Sedimentary Geology 290 (2013) 175–187

Contents lists available at SciVerse ScienceDirect

Sedimentary Geology

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

Experimental modeling of depositional turbidity currents in a sinuous submarine channel

Hesham Ezz [a], Alessandro Cantelli [b], Jasim Imran [a,*]

[a] Department of Civil and Environmental Engineering, University of South Carolina, Columbia, SC, USA
[b] Shell Exploration & Production, 150. N Dairy Ashford, Houston, TX 77079-1197, USA

ARTICLE INFO

Article history:
Received 7 August 2012
Received in revised form 21 March 2013
Accepted 22 March 2013
Available online 29 March 2013

Editor: J. Knight

Keywords:
Turbidity currents
Submarine channels
Flow stripping
Apron
Sediment wedge

ABSTRACT

Submarine channels with intricate meandering patterns and extensive levees are recognized as products of density-driven flows known as turbidity currents. Compared to the fluvial meandering channels, understanding of the flow and morphodynamics of submarine channels is limited. In this paper, we present experimental results on the morphodynamic and stratigraphic evolution of a submarine channel from sedimentation due to the passage of successive flow events. A pre-formed sinuous channel with multiple bends, a trapezoidal cross section, and an initial thalweg slope of 0.43° was emplaced in a large tank. A total of 29 runs, each lasting an hour, were made by releasing heavier fluids containing salt and silica powder at a constant rate in the tank filled with fresh water. The overbank flow was restricted to curvature-induced flow stripping.

The following observations were made from the experimental measurements; (i) asymmetric channel cross sections developed due to higher deposition rates on the outer bank of the channel bends, (ii) an apron or sediment wedge with overlain bedforms appeared near the channel entrance that prograded and aggraded with successive runs, (iii) overbank flow due to flow stripping at bend apices resulted in lobe-shaped deposits, (iv) a higher concentration of solute resulted in flow confinement, and (v) the flow velocity during later runs increased due to channel narrowing and steepening of the gradient.

1. Introduction

Submarine channels have been studied extensively by interpreting outcrops, 2D seismic, sonar, and core data during the past several decades (e.g., Menard, 1955; Komar, 1969; Chough and Hesse, 1980; Piper and Normark, 1983; Hay, 1987a,b; Clark et al., 1992; Pirmez and Flood, 1995; Peakall et al., 2000). Many submarine channels display remarkable similarities with meandering rivers in terms of planform characteristics such as sinuosity, wave-length-width ratio, and non-dimensional curvature (e.g., Pirmez and Flood, 1995; Clark and Pickering, 1996; Straub et al., 2008). Recent studies using 3D seismic data have revealed considerable diversity in their internal architecture and scale, as well as important similarities and differences with subaerial meandering rivers (e.g., Deptuck et al., 2007; Kolla et al., 2007). Process and facies models of submarine channel morphology have been derived from the interpreted field data as well as observations made in the fluvial environment (e.g., Clark and Pickering, 1996; Peakall et al., 2000). Observations of submarine channel morphodynamics in a controlled environment are necessary to validate these models.

Turbidity currents are known to be responsible for the formation of vast sedimentary deposits on the seafloor. Suspended sediments provide a density contrast with the ambient fluid that acts as the driving mechanism of these currents. The density difference between a turbidity current and the ambient fluid, however, is small. Due to this reason, submarine channels and their levees can aggrade vertically in time without experiencing frequent avulsion (Imran et al., 1998; Cantelli et al., 2011). For the same reason, the superelevation of flow height becomes highly exaggerated when the current passes through a channel bend (e.g., Komar, 1969; Imran et al., 1999; Straub et al., 2008; Kane et al., 2010). The nearly vertical aggradation of the channel forms requires rates of overbank sedimentation that are comparable to those within the channels (Straub et al., 2008). This in turn would require that the flow and the channel geometry approach an equilibrium condition.

Two types of mechanisms are considered to be mainly responsible for turbidity currents to overflow out of the channel: overspill, independent of channel curvature (Clark and Pickering, 1996; Peakall et al., 2000; Straub et al., 2008), and flow splitting or stripping at a channel bend as the flow tends to move in the pre-bend direction (Clark and Pickering, 1996; Imran et al., 1999; Peakall et al., 2000; Straub et al., 2008). The height or thickness of a turbidity current can easily exceed the channel relief due to entrainment of ambient water at the upper interface, and cause the upper dilute part of the current

* Corresponding author.
E-mail address: imran@cec.sc.edu (J. Imran).

0037-0738/$ – see front matter
http://dx.doi.org/10.1016/j.sedgeo.2013.03.017

to flow to the overbank area. Overspill leads to the loss of finer sediment fractions that are available at the upper part of the flow. Deposits resulting from overspill lead to massive mud-rich levees observed on large submarine fans (e.g., Pirmez and Imran, 2003). Flow stripping, also known as flow splitting, is an interesting feature of channel flows. Aided by an exaggerated superelevation near the bend apex, a turbidity current may split, leading to the establishment of a flow towards the outer overbank area (e.g., Piper and Normark, 1983; Peakall et al., 2000; Kassem and Imran, 2004; Islam et al., 2008; Straub et al., 2008; Kane et al., 2010; Straub et al., 2011). The part of the flow that leaves the channel continues to flow in the pre-bend direction (Normark and Piper, 1984; Islam et al., 2008).

Direct measurements of turbidity currents in the field are rare due to the episodic nature of these flows (Amos et al., 2010). Notable exceptions include the work of Hay (1987b), Khripounoff et al. (2003), and Xu (2004). In recent years, advances in laboratory experiments and numerical modeling have enabled researchers to pursue quantitative research on the dynamics of turbidity currents in sinuous submarine channels (e.g., Imran et al., 1999; Kassem and Imran, 2004; Keevil et al., 2006; Imran et al., 2007; Islam, 2007; Islam et al., 2008; Kane et al., 2008; Straub et al., 2008; Amos et al., 2010).

A limited number of experimental studies focused on geomorphic implications of density flows in a pre-formed sinuous or curved channel of relatively small scale (e.g., Peakall et al., 2007; Straub et al., 2008; Amos et al., 2010; Kane et al., 2010; Straub et al., 2011). Straub et al. (2008) studied the morphology of an aggrading sinuous submarine channel due to the passage of turbidity currents generated by the successive release of sediment-laden flows. Peakall et al. (2007) and Amos et al. (2010) studied the re-organization of bed sediment inside a submarine channel due to the passage of salt-laden flows. They interpreted the re-organization of the sediment beds as point bars appearing downstream of the bend apex. Straub et al. (2011) studied the effect of channel sinuosity on depositional mechanism of turbidity current. They suggested that higher channel sinuosity is conducive to reducing stratification and thus improving transport efficiency of turbidity currents. They also concluded that when the flow kinetic energy exceeds the potential energy coupled with a gain in elevation similar to channel relief, the current is unlikely to remain contained inside the channel.

The objective of the work reported here is to study the morphological evolution of a sinuous submarine channel and its overbank areas under successive long-duration flows. The research is focused on addressing the following questions: (i) how does the overbank area aggrade relative to the channel bed? (ii) what are the characteristics of overbank deposit resulting from flow stripping? and (iii) what are the effects of inflow condition on sedimentation pattern? Experiments were conducted using gravity flows driven by a mixture of salt and silt in a sinuous channel with an initial slope of 0.75% along the channel axis. The current propagation during the experiment was recorded, and bed elevations were measured at regular intervals. The stratigraphic record was investigated by slicing the deposit along the channel centerline at the end of the experiments. In the following sections, we describe the method followed by experimental results, discussion, and conclusion.

2. Method

2.1. Experimental setup

The design of the experiment was based on an analog modeling approach (Hooke, 1968). Analog models are not scaled from a specific prototype, but they aim to reproduce the general processes and features of a natural system (Chorley, 1967; Peakall et al., 2007). The size of the model is often dictated by the size of the available facility. In the case presented here, the experiments were conducted in a 12.2 m long, 6.1 m wide, and 1.5 m deep tank (Fig. 1). A sand mortar channel was built on a 0.3 m high false floor surrounded by a 0.3 m wide linear sump on three sides. The sump prevented sidewall reflection by allowing free fall of the current exiting the channel and the floodplain. The 3-bend sinuous channel had a sine-generated planform defined as

$$\theta = \theta_0 \sin\left(\frac{2\pi}{\lambda} s\right) \quad (1)$$

where θ is the angle between the channel centerline and the downslope valley direction; θ_0 is the angular amplitude of the channel centerline; λ is the arc wavelength measured along the centerline; and s is the tangential coordinate (Johannesson and Parker, 1989; Imran et al., 1999; Straub et al., 2011). In addition to three full bends, the channel had an entrance and an exit bend at the transition between the sinuous and the upstream and downstream straight parts of the channel. The channel dimensions are summarized in Table 1. The ratio of different characteristic dimensions of the channel was within the range of reported values for rivers and submarine channels (Pirmez and Imran, 2003). The floodplain elevation followed that of the channel bank and the lateral slope was set to be approximately zero. A 15 cm × 15 cm grid was drawn on the floodplain to aid in visualization of the overbank flow.

Three large storage tanks with a total volume of 13,250 L were used to mix water with silt and/or salt. A motorized mixer was run continuously during an experiment. Submerged pumps lifted the sediment water mixture to an overhead tank that maintained a constant water level, thus a constant discharge to the basin. The dense flow coming from the overhead tank entered in a box placed at the upstream end of the channel. Shipping peanuts placed inside the inlet box reduced turbulence by acting as passive suspended particles. The flow exited uniformly through a 7.5 m high screened sluice gate. An instrument bridge spanning the basin width was controlled from a computer. The probes were attached to two trolleys mounted on the bridge, also controlled from a computer. A Keyence laser displacement sensor was used to measure the bed elevation. The long-range mode was used; the elevation range was 250 mm to 750 mm from the sensor head with a spot diameter of 300 μm and precision of 50 μm. The profiler sends output voltage to a computer where the reading is translated to elevation in mm. Nine digital cameras with overlapping coverage were mounted on overhead tracks placed 4 m above the basin floor.

2.2. Experimental procedure

The inflow conditions of the experimental runs are described in Table 2. In a majority of the runs, the mixture consisted of 1.0% medium silt (30.2 μm), 0.1% coarse silt (45 μm), and 0.5% salt by mass with a flow rate of 2.5 L/s. The flow rate was selected to achieve a bank-full flow for the length of the channel except at the bend apices (Islam et al., 2008). Under bankfull conditions, the flow experienced stripping near a bend apex, but spilling to the overbank area due to water entrainment did not occur. The selected concentration represents a typical value expected in the field condition (e.g., Parker et al., 1986; Imran et al., 1998; Pirmez and Imran, 2003). A number of runs were made with different combinations of species (salt and or silt) concentration, and in one case, with a higher flow rate.

An experiment started with mixing the salt or silt, or both with 10,220 L tap water in the mixing tanks. Mixing was started about 4 h prior to the run. The submerged pumps in the mixing tanks pumped the water to the overhead tank where a constant head was maintained. The flow was then introduced to the channel through a screened sluice gate placed inside the inlet box. The density difference between the introduced current and the ambient tap water in the basin acted to drive the current in the downstream direction. A diluted carbon mixture was introduced with the current after it exited the inlet box during the first five minutes of the run. The carbon