Sediment production by landslides in Hong Kong: two case studies

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Abstract Landslide studies in Hong Kong are increasingly providing budgets of active debris through the landslide scar and, in some cases, into the stream system. These data are reviewed and two case studies of landslide debris entering the fluvial system are reported. In the first case study, two small landslides of 50 m^3 and 7 m^3 volume occurred above a stream sediment monitoring station, in 2001 and 2003 respectively. While almost all of the debris remained on the slope, both events resulted in increased stream sediment transport in the stream. In the second case study, debris from a 1600 m^3 landslide formed a delta of approximately 200 m^3 upon entering a reservoir. Sediment budgets from the landslides illustrate the role of mass movement in the production of sediment and the coupling of the hillslope and fluvial systems. They provide information on the nature of material delivered to the drainage system and evidence of the selective transport of materials. Possible influences on the controls on sediment production by landslides are also discussed.

Key words Hong Kong; landslide; reservoir sedimentation; sediment budget; suspended sediment properties

INTRODUCTION

Landsliding is an important process on the undeveloped hill slopes, or “natural terrain”, that form more than 60% of Hong Kong’s land area (Ng *et al.*, 2002). These steep, highly weathered, deforested slopes are susceptible to failure during intense summer rain (Evans *et al.*, 1999; Dai & Lee, 2001). Extensive bouldery colluvium deposits dating back to the early Pleistocene show significant landslide activity in the last one million years (Fyfe *et al.*, 2000) and relict landslides have been dated up to 55 000 years before present (Sewell & Campbell, 2004). Some 8804 landslides were identified from 50 years of recent aerial photographs (Evans *et al.*, 1999), and 0.1% of the land area was classed as “well developed landslide” by Styles & Hansen (1989). Little is known about the contribution of sediment from landslides to the fluvial system in Hong Kong, despite its relevance to land managers and drainage service providers. Recent landslide mapping studies are increasingly providing basic budgets of active debris through the landslide scar and provide a measure of debris production by landslides (GEO, 1997; Franks, 1999; Ruse *et al.*, 2002). This paper uses such data to estimate total landslide debris production in Hong Kong and the quantities of sediment transferred into the stream system from some recently studied landslides. Two case studies involving measurements of the transport of landslide-derived sediment in hillstreams are reported.

SEDIMENT PRODUCTION BY LANDSLIDES

The Natural Terrain Landslide Inventory recorded an average of 325 landslides per year on 660 km^2 of natural terrain in Hong Kong (Evans & King, 1998). Field surveys of 80 recent landslides on natural terrain show a combined source area of 18 500 m^2, with a cumulative initial failure volume of 25 000 m^3 (Table 1). If these values are representative, then annually some 75 000 m^2 (0.011%) of Hong Kong's natural terrain fails, displacing some 100 000 m^3 of hillslope material, an average of some 150 m^3 km^{-2} $year^{-1}$.

More detailed mapping information is available for a swarm of landslides that occurred in the Tsing Shan Foothills area on 14 April 2000 (Ruse *et al.*, 2002). Debris from 51 of 121 mapped landslides was channelized, but it was mostly retained along drainage lines, as occurred in two previous larger debris flows in the area (King 1996, 2001). However a significant proportion of debris, 19–71%, was unaccounted for at 11 landslides, predominantly due to removal of material from the landslide trail by fluvial activity (Table 2) as demonstrated by scouring in the drainage line below the point of channelization. The combined estimated source volume of 121 landslides for the 6.5 km^2 study area was 8600 m^3, with a further 3100 m^3 of entrained material, giving a total of 11 700 m^3 (or 1800 m^3 km^{-2}). As 9700 m^3 was deposited within the landslide scars, the remaining total volume of 2000 m^3 is assumed to have been lost to the fluvial system.

Further observations suggest landslide derived sediment may move rapidly through the steep hillslope streams that drain most natural terrain in Hong Kong. Sediment plumes from landsliding have been observed in four reservoirs on 1993 and 1982 aerial photographs (Emery, unpublished) and the formation of deltas and fans of sediments at the outlets of catchments with a high density of landslides indicate high

Table 1 Summary of field data.

Data source	Number of landslides	Combined source area (m^2)	Displaced volume (m^3)
GEO (1998)	40	4 945	4 270
GEO (1997)	20	5 541	7 898
Unpublished fieldwork	20	7 985	12 431
Total	80	18 497	24 599

Table 2 Sediment washed out (m^3) from landslides in the Tsing Shan Foothills.

Example landslide	Source volume	Entrained volume	Washed out volume
LS no. 20	15	20	14
LS no. 37a	70	0	30
LS no. 37b	58	0	30
LS no. 40a	60	0	23
LS no. 40b	52	0	23
LS no. 41	149	0	73
LS no. 44b	80	0	34
LS no. 48	56	3	14
LS no. 54	95	0	38
LS no. 57	45	0	32
LS no.67	40	30	13
Summary of 121 landslides	8600	3100	2000

sediment production. For example the sedimentary rocks at Lai Chi Chong have a high density of landslides (Evans & King, 1998) and a debris fan of about 11.7 ha has developed where the catchment meets the Tolo Channel. The following case studies detail the transport of sediment from landslides in two catchments.

CASE STUDY 1: TAI TO YAN

Study area at Tai To Yan

The first case study area comprises a very small (0.052 km^2) drainage basin located below Tai To Yan, a prominent ridge near Wong Chuk Hang, Hong Kong. The basin is a headwater stream of the Kam Tin River, reaching a maximum elevation of 380 m above Principal Datum (m PD). The average slope gradient is 30°, locally exceeding 50°. The lower part of the basin consists of completely or highly decomposed granodiorite, mostly obscured by colluvium. Volcanic tuffs, with some siltstone and sandstone interbeds, occur upslope, locally as moderately weathered rock outcrops. The vegetation comprises *Dicronopteris* fern, mixed grassland and scrubland.

A recent landslide is evident on 1964 aerial photographs in the upper part (336 m PD) of the study basin, at the head of an ephemeral drainage line. Minor retrogression of the main scarp was observed in the field in 2000. A larger landslide occurred on 9 June 2001, as an extension of the scarp, and further retrogression was also recorded on 5 May 2003. The case study considers the evidence arising from these last two events in 2001 and 2003. The upslope area that contributes water to the source area totals 0.1 ha.

Nearly 100 mm of rainfall was recorded at the nearby Kadoorie Agricultural Research Centre (KARC) from 09:00 on 8 June to 09:00 on 9 June 2001, with subsequent hourly rainfall totals of 68 and 52 mm, in association with a low pressure trough near the South China coast. The monthly rainfall of 1084 mm at the Hong Kong Observatory was roughly three times the normal. The second event was associated with 190 mm of rainfall recorded at KARC between 09:00 on 4 May and 09:00 on 5 May, with an hourly maximum of 40 mm.

Sediment budget at Tai To Yan: hillslope debris

The failures of June 2001 and May 2003 comprised approximately 1 m depth of colluvium with cobbles and boulders. The 2001 landslide source had an estimated volume of 50 m^3 and a debris trail that extended about 20 m below the source. An estimated 52 m^3 total deposition was also recorded as rafts of intact failed material and minor levees of remoulded material along the ephemeral drainage line. The volume of the minor retrogression of May 2003 was estimated to be 7 m^3. The main debris trail was also about 20 m long, with minor wash beyond this, and total deposition was estimated as 14 m^3, which implies both that the landslide reworked material from previous failures and that most of the material remained in storage in the ephemeral drainage line.

Sediment budget at Tai To Yan: stream debris

A sediment sampling station was established in 1993, 620 m from the 2003 landslide scarp at 125 m PD. Suspended sediment from the landslide-inducing rainstorms was sampled at the station both manually and with an ISCO 2700 automatic sampler, and was then separated by filtration using pre-weighed GF/C filter papers. The June 2001 event generated maximum suspended sediment concentrations of around 2900 mg l^{-1}, contrasting with a previous maximum concentration in the basin of 1419 mg l^{-1} (sample size = 566), as well as the much lower peak values during the first rainstorm after the failure (566, 442 and 420 mg l^{-1}). The time series plots of suspended sediment concentration for both storm events show peak values for suspended sediment concentration lagging behind the maximum water level, particularly for the May 2003 event (Fig. 1) and demonstrate anti-clockwise hysteresis. Such a temporal trend is unlikely to arise from differences in travel time between sediment and water peaks because of the small basin size, and is more likely to reflect the time of the landslides within the rainstorms.

Sediment colour results (Fig. 1), determined using standard soil colour charts, indicate that organic topsoil dry-soil colours dominate the normal streamflow suspended sediment colour, such as the dark olive brown or dull yellowish brown colour recorded in the 7 June 2001 storm. From 09:55 h during the rainstorm of 9 June 2001, there was a marked increase in sediment concentration and yellow colours predominated, concurring with the dull yellow/yellowish and light yellow orange colluvial substrate of the landslide source. The event of 5 May 2003 similarly exhibited sediment colours associated with the substrate.

The carbon (C) and nitrogen (N) content of the suspended matter also deviated from normal streamflow conditions during the events. Measurements were made using a Perkin Elmer 2400 elemental analyser, after the sediment was disaggregated and passed through a 250 μm mesh sieve. Figure 1 reveals that the storm of 7 June 2001 and the early part of the 9 June 2001 landslide generating event are characterized by considerably higher C and N contents (e.g. N = 0.5–0.8%), than those observed later in the 9 June event, from around 10:00 h (e.g. N = 0.2%). This decline in C and N content coincides with the large increase in suspended sediment concentration, indicating that the results do reflect landslide debris entering the fluvial system. A similar trend can be observed in May 2003 (Fig. 1).

Despite these results, the C and N values for the suspended sediment derived from landslide debris are still greater than those associated with material in the landslide source, especially the dominant substrate materials. C and N results for the <10 cm thick "organic" topsoil of the landslide source (n = 6) were 2.85 and 0.31%, while C and N contents of the lower substrate colluvium, which comprised around 90% of the failure scar profile, were 0.36 and 0.09%. This apparent enrichment may reflect the selective removal of fines from the failed materials.

Particle size analysis of material from the 2003 debris trail toe also indicates size selective transport. The particle size composition is 12% clay, 64% silt and 24% sand and gravel in the source area, in addition to large amounts of cobbles and large boulders. It changes to 9% clay, 41% silt and 50% sand and gravel at the end of the trail. The relative reductions in clay and silt and a relative increase in the sand content after transport, coupled with evidence of greatly elevated sediment concentrations in the stream, indicate selective removal of the fines from the debris during the landsliding process.

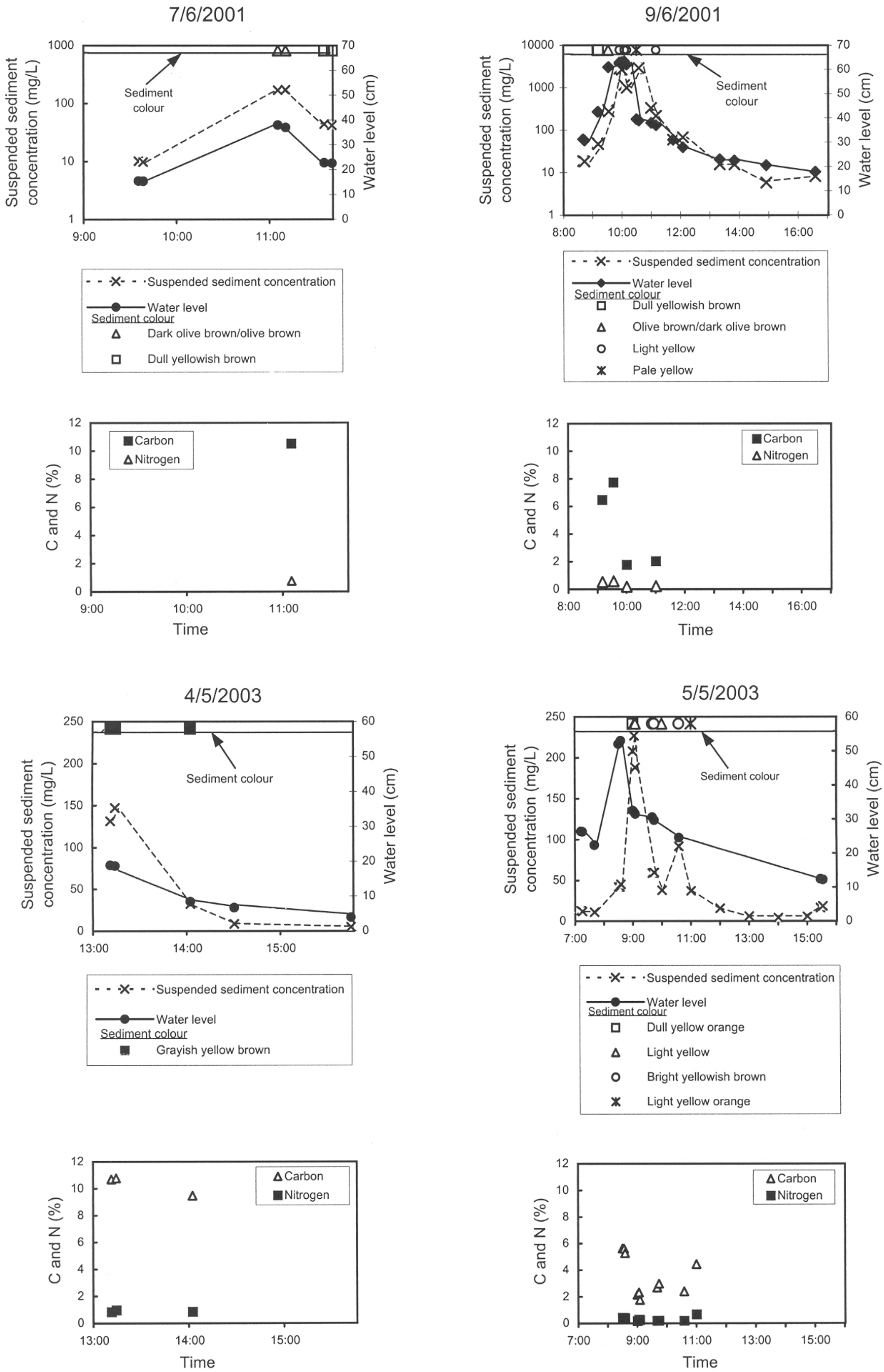

Fig. 1 Temporal variation of water level and suspended sediment properties in the storm events preceding and coinciding with the Tai To Yan landslides.

CASE STUDY 2: PING FUNG SHAN

Study area at Ping Fung Shan

The second case study area is a small (0.38 km^2) upland drainage basin in the northern New Territories, on the western slopes of Ping Fung Shan. The drainage system flows westwards into the Hok Tau Reservoir, in the Pat Sin Leng country park. Slope gradients average 22° but locally exceed 50°, while elevation ranges from 100 m PD at Hok Tau Reservoir to 520 m PD at the crest of Ping Fung Shan. The bedrock geology consists mainly of undivided coarse ash crystal tuffs, with a smaller area of sedimentary sandstones, siltstones and conglomerates in the upper reaches of the basin. Pleistocene debris flow deposits are mapped along the drainage system on the valley floors. Vegetation in the basin is mostly shrubland and grassland, with a small area of woodland.

Three tropical cyclones, Abe, Becky and Dot, affected Hong Kong within a two-week period in September 1993, contributing to a monthly total rainfall of 656 mm, some 356 mm above normal. On 26 September 1993, when Typhoon Dot was closest to Hong Kong, torrential rain was almost continuous and the 300 mm 24-h rainfall represents a 5-year return period at nearby Tai Po Tau (Lam & Leung, 1994). More than 200 landslides occurred on the natural slopes of Ping Fung Shan and nearby Cloudy Hill, and the largest of these is the subject of the present case study.

Sediment budget at Ping Fung Shan

The Ping Fung Shan landslide occurred at 270 m PD, in an area of low shrub and grass, and comprised residual soil and completely decomposed volcanic rock. No previous failure was observed at the site, although there are many past landslides scars in the vicinity. This failure was much larger than those at Tai To Yan, with a source volume of around 1600 m^3. The displaced material was only partially mobilized and thick rafts of intact displaced material were retained immediately below the source. Displaced material, mainly re-moulded debris, formed a temporary dam in a stream course at the slope toe, at a point with a contributing area of 27.1 ha. Field estimates indicate deposition of some 800 m^3 of debris on 100 m of hillslope below the landslide, suggesting that about 800 m^3 reached the stream at the dam site. Some 350 m^3 of this material, particularly cobbles, gravel and sand, were noted along the stream channel between the dam point and the reservoir. A new delta formed some 200 m downstream where the stream enters the Hok Tau Reservoir. A survey of the delta recorded about 200 m^3, predominantly of sand with some coarser materials, when the reservoir was drained for maintenance. There is a contrast between the source material, which is rich in fines, cobbles and boulders, and the particle size of the delta material (1% clay, 6% silt, 56% sand, and 36% gravel with a maximum cobble long-axis of 280 mm). As silt and clay typically form 30% of residual soil/weathered volcanic tuff, it seems reasonable to estimate that of the 800 m^3 washed downstream, some 250 m^3 was fully flushed into the reservoir and the river system as silt and clay. The relative paucity of fines in the delta and in the 200 m of stream channel support the idea of selective transport of material away from the failure.

DISCUSSION

The case studies and examples illustrate that landslide sediment production in Hong Kong is distinctly variable. Landsliding is spatially and temporally clustered, since it is triggered by intense, localized rainfall with long return periods, acting on site-specific landslide susceptibility characteristics (Franks, 1999; Ruse *et al.*, 2002: Parry *et al.*, 2002). Delivery to the fluvial system varies with factors such as landslide volume, nature of the ground surface and proximity to the drainage line (MFJV, 2003). A review of aerial photographs in the Tai To Yan area show that 151 out of 432 landslides reached drainage lines. Of 121 landslides in Tsing Shan, 51 channelized, with the loss of over one sixth of the total landslide volume to the fluvial system.

The mobility of landslide debris within streamlines varies with factors such as the relative proportions of debris and stream flow, as well as position within the catchment. Debris mobility within a stream is significantly influenced by flow magnitude, which in turn reflects the contributing area at the channelization point. This influences, for example, whether a landslide becomes a debris flow or a debris flood (King, 1996). It is perhaps supported by the contrasting presence of fine debris from landslides in some ephemeral channels against the general lack of such material in permanent hillslope channels in Hong Kong.

Variation of sediment properties in transport was noted in the case studies. C and N were preferentially removed from the Tai To Yan debris as a single pulse of elevated stream sediment concentration. Similarly the composition of the Hok Tau delta indicated that sand and fines were travelling further than the coarser fraction at Ping Fung Shan.

For the landslide debris retained on the slopes and along drainage lines, the occasional formation of an erosion ditch (King & Williamson, 2002) may contribute sediment during the later stages of landslide events, but streams running from a landslide scar are commonly clear within a few hours. At Tai To Yan, subsequent rainstorm events recorded suspended sediment maxima well below those of the landsliding events, and recent field observations (July 2004) confirmed no significant change at the Tai To Yan landslide. Only minor reworking of material by rainstorms was observed through the 2001 wet season during the mapping of the Tsing Shan Foothills landslides, particularly in the formation of local rills and soil fingers. Some of the finer material probably washes out in subsequent rainfall events, entering the fluvial system over time, while some material may be retained on the slope until eroded and entrained by subsequent landslides.

CONCLUSIONS

Sediment budgets were presented for two case studies on undeveloped slopes in Hong Kong. Each of the landslides was associated with intense rainfall and demonstrated linkage between the hillslope and fluvial systems. However, while the Tai To Yan case showed that most of the material from the two failures remained in storage close to the source, the much larger landslide at Ping Fung Shan showed much greater transport in the fluvial system. Possible general influences include site specific initiation characteristics, size of failure, distance from drainage lines and position within the catchment with respect to likely streamwater discharge characteristics. Evidence of the selective transport of materials from the landslide debris by streams has also been presented. For each landslide event, the sediment monitoring station at Tai To Yan recorded a pulse of elevated suspended sediment concentration, on one occasion reaching more than double the highest previous recorded concentration, in addition to enrichment of C and N percentages in comparison to source materials. Clear evidence is also given of sediment provision to the fluvial system, of partial storage of sediment in drainage lines and in reservoirs, and of selective removal of fines.

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