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Short communication

Anthropogenic disruption to the seismic driving of beach ridge formation: The Sendai coast, Japan

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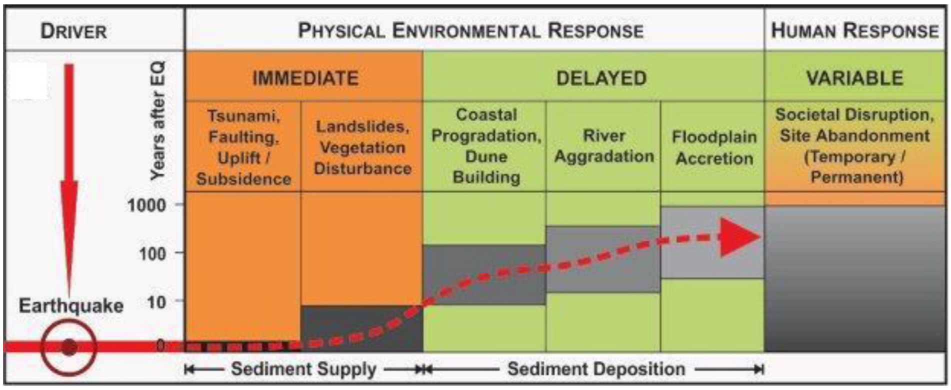
HIGHLIGHTS

- The Tōhoku-oki earthquake led to seismogenic landslides inland.
- Seismogenic sediments are reworked through river systems to the coast.
- River dams are capturing these sediments, reducing sediment supply to the coast.
- Reduced coastal sediment supply is increasing tsunami risk.
- Engineering of river systems is making coastal engineering more necessary than ever.

GRAPHICAL ABSTRACT



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ABSTRACT

The expected geomorphic after-effects of the M_w 9.0 Tōhoku-oki earthquake of 11 March 2011 (eastern Japan) are summarized by a schematic model of seismic driving, which details seismogenic disturbances to sediment systems that affect the rate or timing of sediment delivery to coastlines over timescales of 10^2–10^4 years. The immediate physical environmental responses to this high-magnitude earthquake included a large tsunami and extensive region-wide slope failures. Normally, slope failures within mountain catchments would have significant impacts on Japan's river and coastal geomorphology in the coming decades with, for example, a new beach ridge expected to form within 20–100 years on the Sendai Plain. However, human activity has significantly modified the rate and timing of geomorphic processes of the region, which will have impacts on likely geomorphic responses to seismic driving. For example, the rivers draining into Sendai Bay have been dammed, providing sediment traps that will efficiently capture bedload and much suspended sediment in transit through the river system. Instead of the expected ~1 km of coastal progradation and formation of a ~3 m high beach ridge prior to the next large tsunami, it is likely that progradation of the Sendai Plain will continue to slow or even cease as a result of damming of river systems and capture of river sediments behind dams. The resulting reduction of fluvial sediment delivery to the coast due to modification of rivers inadvertently makes seawalls and other engineered coastal structures even more necessary than they would be otherwise.

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1. Introduction

Terrestrial sediment systems such as rivers, slopes and coastal cells are known to exhibit complex responses to a range of external forcings that may include volcanic eruptions, earthquakes, tropical cyclones, wildfires, climate change, and anthropogenic disturbance (Brooks and Brierley, 1997; Evans, 1997; Terry and Raj, 1999; Shakesby and Doerr, 2006; Walling, 2006; Knight and Harrison, 2009, 2013). Both the forcing mechanisms and the responses of sediment systems operate over different spatial and temporal scales, and these systems are strongly affected by internal nonlinear feedbacks and time lags (Phillips, 1992, 2009; Harvey, 2002; Hooke, 2007; Houben et al., 2012). The operation of feedbacks and time lags means that systems' dynamics commonly have low predictability, in particular with respect to the timing and magnitude of sediment pulses that represent the net response of the system to forcing (Temme and Veldkamp, 2009; Frisbee et al., 2012). River sediment systems have been evaluated with respect to sediment budgets, calculated as the net sediment volume response to wholesale catchment disturbance (Slaymaker et al., 2003; Walling, 2006; Parsons, 2011; Hinderer, 2012). These previous studies, however, cannot easily resolve within-catchment variations in sediment yield driven by episodic events (e.g., rainstorms, landslides) or spatial variations in catchment modification driven by deforestation or urban development (Brierley et al., 2006; Fryirs et al., 2007). The net result is that there is considerable spatial and temporal variation of within-catchment sediment yield (Evans, 1997; Schiefer et al., 2010; Hinderer, 2012), with hysteresis and lag effects (Harvey, 2002; Temme and Veldkamp, 2009; Houben et al., 2012), irrespective of the type, scale and magnitude of forcing (Brooks and Brierley, 1997; Phillips, 2009).

These concepts are of particular relevance to examining slope and fluvial sediment systems that are disturbed by seismic events. For example, landslides within mountain catchments are commonly triggered by earthquakes, but these landslides can vary substantially in size, internal sedimentary composition, runout length, location within the catchment, and connectivity to any river channel. As a result, there is a nonlinear and lagged relationship between seismogenic landslide density (number of landslides per unit area)/magnitude (volume or area of landslide), and catchment sediment response (e.g., Dadson et al., 2004; Korup, 2005; Zhu et al., 2011). Furthermore, landslide dams can dramatically alter river system connectivity and thus any time lags between landsliding and resultant changes in river sediment yield (Korup, 2005; Korup et al., 2006). Sediment connectivity modelling is a key element in predicting sediment transport capacity and sediment yields within such disturbed catchments (e.g., Brierley et al., 2006; Bracken et al., 2015).

Japan, as a tectonically active and mountainous region, has a close genetic association between earthquakes and landslides (e.g., Ayalew et al., 2011). Furthermore, tectonic forcing has been explicitly invoked as a driver of long term changes in sediment flux from the Japanese mountains (Korup et al., 2014). For example, earthquake-induced landslides and debris flows can act as significant point sources of sediments within river systems (Oguchi et al., 2001; Lin et al., 2008), but these events are superimposed on longer-term tectonic uplift that drives land surface weathering and river incision (Carter et al., 2010). Oguchi et al. (2001) cite an example of the 1984 Nagano-ken Seibu earthquake (M_w 6.8) which resulted in five significant mountain landslides with a cumulative volume of 36 million m^3 (Okusa et al., 1986, 1987). Downslope of these landslides, debris flows with a velocity of <70 km h^{-1} formed 30–40 m thick colluvial fans within valleys (Okusa et al., 1987). Such mass movements are associated with dam failures and significant geomorphic change of individual river systems (Oguchi et al., 2001). It is notable that Japan exhibits a greater proportion of coastal plain (15%) relative to other parts of the world (5%; Yoshikawa et al., 1981), which is indicative of this very high fluvial sediment supply.

At a catchment scale, Goff and McFadgen (2002) presented a Seismic Driving Model (SDM) that conceptualises the sediment system links between a number of seismogenic processes, including landslides, fluvial sediment transport, river channel aggradation, floodplain accretion, coastal progradation and beach ridge formation. These processes combine to create a 'staircase sequence' of geomorphological responses in the landscape over time following a large earthquake (Fig. 1a). The size of earthquakes required to drive such downstream morphological and sedimentary impacts depends on topography and substrate properties, but it is notable that the very large landslides from the Nagano-ken Seibu earthquake took place on weak, weathered pyroclastic rocks, tuff and pumice (Okusa et al., 1986).

Critical to the functioning of the SDM is sediment connectivity within river systems, whereby mountain-derived sediments can be transported to fronting coasts, and ultimately to deep sea fans (e.g., Carter et al., 2010). A distinctive expression of such seismogenic sediment connectivity on high sediment-supply, prograding coasts is the formation of beach ridges. Although beach ridges can form under different coastal conditions (Tamura, 2012), studies have identified the seismic driving of beach ridge formation on the coastlines of several tectonically active countries, including Peru (Moseley et al., 1992), Japan (Goff and Sugawara, 2014) and New Zealand (Wells and Goff, 2006, 2007). The beach ridges formed in this context are an expression of (1) the seismogenic origin of invigorated sediment systems, and (2) the integrated connectivity of the systems responsible for sediment transport. Beach ridges developed in fine sediments provided by this temporal sequence of hillslope, fluvial and marine processes may ultimately form many decades after the initial earthquake event (Wells and Goff, 2006, 2007), which may represent the timeframe of sediment transport pathways from source to sink in such tectonically-active settings. The SDM is conceptually similar to models of paraglacial landscape relaxation in deglaciating mountains (Ballantyne, 2002; Knight and Harrison, 2014), in which episodic landscape disturbance resulting from landslides, rockfalls and slope-driven instability of glacial sediments (Schrott et al., 2002; Schlunegger et al., 2009) enhances fluvial sediment supply, which can contribute to sediment accumulation along fronting paraglacial coasts (Knight and Harrison, 2009, 2014). The SDM is therefore well-founded in this wider context of source-to-sink studies.

2. Variable time lags

Time lags in delayed environmental responses to seismic driving events are highly variable. For example, Moseley et al. (1992) reported the growth of a new beach ridge at the mouth of the Rio Santa in the arid region of north central Peru. They used satellite imagery to chart sediment transfer following a M_w 7.7 earthquake in 1970. The earthquake caused numerous landslides that produced an excess of sediment in the upper basin. But it was not until heavy rains and elevated river discharges during the strong El Niño of 1972–1973 that the river was capable of transporting the bulk of this material downstream. The steep ~100 km-long river channel meant that a new sand beach ridge had already formed by 1974. This short (5 year) time lag contrasts with longer time lags observed elsewhere, such as on the west coast of New Zealand, where multiple catchments along hundreds of kilometres of coastline showed beach ridge formation 10–50 years after the initial fault rupture (Wells and Goff, 2007), 100–200 years on New Zealand's east coast (McFadgen and Goff, 2005), and 20–100 years for the Sendai Plain in the north east of Honshu Island in Japan (Goff and Sugawara, 2014). Variability in time lags until beach ridges develop appears to relate mainly to differences in steepness and length of the individual catchments affected, which is also consistent with paraglacial sediment yield models (Ballantyne, 2002).

Here, we highlight an issue in interpreting the location, timeframe and forcing mechanism of seismogenic beach ridges, which is that of river system modification by dams. Japan's rivers are highly engineered by check dams. Studies have explored the influence of these dams on bedload sediment supply to coastlines (suspended and dissolved river