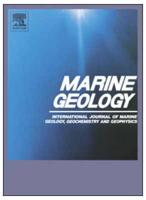
Marine Geology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo



Which earthquakes trigger damaging submarine mass movements: Insights from a global record of submarine cable breaks?

Ed L. Pope [a,*], Peter J. Talling [a], Lionel Carter [b]

[a] *National Oceanography Centre, Southampton, European Way, Southampton SO14 3ZH, UK*
[b] *Antarctic Research Centre, Victoria University of Wellington, Wellington, New Zealand*

ARTICLE INFO

Article history:
Received 23 July 2015
Received in revised form 14 January 2016
Accepted 18 January 2016
Available online xxxx

Keywords:
Submarine mass movements
Earthquakes
Cable breaks
Palaeoseismology
Peak ground acceleration
Hazards

ABSTRACT

Submarine landslides, debris flows and turbidity currents are significant geohazards for seafloor infrastructure in many locations around the world. Their deposits potentially provide a valuable record of major earthquakes, which extends further back in time than most terrestrial earthquake records. It is therefore important to determine their frequency and triggering mechanisms, and what types of earthquake trigger submarine slides and flows in different settings. Submarine cable breaks provided the first evidence of submarine mass movements, as shown by the 1929 Grand Banks earthquake. Even now the global network of subsea telecommunication cables provides our only means to monitor flows globally. Here, we present the first global analysis of the occurrence of submarine mass movements caused by earthquakes using cable break data. Using a global database of subsea fibre-optic cable breaks we identify earthquakes that triggered (and did not trigger) submarine mass movements from 1989 to 2015. We note that cable breaks are not a perfect record of submarine mass movements, and may only record more powerful ($>\sim 2$ m s^{-1}) flows. However, our results show, in contrast to previous assertions, that there is no specific earthquake magnitude that systematically trigger mass flows capable of breaking a cable. Some earthquakes with magnitudes >7.0 M_w triggered cable breaking flows, but many >7.0 M_w earthquakes have failed to break nearby cables. We also show that some very small (3.0–4.0) magnitude earthquakes are capable of triggering cable breaking flows. The susceptibility of slopes to fail as a consequence of large and small earthquakes is dependent on the average seismicity of the region and the volume of sediment supplied annually in addition to other preconditioning factors such as slope architecture and mechanical sediment properties.

1. Introduction

Since the laying of the first submarine cables in 1842, this technology has acted as a detector of natural hazards in the ocean (Carter et al., 2012). Indeed, even now there have been relatively few studies where submarine mass movements have been directly monitored, and those that have are limited to only a few locations globally (Khripounoff et al., 2003; Andrieux et al., 2013; Cooper et al., 2013; Xu et al., 2014). The use of submarine cable breaks therefore still plays a crucial role in understanding submarine mass movements in different areas around the world (Heezen and Ewing, 1955; Heezen et al., 1964; El-Robrini et al., 1985; Piper et al., 1999; Hsu et al., 2008; Carter et al., 2012; Talling et al., 2014).

Turbidity currents, and other types of submarine sediment density flow (Talling et al., 2012) can travel at speeds of 3 up to 19 m s^{-1} for hundreds of kilometres. These flows represent a significant geohazard for submarine telecommunication cables and other seafloor infrastructure including that for the recovery of hydrocarbons (Carter et al., 2009; Parker et al., 2009). These submarine cables now carry >95% of global data and communication traffic, giving them considerable strategic importance. Large submarine landslides also have the potential to generate damaging tsunami (Tappin et al., 2001; Haflidason et al., 2005; Boe et al., 2007; Tappin et al., 2014). Determining the frequency and triggers of these mass movements is key to submarine geohazard assessment.

A number of possible triggering mechanisms have been identified for submarine mass movements. Earthquakes, storm and tsunami wave loads, rapid depositional loading, hyperpycnal flows, volcanism and gas hydrate dissociation have all been identified as possible triggers (Adams, 1990; Mulder et al., 2003; Shanmugam, 2008; Piper and Normark, 2009; Stigall and Dugan, 2010; Talling, 2014). Despite identifying multiple triggers, there have been few occasions when a precise trigger for an event has been identified. In most case studies where a triggering mechanism has been identified, the trigger was identified using cable breaks.

1.1. Previous studies using cable breaks

Numerous studies have used cable breaks to study individual submarine mass movements (Heezen, 1956; Heezen et al., 1964; Heezen and Johnson, 1969; Krause et al., 1970; Piper et al., 1999; Hsu et al.,

---

* Corresponding author.
E-mail address: ed.pope@noc.soton.ac.uk (E.L. Pope).

http://dx.doi.org/10.1016/j.margeo.2016.01.009

Please cite this article as: Pope, E.L., et al., Which earthquakes trigger damaging submarine mass movements: Insights from a global record of submarine cable breaks?, Marine Geology (2016), http://dx.doi.org/10.1016/j.margeo.2016.01.009

2008; Carter et al., 2012; Cattaneo et al., 2012; Su et al., 2012; Ratzov et al., 2015). Earthquakes, hurricanes and hyperpycnal flows have all been identified as triggering mechanisms for submarine mass movements using cable breaks. The classic example is the 1929 Grand Banks submarine landslide. This submarine landslide was triggered by a M_w 7.2 earthquake (Heezen and Ewing, 1952; Piper et al., 1999). More recently cable breaks identified multiple submarine landslides offshore Algeria triggered by the 2003 Boumerdès earthquake (Cattaneo et al., 2012), whilst multiple submarine flows were caused by the 2006 Pingtung earthquake offshore Taiwan (Carter et al., 2012). In these cases, geophysical and shallow cores have corroborated the cable break data showing cable breaks can be used as proxy for mass flow triggering. Submarine cable breaks were also used to identify the occurrence of turbidity currents offshore Oahu, Hawaii as a result of the passing of Hurricane Iwa (Dengler et al., 1984). The passing of Typhoon Morakot over Taiwan in 2006 did not generate a submarine mass movement itself; it did, however, generate an exceptional discharge from the Gaoping River which generated a hyperpycnal flow (Kao et al., 2010). This was followed a few days later by the main flow triggered by failure of the recently deposited sediment (Carter et al., 2012). Cable break studies have also provided us with unique insights into submarine mass movement dynamics. Sequential breaks in networks of cables have enabled turbidity current flow speeds to be calculated (Heezen and Ewing, 1952; Piper et al., 1999; Carter et al., 2012).

In spite of the insights afforded by breaks to submarine cable networks, no study has previously been able to analyse the frequency and triggering mechanisms of submarine mass movements globally. Here, for the first time we have access to a global compilation of cable breaks over 25 years. The compilation allows us to analyse precisely what triggers and does not trigger submarine mass movements globally and identify whether these triggers are regionally specific or act at the global scale.

1.2. Turbidite palaeoseismology

Earthquakes and their related hazards (tsunami, fire, etc) are predicted to claim >2.5 million lives during the 21st century (Holzer and Savage, 2013). Efforts to reduce losses use estimates of earthquake size and recurrence. To achieve this, palaeoseismology attempts to extend the earthquake record beyond the instrumental record. One method of extending the earthquake record is turbidite palaeoseismology (Adams, 1990; Gràcia et al., 2013). This approach relies on discriminating between the mechanisms, which trigger turbidity currents and the resulting deposits (Goldfinger, 2011; Gràcia et al., 2013). It is achieved by (1) establishing synchronous triggering of sediment gravity flows over large areas using correlation of core deposits (Adams, 1990; Beck et al., 2007; Goldfinger, 2011; Patton et al., 2013; Atwater et al., 2014), (2) identifying specific seismo-turbidite facies within core deposits (Nelson et al., 1995; Goldfinger et al., 2012; Talling, 2014), (3) confluence tests (Adams, 1990), and (4) linking onshore geological records with offshore core data (Nanayama et al., 2007). The methods for testing whether a turbidite is earthquake triggered are summarised in Table 1.

Robust reconstruction of earthquake histories requires (1) deposits to be precisely dated; (2) the sedimentary regime of the region to be well constrained; (3) the sedimentary record to be complete; and (4) knowledge of which magnitude earthquakes do and do not trigger sediment gravity flows (Atwater and Griggs, 2012; Sumner et al., 2013; Atwater et al., 2014). Of these requirements, understanding which magnitude earthquakes do (and do not) trigger submarine mass movements is of critical importance. Onshore, landslides triggered by earthquakes can be directly observed (Keefer, 1984). From observations onshore it is possible to link different earthquake magnitudes, distances from hypocentres and changes in local geology to mass movements (Keefer, 1984, 2002; Owen et al., 2008). In contrast, it is more problematic to identify the occurrence or extent of well-dated synchronous mass movements in the marine environment. Access to a global submarine cable fault dataset provides the first opportunity to attempt such a study offshore.

Table 1
Methods for testing whether a turbidite is earthquake triggered.
After Talling (2014).

How do you know if a turbidite records earthquake triggering?	Comment
1. Confluence test: Same number of turbidites on upstream and downstream sides of confluence indicates synchronous wide-spread triggering. Origin of flow is too widespread for other triggers of synchronous turbidity currents, such as cyclones that can produce hurricane-force winds across distances of several hundred kilometres.	Number of turbidites can vary with height above channel flow as flow thickness is variable. It is difficult to precisely locate cores (e.g. at a consistent height above the channel floor) using ship-mounted coring methods.
2. Synchronous deposition of turbidites in multiple basins indicates widespread slope failure. Origin of flow is too widespread for other triggers of synchronous turbidity currents.	Uncertainties in dating 'synchronous' turbidites
3. Turbidite volume is much larger than that expected for other trigger mechanisms such as river floods.	Deposit volume is rarely precisely known. Note that flows may incorporate sediment and increase their volume, through conduit erosion. Processes other than earthquakes can have the potential to trigger large landslides.
4. Earthquake and turbidite timing is independently well known, as timing observed directly – or in the case of earthquakes – through reliable historical records.	Cable breaks or mooring data may be needed to date turbidity currents precisely, as other methods (e.g. ^{210}Pb or ^{137}Cs) profiles of 'recent' turbidites have greater uncertainties. Ideally, repeat coring or mapping of the seafloor is needed to establish timing of turbidite emplacement. 4 is generally more reliable than 1-to-3.
5. Multiple stacked fining upward sequences inferred to be characteristic of earthquake triggered turbidites, as failure occurs in many locations across a wide area.	The grading pattern is not strongly diagnostic as multiple fining upward sequences can also result from multi-stage slope failure, flow reflection, or pulsing hyperpycnal flows.

1.3. Aims

Two main questions are posed. First, which magnitude earthquakes do (and do not trigger) submarine mass movements that break cables and does this vary on a regional basis? Second, do other parameters such as local sediment supply need to be assessed as part of turbidite palaeoseismology rather than just ground shaking (e.g. earthquake magnitude/peak ground acceleration)?

2. Terminology

Throughout this study the term 'cable break' or 'break' is used. Here we use these terms to refer to clean breaks and other faults in the cables. Faults can result from damage to a fibre-optic cable casing that allows the ingress of seawater and shorting of the power supply and/or stretch the cable to a point where optical fibres are damaged (Burnett et al., 2013).

We use the term *submarine mass movement* to denote an overall flow event driven by the excess density of the sediment that it contains. *Submarine mass movements* can refer to *turbidity currents*, *debris flows*, *hyperpycnal flows*, *slumps* and *landslides*. Transformation may occur between these different flow types as the submarine mass movement evolves. For further information on terminology for different types of flow see Talling et al. (2012). We refer to *submarine mass movements* and later *mass flows* as the cable break database only donates that a

Please cite this article as: Pope, E.L., et al., Which earthquakes trigger damaging submarine mass movements: Insights from a global record of submarine cable breaks?, Marine Geology (2016), http://dx.doi.org/10.1016/j.margeo.2016.01.009