sediment. The source area is also uncertain because mid-canyon cables were damaged by Flow 1 and could not record subsequent events. However, the upper canyon is a possible source because it is a known temporary sink of typhoon flood sediment [e.g., *Liu et al.*, 2006, 2009].

[10] Typhoon Morakot produced the first observed subsea cable damage by a hyperpycnal flow (Flow 1) presumably reflecting the exceptional river discharge caused by the extreme conditions (rainfall 2,777 mm; peak flood 27,447 m^3/s, sediment discharge ca. 150 Mt). The Gaoping River has exceeded the hyperpycnal threshold on previous occasions, the most recent in 1996 when Typhoon Herb produced 1,736 mm of rain [*Ge et al.*, 2010] and the river flow peaked at 19,700 m^3/s. An estimated 48 Mt of sediment was discharged, 56% under hyperpycnal conditions [*Milliman and Kao*, 2005]. Even so, Herb apparently failed to break cables, given the limitations of cable databases (auxiliary material). Hence not all hyperpycnal floods form damaging sediment flows in this system.

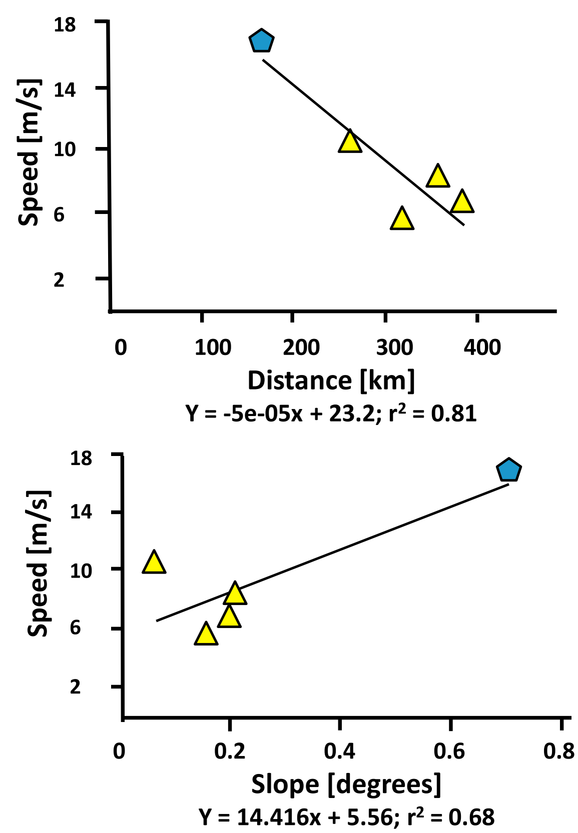

Figure 4. Regression plots for Flow 1 (blue polygon) and Flow 2 (yellow triangles) and their correlation with run-out distance and seabed slope. The regressions assume that Flows 1 and 2 had similar properties, but if the flows were dissimilar then, the value of the regressions are more limited.

[11] If Typhoon Morakot is a harbinger of a warmer, more turbulent climate [e.g., *Kao et al.*, 2010] then determining the impacts of flood-generated submarine flows on a strategic communications corridor takes on a sense of urgency, as does ascertaining their impact on the deep ocean environment through the rapid transfer of heat, nutrients and organic carbon [*Sparkes et al.*, 2010].

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